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Impact of Sodium Ingestion During Exercise on Endurance Performance: A Systematic Review

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Abstract Sports nutrition guidelines frequently encourage sodium ingestion during endurance exercise, and much work has been undertaken to quantify sweat sodium losses during exercise. However, current guidelines for sodium do not recommend specific quantities, nor provide justification for the effectiveness of sodium to improve endurance performance. A systematic review was undertaken using six databases (CINAHL, Embase, Medline Ovid, Scopus, SPORTDiscus, and Web of Science) to determine the effect of sodium ingestion during exercise on endurance performance. Five studies met the inclusion criteria. They varied in quantity of sodium consumed (280 to 900mg/h), ingestion method (capsules or solutions), fluid intake (programmed or *ad libitum*) and performance outcomes (time trial, distance-test, time to exhaustion following steady state exercise, and finish time in an organized competition). Only one study reported a significant benefit from sodium ingestion (504mg/h) of 7.8%. All other studies found no significant effect of sodium on performance. Several limitations were found, including different ambient conditions across study days, *ad libitum* carbohydrate intake that was not reported, and performance measured during an organized competition where other factors may have influenced finish time. No study measured performance in hot ambient conditions (e.g., ≥30°C), and no study quantified each participant's sweat sodium losses beforehand, thus providing sodium intake as a proportion of expected losses. It is concluded that there is currently minimal evidence that sodium ingestion during exercise improves endurance performance. The limited number and quality of existing studies indicates a need for future work in this area.

Keywords Salt, Sweat sodium, Physical activity, Endurance exercise, Endurance performance

1. Introduction

During endurance exercise, the production of sweat for purposes of thermoregulation results in significant losses of body water, as well as electrolytes [1]. Because sodium is the predominant electrolyte lost through sweating, the quantification of these losses through sweat collection and analysis has been the subject of much attention from researchers [2-9]. It is generally accepted that optimal replacement of fluid and sodium during endurance exercise will enhance the rate of fluid absorption and gastrointestinal comfort, maintain total body water (TBW), plasma volume (P_V) and serum sodium concentration (serum $[Na^+]$) [1]. The maintenance of TBW and P_V, through adequate fluid and/or sodium intake, has been shown to prevent a performance decline in high intensity endurance efforts when they follow prolonged steady state exercise, with TBW losses of as little as 1-2% of initial body mass resulting in performance decrements [10, 11]. In contrast, larger TBW deficits appear to be required before a reduction in performance is seen in longer, submaximal endurance efforts [12]. In addition to the effect on body water, maintenance of blood sodium concentration is particularly important for the health of the athlete, with the consequences of exercise-associated hyponatraemia (EAH) a cause for great concern, especially in ultra-endurance sports populations [13-15]. Perhaps due to its greater overall influence on P_V and serum $[Na^+]$ [13, 16], and because it is easy to quantify in athletes [17], there has been significant attention paid to fluid replacement guidelines during exercise [1, 6]. Despite much effort to collect and analyse sweat composition in athletes, there are currently no specific recommendations for sodium replacement during exercise, with current guidelines stating only that sodium should be replaced "…when large sweat losses occur…" [18].

Anecdotally, many endurance athletes and their support teams seek to quantify sweat sodium losses through 'sweat testing' services, with the belief that specific sodium replacement will improve performance. This belief appears to include both direct performance benefits from sodium consumption, or indirect benefits through the prevention of exercise-associated muscle cramps (EAMC) and/or EAH.

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Commercial sweat composition testing services exist in many countries, and much work has been undertaken to improve the validity and reliability of field techniques for sweat collection and analysis [2, 8, 9, 19, 20]. However, the dichotomy between well validated sweat composition and testing protocols, and lack of specific sodium replacement guidelines, suggests an absence of research examining the effect of specific sodium replacement during exercise on subsequent endurance performance. Therefore, the aim of this systematic review was to determine the impact of quantifiable sodium replacement during exercise on endurance performance, either directly or by attenuating EAMC or EAH.

2. Methods

A systematic literature search was undertaken by two researchers, to determine the impact of sodium replacement during endurance exercise on measures of performance in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) statement [21].

2.1. Search Strategy

A three-step search was undertaken of published English-language studies in six online scientific databases from inception to March 2018 (CINAHL, Embase, Ovid MEDLINE, Scopus, SPORTDiscus, and Web of Science). In addition, the reference lists of all identified studies and other known review papers relevant to the topic were searched to identify additional studies that may have been missed by the original search. In order to obtain the level of methodological detail required, book chapters, opinion articles, reviews, unpublished works, abstracts, short reports, and case-studies were not considered. The keywords applied in the literature search are shown in Table 1.

2.2. Eligibility Criteria

Eligibility criteria were established by the researchers *a priori* in accordance with the Participant Intervention Comparator Outcomes Study (PICOS) design format [21]. Original field observational studies and/or laboratory-controlled trials, presenting quantified data on endurance performance, within an exercise protocol of more than 1 h duration, from participants exercising with two or more levels of sodium intake during exercise were considered for the review. Studies were suitable for inclusion if they involved either a time trial or distance-test, or time to exhaustion performance test, either as the entire exercise bout or following a period of steady state exercise. After duplicates were removed, the titles and abstracts were reviewed by two researchers against the eligibility criteria (Figure 1).

2.3. Data Extraction

Relevant data was extracted by two researchers and cross-checked. Variables extracted were the number of participants, age, training status (years of experience and $\dot{V}O_{2max}$ where available); dietary intervention (sodium intake during exercise); exercise protocol used, including performance test; environmental conditions during the exercise bout; hydration status before and changes during the exercise bout; heart rate, perceived exertion, and outcomes of the performance test. During the data extraction process eligibility was again checked, and appropriate inclusion or exclusion action was taken. Any difference of opinion between researchers during the review process was resolved by discussion and consensus. Where possible, units were standardised by simple mathematical conversion. Data were not considered appropriate for further synthesis into a meta-analysis due to the absence of homogeneous outcome measures.

2.4. Risk of Bias Assessment

Risk of bias assessment was performed using the Cochrane 'Risk of bias' assessment tool [22]. The tool assesses the risk of selection bias (due to random sequence generation and concealment of allocation), performance bias (from inadequate participant blinding), detection bias (inadequate personnel blinding), attrition bias (incomplete outcome data), reporting bias (selective reporting of outcomes), and other potential forms of bias.

Table 1. Search strategy for the systematic review on the effect of dietary sodium intake during exercise on endurance performance

Field One (combine with OR) – Population		Field Two (combine with OR) – Intervention and Comparison		Field Three (combine with OR) - Outcome
Keywords: Athlet*, Physical Exertion, Physical Activit*, Exercis*, Sport*	AND	Keywords: sodium*, sodium intake*, salt intake*, diet* adj2 salt, salt adj2 restrict*	AND	Keywords:, athletic perform*, endurance perfor., perform*
MeSH headings: Athletes, Exercise, Physical Exertion, Physical Activity, Exercise, Sports		MeSH headings: Sodium (dietary), Sodium, Diet (Sodium-restricted)		MeSH headings: athletic performance, endurance, endurance capacity

* used to retrieve unlimited suffix variations.

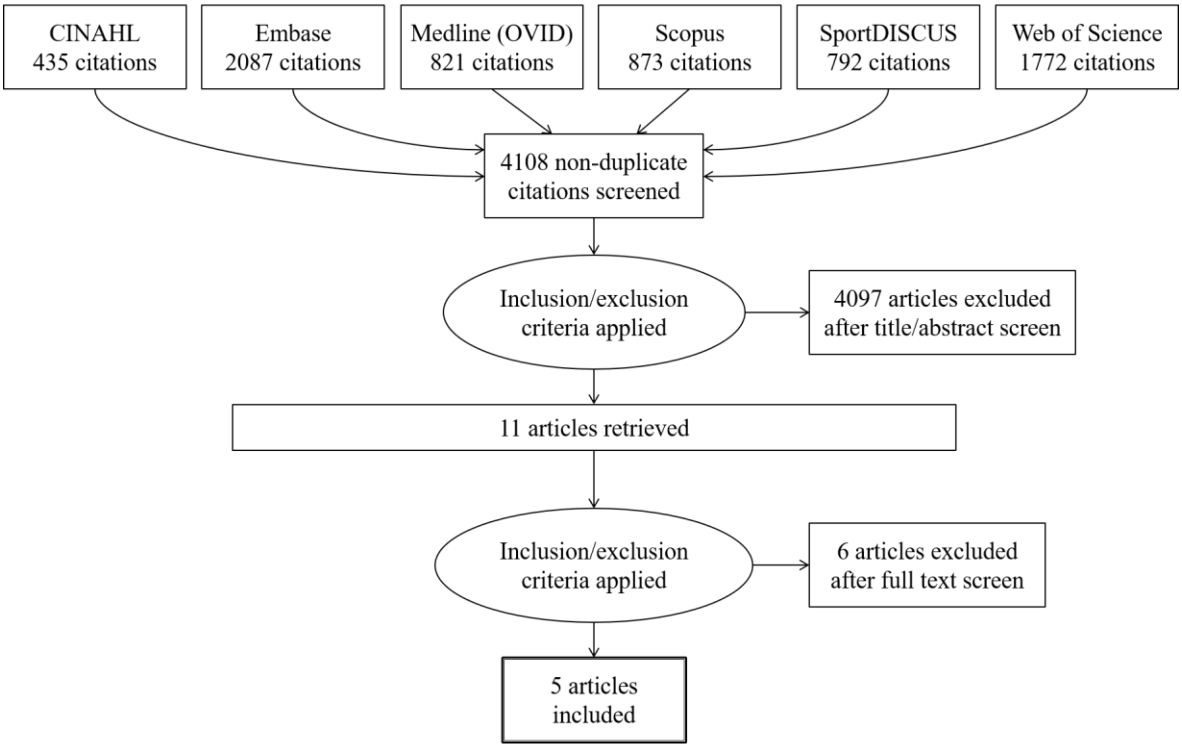

Figure 1. PRISMA diagram, showing the inclusion and exclusion of papers in the review

3. Results

3.1. Search Results

The initial database search yielded 4108 non-duplicate citations. 4097 of these were excluded on title and abstract screening, leaving 11 papers. Following the full text screening, five papers met all inclusion criteria and are included in this review (Table 2).

3.2. Study Characteristics

The five studies investigated the effect of sodium ingestion during exercise on different aspects of endurance performance. One study [23] used a time trial, one a distance-test [24], one time to exhaustion following steady state exercise [25], and two provided known quantities of sodium during an organized endurance competition [26, 27]. Each of these performance types will be described separately. Participants across these studies included both sexes. Mean or median age varied between studies, from 27 [23] to 40 years [24]. Training experience (in years) or cardiorespiratory fitness ($\dot{V}O_{2max}$) was not reported in three of the five studies [24, 25, 27]. All studies were undertaken in temperate ambient conditions with minimal variation between interventions, except one study in which the temperature varied from 2.6-20.6°C across trial days, resulting in an effect of trial order on performance [24]. Pre-exercise hydration status, by measurement of any combination of TBW, plasma osmolality, plasma or serum [Na^+], or urine osmolality was reported in all but one study [25]. The rate of sweat loss and subsequent changes in body mass were reported in all studies and were not significantly different between interventions. P_V changes were reported only in one study [23], in which sodium supplementation increased P_V by 1.8%, whilst placebo resulted in a 0.9% reduction ($p < 0.05$).

3.3. Dietary Intervention

All studies provided sodium in the form of sodium chloride. In four of the studies this was provided in capsules and compared to a placebo capsule that contained no sodium in a blinded manner [23, 25-27], whilst in the fifth study [24] sodium was provided unblinded in a solution, with a high and low sodium concentration as well as a water only control. The quantity of sodium provided varied between studies from 280 to 900 mg/h. The quantity provided per hour was not related to the exercise duration or ambient conditions. In all studies the amount of sodium provided was the same for every participant per hour of exercise, with no individualisation of sodium dose based on the participant's body mass, sweat sodium concentration, or expected sweat sodium losses.

Table 2. Systematic review search results, showing included papers to determine the impact of sodium ingestion during exercise on endurance performance

Reference	Participants	Sodium intake intervention, fluid & CHO intake during exercise	Environmental conditions	Exercise Protocol	Change in hydration status	Heart Rate (bpm) and Rating of Perceived Exertion	Performance, EAH and EAMC
Cosgrove & Black (2013)	9 well trained cyclists (male: 5, female: 4), Age 27 ± 9 years, VO_{2max} 62 ± 8 mL/kg/min	Crossover trial: Na: 280mg/h given in capsules (NaCl or placebo) Fluid: *Ad libitum* Na: 428 ± 166 mL/h Placebo: 269 ± 65 mL/h * CHO: *Ad libitum*, quantities consumed not reported	Na: T_{amb} 14.0 ± 2.1°C, 63% RH Placebo: T_{amb} 13.5 ± 2.1°C, 63% RH	72km cycling TT outdoors (undulating course)	Sweat Rate: Na: 570 ± 220 mL/h Placebo: 710 ± 290 mL/h ^{NS} Body Mass Loss: Na: 1.0 ± 0.8% Placebo: 1.0 ± 0.6% ^{NS} P_V Change: Na: +1. 8 ± 2.2% Placebo: -0.9 ± 1.8% * Pre-ex Plasma $[Na^+]$: Na: 142 ± 2 mmol/L Placebo: 140 ± 1 mmol/L *	Mean HR: Na: 158 ± 9 Placebo: 157 ± 9 ^{NS}	72km TT performance: Na: 171.3 ± 23.5 min Placebo: 172.3 ± 23.3 min ^{NS} EAH: None in either group EAMC: Not reported
Del Coso et al. (2016)	26 well trained male triathletes Age 37 ± 7 years Experience 8 ± 3 years	Randomised trial: Na: 504mg/h, given in capsules (Saltstick caps or placebo) consumed during transitions & bike leg. Fluid: *Ad libitum* Na: 371 ± 78 mL/h Placebo: 273 ± 109 mL/h* CHO: *Ad libitum* Na: 32 ± 14 g/h Placebo: 40 ± 17 g/h ^{NS}	T_{amb} 22.5 ± 2.7 °C, 36.8 ± 8.3% RH	Half IM distance triathlon race	Sweat Rate: Na: 781 ± 214 mL/h Placebo: 721 ± 198 mL/h ^{NS} Body Mass Loss: Na: 3.4 ± 1.3% Placebo: 2.8 ± 0.9% ^{NS} P_V not reported POsm (Na intervention): Pre-ex: 291 ± 4 mOsm/kg Post-ex: 304 ± 5 mOsm/kg † POsm (Placebo): Pre-ex: 291 ± 6 mOsm/kg Post-ex: 300 ± 4 mOsm/kg † Serum $[Na^+]$ (Na intervention): Pre-ex: 142 ± 2 mmol/L Post-ex: 145 ± 2 mmol/L † Serum $[Na^+]$	HR not reported Whole-race RPE obtained post-exercise: Na: 17 ± 2 Placebo: 16 ± 3 ^{NS}	Race finish time: Na: 307 ± 32min Placebo: 333 ± 40 min * EAH: Not reported EAMC: Not reported

					(Placebo): Pre-ex: 141 ± 1 mmol/L Post-ex: 143 ± 2 mmol/L †		
Earhart et al. (2015)	11 experienced runners/ cyclists (male: 4, female: 7), 2 cycling, 9 running Age 31 ± 12 years	Crossover trial: Na: 900mg/h, given in capsules (NaCl or placebo) Fluid: 400 mL/h for body wt up to 70kg, 600 mL/h to body wt 70-89kg, 800 mL/h for body wt >90kg. CHO: Not reported	Na: 21.0 ± 0.6℃, 34.5 ± 11.0% RH Placebo: 21.3 ± 0.3℃ 34.88 ± 10.6% RH	2hr treadmill running or stationary cycling at 60% HRR, followed by TTE at incremental increasing intensity	Sweat Rate: Na: 1016 ± 239 mL/h Placebo: 1054 ± 278 mL/h NS Body Mass Loss: Na: 2.0 ± 0.4% Placebo: 2.3 ± 0.7% NS P_V not reported	Peak HR: Na: 181 ± 13 Placebo: 180 ± 12 NS Mean RPE during steady state: Na: 13 ± 1 Placebo: 13 ± 1 NS	Time To Exhaustion: Na: 6.88 ± 3.88 min Placebo: 6.96 ± 3.61min NS EAH: Not reported EAMC: One participant in the evening after the Na trial
Hew-Butler et al. (2006)	114 IM triathletes (male: 104, female: 10) Age 34 ± 7 years	Randomised trial: Na: 284 ± 160 mg/h, given in capsules (NaCl or placebo) Fluid: *ad libitum* and not reported CHO: *ad libitum* and not reported	Range: T_{amb} 15.6-20.9℃, 48-79% RH	IM triathlon race	Sweat Rate: Na: 229 ± 102 mL/h Placebo: 236 ± 134 mL/h NS Body Mass Loss: Na: 3.6 ± 1.4% Placebo: 3.9 ± 2.1% NS P_V not reported Serum [Na^+] (Na intervention): Pre-ex: 141 ± 2 mmol/L Post-ex: 142 ± 3 mmol/L NS Serum [Na^+] (Placebo): Pre-ex: 141 ± 2 mmol/L Post-ex: 141 ± 4 mmol/L NS	HR not reported Exercise intensity (1-10 scale, converted to 6-20 RPE scale): Na: 16 ± 9 Placebo: 16 ± 9 NS	Race finish time: Na: 758 ± 88 min Placebo: 762 ± 101min NS EAH: One participant in the placebo group developed EAH. EAMC: Not reported
Twerenbold et al. (2003)	13 well trained female runners Age: Median (range) 40 (22-53) years	Crossover trial: High Na – 680 mg/h Low Na – 410 mg/h Water – 0 mg/h Taken in water with different NaCl concentrations Fluid: 1000 mL/h in all	Range T_{amb}: 2.6-20.6°C, large differences on different trial days, RH not reported	4 hour running DT on outdoor athletics track	Sweat Rate: High Na: 525 ± 250 mL/h Low Na: 450 ± 300 m/h Water: 475 ± 475 mL/h NS Body Mass Loss: High Na: 3.6 ± 1.7% Low Na: 3.1 ± 2.1% Water: 3.3 ± 3.3%	HR and RPE not reported	4hr Distance Trial: High Na: 39.9 ± 4.3 km Low Na: 42.0 ± 4.8 km Water: 40.6 ± 5.2 km NS Mild EAH (plasma [Na^+] 130-135mmol/L): High Na: 46% of

trials	NS	participants Low Na: 69%
CHO: 60 g/h in Low Na and water trials, 63 g/h in High Na trial.	P_V not reported	Water: 92%
	Plasma [Na^+] Pre-ex: High Na: 137 ± 1 mmol/L Low Na: 137 ± 1 mmol/L Water: 138 ± 2 mmol/L NS	Severe but asymptomatic EAH (plasma [Na^+] <130mmol/L): High Na: 0% of participants Low Na: 0% Water: 17%
	Plasma [Na^+] Pre-ex: High Na: 135 ± 3 mmol/L Low Na: 133 ± 2 mmol/L Water: 131 ± 2 mmol/L §	Symptomatic EAH: None in any group EAMC: Not reported

EAH: Exercise-associated hyponatraemia, EAMC: Exercise-associated muscle cramps, Na: Sodium, NaCl: Sodium chloride, CHO: Carbohydrate T_{amb}: ambient temperature, RH: relative humidity, TT: time trial, TTE: time to exhaustion, DT: distance-test, IM: Ironman, HRR: Heart Rate Reserve, RPE: Rating of Perceived Exertion (6-20), P_V: Plasma volume, NS: Not significant, † Difference pre- to post-exercise, * Difference between sodium intakes ($p < 0.05$), § Difference between high Na and water interventions ($p < 0.05$).

3.4. Effect of Sodium Intake on Time Trial Performance

One study assessed time trial performance in a 72 km cycling time trial on an outdoor course, including both male (n= 5) and female (n= 4) athletes. Capsules provided either 280 mg/h or 0 mg/h of sodium, and mean heart rate (p= 0.86) and time trial performance was not different between interventions (p= 0.46).

3.5. Effect of Sodium Intake on Distance-test Performance

One study assessed the distance covered in four hours around an outdoor running track in female ultramarathon runners (n= 13) [24]. In a crossover design, a high and low concentration of sodium solution were consumed as well as water in separate trials, in an unblinded fashion. There were no significant differences in the distance completed between interventions, however it should be noted that an effect of trial order was found (p < 0.0001), most likely due to the variable ambient conditions on each trial day (temperature range of 2.6-20.6°C across trials).

3.6. Effect of Sodium Intake on Time to Exhaustion following Steady State Endurance Exercise

One study assessed the time to exhaustion of male (n= 7) and female (n= 4) endurance athletes during an incremental exercise test using either stationary cycling with increasing power output (n= 2), or treadmill running with increasing gradient (n= 9) in a laboratory setting [25]. The incremental test was preceded by two hours of steady state cycling or running at 60% of heart rate reserve. Capsules provided either 900 mg/hr or 0 mg/hr sodium, and time to exhaustion was not different between interventions (p= 0.919).

3.7. Effect of Sodium Intake on Performance during Organized Endurance Competitions

Two studies assessed the effect of sodium intake on performance during an organized half- (n= 26, all male) [26] and full-Ironman (IM) triathlon (n= 114, 104 male) [27]. Participants were randomised to consume either sodium or placebo capsules throughout the race (half-IM 504 mg/h, IM 284 mg/h). Fluid and carbohydrate (CHO) were consumed *ad libitum* in both studies. In the half-IM, fluid intake was significantly greater in the sodium compared to placebo group (371 ± 78 and 273 ± 109 mL/h respectively, p= 0.05) with no significant difference in CHO intake (p= 0.39) [26]. Fluid and CHO intake were not reported in the IM study [27]. In the Half-IM, mean finish time was 7.8% faster in the sodium group compared to placebo (p= 0.04) [26], whereas there was no difference in finish time between groups in the IM (p= 0.14) [27].

3.8. Effect of Sodium Intake on EAMC and EAH

Only one study reported on the incidence of EAMC, noting only one participant reported EAMC, in the evening after the exercise bout was completed, having consumed the high Na intake during exercise [25]. Three of the five studies reported incidence of EAH. One reported no cases of EAH [23]. Another reported a single participant developing symptomatic EAH requiring hospitalisation, following excessive fluid ingestion and substantial body mass gain [26]. A third study reported an incidence of more than 40% for asymptomatic EAH in participants with no, low and high sodium ingestion [27], when fluid was ingested at around double the rate of sweat losses. The incidence of mild EAH (plasma sodium concentration

130-135 mmol/L) was lower with increasing sodium intake (High Na: 46%, Low Na: 69%, Water: 92%) and post-exercise plasma sodium concentration was significantly lower with water compared to low and high sodium intakes ($p < 0.001$) [27].

3.9. Risk of Bias Assessment

Results of the risk of bias assessment are shown in Table 3. Selection bias was not evident in any study. Potential performance and detection bias was observed in one of the five papers [24], due to a lack of blinding of the sodium intervention. Potential reporting bias was seen due to uneven or unreported participant drop outs in two studies [25, 27], although the effect of this was unclear. The main sources of bias however came from inadequate control of ambient conditions and dietary intake, with at least one of these factors evident in all included studies. Overall none of the studies were deemed low risk of bias, with three deemed unclear [25-27] and two high risk of bias [23, 24].

4. Discussion

The ingestion of sodium during endurance exercise is commonplace and is reflected in the specific inclusion of sodium in sports nutrition guidelines and many sports nutrition targeted commercial products [1, 6, 18]. This systematic review aimed to determine the effect of quantifiable sodium ingestion during exercise on endurance performance outcomes. Our search of the literature found only five studies that met the inclusion criteria, and only one that suggested a benefit from sodium replacement on endurance performance [26], at least for the exercise intensities, durations, and sodium intake doses studied. It should also be noted that the quality of the included studies was generally poor, due to variations in ambient conditions between trial days, and differences in CHO or fluid intake between interventions.

Table 3. Risk of bias assessment for the systematic review to determine the impact of sodium ingestion during exercise on endurance performance, using the Cochrane Collaboration's 'Risk of bias' tool [20]

Criteria	Cosgrove & Black (2013)	Del Coso et al. (2016)	Earhart et al. (2015)	Hew-Butler et al. (2006)	Twerenbold et al. (2003)
Random sequence generation	Randomized crossover design	Participants were pair-matched for age, anthropometry, experience and best race time, then randomly allocated	Randomized crossover design	Random allocation	Randomized crossover design
Allocation concealment	Randomized crossover design	Not stated	Randomized crossover design	Not stated	Randomized crossover design
Participant/ personnel blinding	Participants and personnel blinded	Participants and personnel blinded	Participants blinded. Personnel blinding not stated	Participants blinded. Personnel blinding not stated	Not blinded.
Outcome assessment blinding	Personnel blinded	Personnel blinded	Not stated	Not stated	Not stated
Incomplete outcome data	Complete	Drop outs reported and even across both groups	Incomplete – one drop out due to GI distress from NaCl capsules, two due to schedule conflicts	Drop outs described but not clear from which group	Not stated
Selective reporting	N/A - only one outcome measure reported	N/A - only one outcome measure reported	N/A - only one outcome measure reported	N/A - only one outcome measure reported	N/A - only one outcome measure reported
Other potential sources of bias	Outdoor time trial on two separate occasions, possible differences in wind speed/direction. CHO intake *ad libitum* but intake not reported. Fluid intake greater in Na trial compared to placebo ($p < 0.05$).	Fluid intake greater in Na trial compared to placebo ($p < 0.05$). Performance measured in organized race with other competitors, which may influence performance	CHO intake not reported – presumed to be none	CHO and fluid intake *ad libitum* but not reported – possible differences between groups. Performance measured in organized race with other competitors, which may influence performance	Large differences in ambient temperature between trial days (by 15°C). Effect of trial order on performance.
Judgement	High risk of bias	Unclear risk of bias	Unclear risk of bias	Unclear risk of bias	High risk of bias

4.1. Study Methodologies

Sweat sodium losses vary significantly between and within individuals, with sweat fluid losses and sweat sodium concentration both determinants [2]. These factors in turn are influenced by exercise mode, intensity, duration and ambient conditions; body composition; sweat gland density and distribution; heat acclimation and/or acclimatisation, and possibly dietary sodium intake [2, 4, 15]. Although four of the five studies provided sodium or placebo in capsules during exercise, in temperate ambient conditions, the sodium dose consumed per hour varied by a factor of three between studies. The amount was not related to participant body mass, ambient conditions or exercise duration. We were surprised to find no studies have attempted to measure the participant's sweat sodium losses in well-controlled laboratory conditions, and/or provide sodium in quantities that represented a specific proportion of their expected losses. It cannot be determined from the included studies if the sodium ingested was adequate to replace a given proportion of sodium losses in some, all or none of the participants. The arbitrary nature of the sodium interventions would make interpretation of results difficult, if indeed there was a dose-dependent effect of sodium ingestion on performance.

The performance outcomes measured in the included studies also varied considerably. Notwithstanding the differences in validity between time to exhaustion and time trial or distance-tests [28], there was no particular effect of the type of performance measured on whether or not sodium intake was beneficial. The single study to show a performance improvement did so by measuring the effect of ingestion of sodium or placebo capsules, in a blinded manner, on finish time of a half-IM triathlon [26]. In contrast, the study of sodium supplementation on performance in a full distance Ironman triathlon failed to find a difference in performance [27]. The inclusion of these two studies is also of interest, with advantages and disadvantages of measuring performance during an organized competition. Ultimately, performance during actual endurance events is the outcome of most importance to athletes, so it can be argued that these studies represent ecologically valid performance measures. On the other hand, this design introduces the possibility that performance outcomes are influenced by factors other than the intervention studied (e.g. sodium ingestion), reducing the reliability of this study design [28]. As both studies that occurred during organized competitions were triathlon events, variables such as the time spent in transition between legs, stopping or slowing down at aid stations, race tactics in response to other competitors and changes in race scenario could all conceivably influence the primary outcome, namely event finish time. We note that the performance improvement attributed to sodium supplementation in the half-IM event was 7.8% [26], a performance difference that would seem implausibly high from a single nutritional intervention alone. In laboratory-controlled studies measuring time trial performance, the beneficial effects of varied CHO, fluid, and/or caffeine ingestion are rarely greater than 5% [29-31]. Therefore, we suggest that future studies use an ecologically valid exercise model, but do so in a more controlled laboratory or field-based setting to improve their reliability.

Four of the five included studies were conducted outdoors [23, 24, 26, 27]. This means that ambient temperature, relative humidity, wind speed and direction could vary considerably between intervention groups. In the organized competition studies, participants competed at the same time, taking either sodium or placebo supplementation. Therefore conditions were not different between groups at race start, but may have differed as event duration increased in time. For the crossover trials however, participants completed trials on different days. One study [24] observed an effect of trial order, likely due to large differences in ambient temperature between trial days. Cosgrove and Black [23] reported no significant difference in ambient conditions between trial days but did not report wind conditions, other than to state the course and time of day was chosen to minimise the influence of the wind. Cycling time trial performance is significantly affected by wind speed and direction, whereby even subtle changes could conceivably have measurable effects on performance [32]. To our surprise, none of the included studies were completed in hot ambient conditions (e.g., ≥30°C), where any theoretical benefit of sodium ingestion on performance would be expected to be greater, due to increased fluid and sodium losses. Moreover, in hot ambient conditions the total sodium losses would be expected to be greater than temperate conditions due to increased sweating rate, especially for individuals who are not heat acclimated [2]. Although excessive fluid intake has been identified as the main cause of EAH in most cases, there are suggestions that excessive sweat sodium losses even in the absence of fluid excess can increase the risk of a hypovolaemic EAH, the development of which, if symptomatic, would almost certainly impair performance [13]. Ideally, studies of sodium intake during exercise and performance would be conducted in a laboratory setting, in both hot and temperate ambient conditions, with careful control of all environmental variables.

Two other major control variables when measuring endurance exercise performance are the intake of CHO and fluid during the exercise bout. The effect of CHO intake on performance is well established, with increased CHO ingestion during the exercise durations of the included studies likely to be beneficial to performance [31]. Despite this, only one of the included studies provided a standardised CHO intake across intervention groups (60g/h in low and no sodium trials, 63g/h in high sodium trial) [24], while one of the included studies conducted during an organized competition allowed *ad libitum* CHO intake and reported no difference between groups (sodium intervention:

32 g/h, placebo: 40 g/h) [26]. Differences in fluid intake between intervention groups may also be of significance to the performance outcomes of the included studies. It is therefore perhaps surprising that only two of the included studies standardised fluid intake between interventions [24, 25], with the other three allowing *ad libitum* fluid intake [23, 26, 27]. Of the three studies where fluid intake was allowed *ad libitum*, two reported actual fluid intake, and in both cases fluid intake was significantly greater with sodium supplementation compared to placebo [23]. Some authors have suggested that one of the benefits of sodium ingestion during exercise is the stimulation of thirst and subsequently greater voluntary fluid intake and fluid retention [1]. Therefore, it could be argued that the lack of standardisation of fluid intake represents a feature rather than a flaw in study design. In future studies, comparison of sodium intake with both standardised and *ad libitum* fluid intakes would be helpful in understanding whether sodium has a direct (when fluid intake is standardised) or an indirect effect (due to stimulation of greater fluid intake) on performance in different scenarios.

Finally, the method of sodium ingestion may also be important in determining any performance effect. Four of the five included studies provided sodium in capsule form. This provides the distinct advantage of participant blinding, since the distinctive taste of sodium chloride cannot be detected and compared to the placebo. The use of capsules assumes that any effect of sodium ingestion occurs from absorption of sodium from the gastrointestinal tract, and subsequent effects on P_V, osmolality and thirst drive. Given that there appear to be effects of both CHO and caffeine in the oral cavity on performance, without ingestion [33, 34], it is conceivable that there could be an independent effect of sodium in the oral cavity that is independent of consuming it in capsule form. Future studies may be able to examine this relationship by comparing the consumption of sodium capsules and solutions on endurance performance.

4.2. Mechanisms for a Potential Effect of Sodium Intake during Endurance Exercise on Performance

Guidelines that encourage the consumption of sodium during endurance exercise suggest two mechanisms that could theoretically improve performance. Firstly, sodium intake increases thirst and promotes greater voluntary fluid consumption [1]. Secondly, sodium ingestion promotes greater P_V retention and reduces urine output [1, 6]. These mechanisms are often cited by sports nutrition companies commercialising sodium containing products, implying exercise performance benefits from quantified sodium ingestion during endurance exercise. Of the three studies included in this review where fluid was consumed *ad libitum* during exercise, two found increased fluid consumption with sodium supplementation [23, 26], whilst the other did not report fluid intake [27]. But despite the theoretical rationale that increased fluid intake would improve performance, only one of these three studies found a performance benefit from increased sodium (and subsequently increased fluid) intake [26]. It is possible that the exercise duration and subsequent relative exercise intensity required to optimise performance in these scenarios was too long and too low respectively; such that TBW and P_V are not limiting factors on performance, or that because the rate of sweating is less with lowered exercise intensity, *ad libitum* fluid intake is adequate to maintain P_V even in the absence of sodium ingestion. Only one of the included studies reported change in P_V during exercise, and although there was an effect of sodium ingestion, P_V in the placebo group showed a reduction of less than 1% [23]. Studying the effect of sodium ingestion during exercise in hot ambient conditions (e.g., ≥30°C) would provide more insight into whether the greater maintenance of TBW and P_V with sodium ingestion subsequently improves performance.

4.3. Sodium Ingestion during Exercise, Endurance Performance and Current Sports Nutrition Guidelines

Current sports nutrition guidelines specifically include sodium as a key nutrient of interest, especially for endurance athletes [1, 18]. However unlike CHO and fluid, no specific sodium consumption recommendations are advised, and there is minimal evidence to draw a link between sodium ingestion and endurance performance. This is not surprising given the findings of this systematic review, which found only a small number of studies on the topic, with methodologies that resulted in an unclear or high risk of bias in all cases, and with no participant-specific sodium intake levels used. This points to the need for more controlled and robust research in this area, in order to better inform sports nutrition recommendations and guidelines in the future. Such research should include careful dietary standardisation of both macronutrient and sodium intake in the days prior to exercise, careful control of exercise intensity and duration, pre-exercise hydration status, heat acclimation status and ambient conditions [4]. In addition, sweat sodium losses should be measured in an identical prior exercise bout, with whole body washdown the preferred method of sweat collection [2], and sodium replacement provided during exercise as a proportion of the expected losses, which can vary considerably [3].

4.4. Study Limitations

One potential limitation to this systematic review is that other existing studies were missed during our search. We attempted to minimise this risk by searching the reference lists of the identified papers, and of known review papers relevant to the topic. We were also unable to perform a meta-analysis of the included papers, due to the large differences in study design, particularly the exercise performance outcome measures used.

5. Conclusions

Endurance athletes anecdotally consume sodium containing foods, fluids, and supplements during endurance exercise, partly in the belief that it will improve their exercise performance. In addition, commercial sweat testing services allow quantification of sweat sodium losses during exercise, providing athletes with an information guide to replace expected losses during training or competition. However, our systematic review failed to find any studies that examine the effect of quantified sodium replacement according to expected losses during endurance exercise. In addition, we found that arbitrary sodium ingestion during endurance exercise does not improve endurance performance compared to no sodium intake in temperate ambient conditions, albeit that all of the identified studies were found to have either a high or unclear risk of bias, and participants were not impaired during exercise by either EAMC or symptomatic EAH from either the presence or absence of sodium intake during the exercise bout. There are currently no studies that describe the effect of sodium ingestion during exercise on endurance performance in hot ambient conditions. Future research should attempt to address these issues, with valid and reliable quantification of sweat sodium losses to inform sodium replacement strategies, both programmed and *ad libitum* fluid ingestion, during well controlled exertional-heat stress models, whilst ensuring adequate control of study blinding and potentially confounding variables such as CHO intake, hydration status, wind speed and direction.

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