Appetite 180 (2023) 106375

Contents lists available at ScienceDirect

Appetite

journal homepage: www.elsevier.com/locate/appet

Influence of water-based exercise on energy intake, appetite, and appetite-related hormones in adults: A systematic review and meta-analysis

Marie J. Grigg [a,*], C. Douglas Thake [a], Judith E. Allgrove [b], James A. King [c,d], Alice E. Thackray [c,d], David J. Stensel [c,d,e], Alun Owen [a], David R. Broom [a]

[a] *Centre for Sport, Exercise and Life Sciences, Coventry University, CV1 2DS, United Kingdom*
[b] *Applied and Human Science Department, Kingston University, London, KT1 2EE, United Kingdom*
[c] *National Centre for Sport and Exercise Medicine, School of Sport, Exercise and Health Sciences, Loughborough University, Epinal Way, Loughborough, United Kingdom*
[d] *National Institute for Health Research (NIHR) Leicester Biomedical Research Centre, University Hospitals of Leicester, National Health Service (NHS) Trust and the University of Leicester, Leicester, United Kingdom*
[e] *Waseda University, Faculty of Sport Sciences, 2-579-15 Mikajima, Tokorozawa, Saitama, 359-1192, Japan*

ARTICLE INFO

Keywords:
Appetite
Energy intake
Appetite-related hormones
Energy balance
Exercise
Energy compensation

ABSTRACT

Single bouts of land-based exercise suppress appetite and do not typically alter energy intake in the short-term, whereas it has been suggested that water-based exercise may evoke orexigenic effects. The primary aim was to systematically review the available literature investigating the influence of water-based exercise on energy intake in adults (PROSPERO ID number CRD42022314349). PubMed, Medline, Sport-Discus, Academic Search Complete, CINAHL and Public Health Database were searched for peer-reviewed articles published in English from 1900 to May 2022. Included studies implemented a water-based exercise intervention versus a control or comparator. Risk of bias was assessed using the revised Cochrane 'Risk of bias tool for randomised trials' (RoB 2.0). We identified eight acute (same day) exercise studies which met the inclusion criteria. Meta-analysis was performed using a fixed effects generic inverse variance method on energy intake (8 studies (water versus control), 5 studies (water versus land) and 2 studies (water at two different temperatures)). Appetite and appetite-related hormones are also examined but high heterogeneity did not allow a meta-analysis of these outcome measures. We identified one chronic exercise training study which met the inclusion criteria with findings discussed narratively. Meta-analysis revealed that a single bout of exercise in water increased *ad-libitum* energy intake compared to a non-exercise control (mean difference [95% CI]: 330 [118, 542] kJ, $P = 0.002$). No difference in *ad libitum* energy intake was identified between water and land-based exercise (78 [-176, 334] kJ, $P = 0.55$). Exercising in cold water (18–20 °C) increased energy intake to a greater extent than neutral water (27–33 °C) temperature (719 [222, 1215] kJ; $P < 0.005$). The one eligible 12-week study did not assess whether water-based exercise influenced energy intake but did find that cycling and swimming did not alter fasting plasma concentrations of total ghrelin, insulin, leptin or total PYY but contributed to body mass loss 87.3 (5.2) to 85.9 (5.0) kg and 88.9 (4.9) to 86.4 (4.5) kg ($P < 0.05$) respectively. To conclude, if body mass management is a person's primary focus, they should be mindful of the tendency to eat more in the hours after a water-based exercise session, particularly when the water temperature is cold (18–20 °C).

1. Introduction

Exercise is an effective way to improve mental and physical health and can influence weight management due to the energy expenditure (Stensel, 2010). Energy balance is influenced by day-to-day variations in energy intake and expenditure and evidence suggests a single bout of vigorous intensity exercise suppresses appetite during and in the immediate post-exercise period (Broom et al., 2007). This coincides with changes in both orexigenic (appetite stimulating) hormones such as ghrelin and anorexigenic (appetite suppressing) hormones such as

* Corresponding author.
E-mail addresses: hutsonm2@uni.coventry.ac.uk (M.J. Grigg), apx223@coventry.ac.uk (C.D. Thake), J.Allgrove@kingston.ac.uk (J.E. Allgrove), j.a.king@lboro.ac.uk (J.A. King), A.E.Thackray@lboro.ac.uk (A.E. Thackray), D.J.Stensel@lboro.ac.uk (D.J. Stensel), aa5845@coventry.ac.uk (A. Owen), ad5173@coventry.ac.uk (D.R. Broom).

https://doi.org/10.1016/j.appet.2022.106375
Received 29 September 2022; Received in revised form 10 November 2022; Accepted 11 November 2022
Available online 12 November 2022

Peptide Tryosine Tryosine (PYY) and Glucagon Like Peptide-1 (GLP-1) (Dorling et al., 2018). The phenomenon has been described as exercise-induced anorexia but does not necessarily lead to compensation i.e., eating more at the next meal (Schubert et al., 2013).

Many studies investigating the effects of exercise on appetite and energy intake have used land-based physical activities such as walking, jogging and running on treadmills, rowing and cycling on ergometers or resistance training using body mass, free weights or machines. This is potentially because the equipment to undertake these exercise modes is more accessible and readily available and participants are more accustomed to them.

Water-based exercise (WBE) is also an effective mode of physical activity to encourage people to move more for health and to reduce the risk of developing diseases associated with physical inactivity and sedentary behaviour (Chase et al., 2008). The lower stress and impact nature of WBE has been shown to reduce age-related bone deterioration when compared to no-exercise (Simas et al., 2017) making it a suitable alternative to land-based exercise for older adults or those living with a disability or obesity who may have joint problems (Scheer et al., 2020). Evidence suggests WBE improves strength, balance, and cardiorespiratory fitness in healthy people (Reichert et al., 2018) and improves overall quality of life in people suffering with chronic diseases such as musculoskeletal disease, heart disease, type 2 diabetes, multiple sclerosis, and Parkinson's disease (Faíl et al., 2022).

Anecdotal evidence suggests that water-based exercise influences appetite differently to land-based exercise, with participants commenting that they felt 'ravenous' after swimming (Shaw et al., 2014). Empirical evidence suggests that exercising in cold water may increase appetite, making it a less favourable mode of exercise to promote body mass loss and facilitate weight loss maintenance. White et al. (2005) reported 45-min of aqua-cycling in water temperature set at 20 °C caused post-exercise *ad-libitum* energy intake to increase by 44% when compared to aqua-cycling in 33 °C water temperature. Although Thackray et al. (2020) demonstrated that *ad-libitum* energy intake was similar after a 42-min bout of swimming versus land-based cycling, hunger was rated higher after swimming versus cycling.

The arcuate nucleus, housed within the hypothalamus is responsible for regulating energy intake and expenditure (Na et al., 2022) and expresses two appetite related peptides; agouti-related peptide (ArRP) responsible for stimulating appetite, and proopiomelanocortin (POMC) responsible for suppressing appetite (Vicent et al., 2018). A group of cation channels located within the brain, called transient receptor potential (TRP) channels act as pain, taste, chemical and temperature sensors (Tsuji & Aono, 2012). Jeong et al. (2018) reports that when body temperature rises in response to exercise, the POMC neurons express signals via transient receptor potential vanilloid 1 (TRPV1) which results in the suppression of appetite. When body temperature falls in response to cold exposure, Yang et al. (2021) shows in mice that ArRP neurons are activated, which results in hunger-dependent feeding behaviour.

When immersed in water, body heat is lost through both conduction and convection (Fudge, 2016). Habitual cold-water swimmers may develop a greater storage of body fat than individuals primarily engaging in land-based forms of exercise (Flynn et al., 1990). Having more body fat and skin-fold thickness protects against heat loss (Pugh et al., 1960) which has been shown to be necessary for survival in cold water (Tarlochan & Ramesh, 2005) and makes swimming in cold water more tolerable (Knechtle et al., 2009). As the temperature of swimming pool water is typically between 20 and 25 °C, and seasonal open water swimming can involve temperatures as low as 10 °C–15 °C (Tipton & Bradford, 2014), exercising in cold water could stimulate hunger encouraging energy intake after exercise. There is a paucity of data examining this hypothesis.

Greater understanding of whether exercising in water influences appetite and energy intake differently to land based exercise is necessary when considering weight management strategies. This is the first systematic review and meta-analysis to address the research question, does water-based exercise influence energy intake, appetite, and appetite related hormones differently to land based exercise in adults?

2. Methods

The reporting and conduct of this systematic review and meta-analysis are based on the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement (Page et al., 2021). This review is registered with the Prospective Register of Systematic Reviews (PROSPERO) database (ID number CRD42022314349).

2.1. Research objectives

The objectives of this systematic review and meta-analysis are to examine the acute and chronic effects of water-based (swim, aqua-bike, aqua-walk/run) versus land-based (walk, run, bike) exercise, water-based exercise versus no exercise control and water-based exercise at different temperatures, on energy intake, appetite, and appetite related hormones (ghrelin, PYY, GLP-1) in adults. This review addresses the question, does water-based exercise affect appetite differently to land-based exercise or exercise in water at different temperatures?

2.2. Eligibility criteria

We included randomised controlled/crossover trials of adults (≥18 years) of varying weight status. Studies excluded participants taking medication known to influence appetite, who had an eating disorder, exercised for rehabilitation purposes, was pregnant or lactating, had lost significant body mass (>2 kg) in the past 6 months (Broom et al., 2017) or who smoked, took weight management medication, or abused alcohol. We also excluded any studies which solely included children or young people (<18 years).

We considered all supervised exercise and physical activity that was water-based (i.e., swimming, aqua-bike, aqua-walk/run) when compared to supervised land-based exercise (i.e., walking, running, cycling). Whilst rowing could be considered 'water-based' participants are not immersed in water so studies involving rowing on water or using indoor rowing ergometers were considered 'land-based'. Studies were also eligible if they compared water-based exercise to a resting control or compared water-based exercise at different temperatures.

Studies had to include at least one of the following outcomes to be eligible: energy intake, hunger, circulating concentrations of appetite related hormones (e.g., acylated-ghrelin (AG), des-acyl ghrelin (DAG), total ghrelin, leptin, insulin, total $PYY_{1\text{-}36}$, $PYY_{3\text{-}36}$, GLP-1, pancreatic polypeptide (PP), cholecystokinin (CCK)). Studies that measured fasted and/or postprandial measures of hunger and appetite-related hormones were eligible for inclusion. Studies were excluded if they were performed on animals or if they were not written in English.

Studies were eligible that were designed to examine the effects of water-based exercise on energy intake, appetite, and appetite related hormones during and after an exercise intervention. There were 5 acute studies that measured EI from self-report and 3 studies that used a combination of lab feeding and self-report.

2.3. Search strategy

On March 07, 2022, the search was undertaken in six health and sports related databases and full details are provided in Table 1. The search strategy adopted was based on a population, intervention, comparator, outcome (PICO) approach and used Boolean operators AND/OR/NOT to limit results to documents containing relevant key terms. The search consisted of keywords related to the population (e.g., overweight, obese, healthy), intervention (e.g., water-based exercise), comparator (e.g., land-based exercise, resting control) and outcome (e.g., energy intake, appetite, appetite hormones). A manual search was

Table 1
The table displays each database consulted by its name (i.e., PubMed), the interface or platform through which the database was searched (i.e. EBSCO-host), and the dates of coverage. Full search string along with filters and results are also presented.

Database	Coverage
National Library of Medicine	
PubMed	1900 to present Results: 261
((((((((overweight) OR (obese)) OR (obesity)) OR (lean)) OR (healthy)) AND ((physical activity) OR (exercise))) AND ((((((("water based exercise") OR (swim)) OR ("aqua cycle")) OR ("aqua walk")) OR ("water immersion")) OR (bike)) OR (run)) OR (treadmill))) AND ((((((((((energy intake) OR (appetite) OR (appetite hormone*)) OR (GLP-1)) OR (PYY)) OR (Ghrelin)) OR (Leptin)) OR (satiety)) OR (hunger)) OR (reward)) OR (fullness)) OR (CCK)) Filters: Humans	
EBSCOhost	
Medline	1900 to present Results: 112
Sport-Discus	1900 to present Results: 46
Academic Search Complete	1900 to present Results: 128
CINAHL	1900 to present Results: 48
Public Health Database	1900 to present Results: 20
(overweight or obesity or obese or healthy or lean) AND (physical activity or exercise) AND (water based exercise or swim or aqua cycle or aqua walk or water immersion or bike or run or treadmill) AND (energy intake or appetite or appetite hormone* or GLP-1 or PYY or Ghrelin or Leptin or satiety or hunger or reward or fullness or CCK) Filters: Humans	

also undertaken to identify any additional studies using Google Scholar and by checking the reference lists of the included published articles.

2.4. Data selection and extraction

Data selection and extraction was conducted independently by the principal investigator (MG) and then checked independently by other members of the review team. Title and abstract screening was completed independently by MG. Three reviewers (DB, DT and JA) then checked all title and abstract screening. All full texts were individually screened by three reviewers (DB, DT and MG) to assess suitability for inclusion in the systematic review. In the case of any unresolvable disagreements by the principal investigator, and the second reviewer, a third member of the review team was contacted for a resolution. This only happened in one instance as to whether a screened abstract should progress to full article screen.

A data extraction form was adapted from Higgins et al. (2019), which the principal investigator (MG) used to extract data from eligible studies. Information on the publication details (authors, title, date), participant characteristics (age, body mass, physical activity levels), exercise protocol (frequency, intensity, duration, mode, water temperature) and relevant outcome measures (energy intake, appetite, appetite related hormone measurements; (AG (pg/mL); leptin (pg/mL); PYY (pg/mL); GLP-1 (pg/mL)) & the subjective appetite measure (hunger) were extracted from eligible studies. If the required data was missing, the principal investigator (MG) contacted the corresponding author, and the study was not included if the required information was unavailable. Outcome data presented graphically was extracted where possible using WebPlotDigitizer, Version 4.0 (Drevon et al., 2017). MG extracted and entered data into a Microsoft Excel® spreadsheet, with DB double checking for accuracy.

Our PROSEPRO submission highlights that we would have examined other outcomes including PP and CCK, but these were not measured in any of the included studies.

2.5. Meta-analysis procedures

Meta-analysis was performed on energy intake only (8 studies (water versus control), 5 studies (water versus land) and 2 studies (water at two different temperatures)). After data extraction, data was entered into software designed specifically for meta-analysis (RevMan 5.4.1). The meta-analysis was performed using the fixed effects, generic inverse variance method (Dettori et al., 2022; Murad et al., 2015). When data was missing the standard deviation was inputted using an estimate from Thackray et al. (2020). This method is considered reasonable when analysing a small number of studies (Furukawa et al., 2006; Higgins et al., 2019). Heterogeneity was calculated using the I^2 index with values representing 0%–40%: might not be important; 30%–60%: may represent moderate heterogeneity; 50%–90%: may represent substantial heterogeneity; 75%–100%: considerable heterogeneity (Higgins et al., 2003). Sensitivity analyses were conducted by excluding one study at a time to examine if the results were influenced by any one study. Statistical significance was set at $P < 0.05$. The meta-analyses are based on two-tailed Z tests to examine if overall mean treatment differences were significantly different from zero.

2.6. Risk of bias

Risk of bias was assessed using the revised Cochrane Risk of bias's tool for randomised trials (RoB 2.0). RoB 2.0 addresses five specific domains: (D1) bias arising from the randomisation process; (D2) bias due to deviations from intended interventions; (D3) bias due to missing outcome data; (D4) bias in measurement of the outcome; and (D5) bias in selection of the reported result. Two review authors (MG and DB) independently applied the tool to each included study and recorded supporting information and justifications for judgements of risk of bias for each domain (low; some concerns; high). Any discrepancies in judgements of risk of bias or justifications for judgements were resolved by discussion to reach consensus between the two review authors, with a third review author ready to act as an arbiter but this was not necessary. Following guidance given for RoB 2.0 (Higgins et al., 2011), we derived an overall summary risk of bias judgement (low; some concerns; high) for each specific outcome, whereby the overall RoB for each study was determined by the highest RoB level in any of the domains that were assessed.

3. Results

3.1. Search results

Fig. 1 illustrates the systematic review flow diagram presented according to PRISMA guidelines. The database search yielded 615 articles. After removing duplicates (n = 218), 293 articles were excluded in the title/abstract screening and of the 104 articles undergoing full text screening, a further 95 articles were excluded based on inclusion and exclusion criteria. A total of 9 studies were sourced for analysis and review.

3.2. Study characteristics

The characteristics of the nine studies located are presented in Table 2. The studies were published between 1999 and 2021. They include randomised crossover (n = 7), semi-random (n = 1) (water-trial was required prior to iso-energetically matched water trial) and

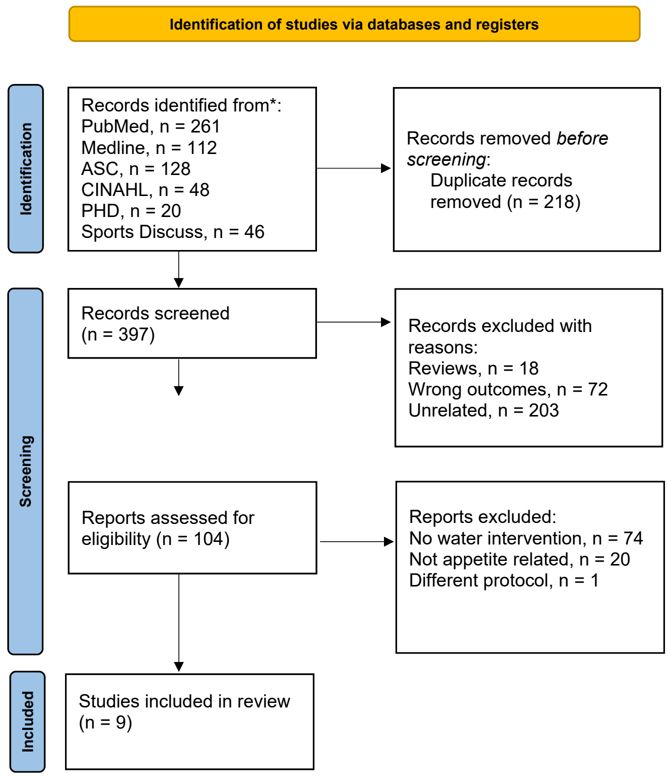

Fig. 1. Prisma flow diagram for identification of studies for inclusion.

independent group (n = 1) (used in the 12-week study) designs. Six studies included water-based exercise versus a non-exercise (land-based) control, six included water-versus land-based exercise, and two included water-based exercise only performed at different water temperatures.

Eight acute studies were undertaken over a single day for each experimental trial (duration 5–8 h), with trial arms separated by 4–7 days. All eight studies included a single bout of exercise (≤60 min) which was fully supervised. Of these, five studies adopted a continuous exercise protocol, whereas three implemented an intermittent/interval protocol. The intensity of the exercise ranged between 45 and 90% of maximal oxygen consumption (Vo_2max) or heart rate reserve (HRR). The mode of the water-based exercise included aqua-cycling (n = 4), aqua-walking (n = 1) and swimming (n = 3). Land-based exercise modes included cycling (n = 3), treadmill walking (n = 1) or treadmill running (n = 1).

Five acute studies included male only participants (n = 56), two studies included female only participants (n = 31) and one study included a mixed sample of males and females (n = 32).

All participants were considered to have a healthy BMI (18.5–24.9 kg/m^2) and were aged between 19 and 39 years. Four of the acute studies included participants who took part in recreational or habitual exercise, three included participants who did not take part in exercise and one included well-trained triathletes. An *ad-libitum* buffet was provided either 15 min after exercise (n = 1), 30 min after exercise (n = 6) or 1 h and 5.5 h after exercise (n = 1), and total energy intake was reported. We have highlighted that in the acute studies for the *ad libitum* meals, (n = 2) studies used a homogenous meal and (n = 6) studies used a variety of foods The one chronic study didn't measure energy intake.

The search identified only one chronic training study (Fico et al., 2021), which was carried out over a 12-week period. The mode of exercise compared swimming with static cycling and all exercise sessions were supervised. Participants increased the exercise volume from 20 to 30 min per day on 3 days a week to 40–45 min per day on 3 days a week, across the 12-week study period. Intensity also progressively increased from 40 to 50% HRR to reach 60–70% HRR by the end of the trial. The study included 3 males and 36 females (n = 39) who were all living with obesity (BMI 30.5–34.7 kg/m^2) and had a mean (SD) age of 59 (1) years. Although this study did not measure energy intake, the data shows a clear reduction in body mass and BMI after both exercise groups (swimming and cycling) and results will be narratively discussed.

A summary of the risk of bias assessment is provided in Fig. 2. Of the eligible studies, 55.6% were considered low risk and 44.4% presented with some concerns. The study by Metz, Isacco, Fearnbach, et al. (2021) contained a land–ISO–cycle which involved participants cycling faster and for longer to achieve the necessary HR to match it to the aqua-cycle session. The data for the land–ISO–cycle session was therefore omitted from the meta-analysis and only the land-cycle versus aqua-cycle data was used). The study by Thackray et al. (2020) applied different methods of measuring energy expenditure which could have affected the outcome. Swimming was measured using metabolic equivalents and cycling was measured using indirect calorimetry. The study by Fico et al. (2020) was a 12-week study which didn't monitor energy intake, and appetite-related hormones were measured in their total form which is less sensitive to appetite.

3.3. Study characteristics

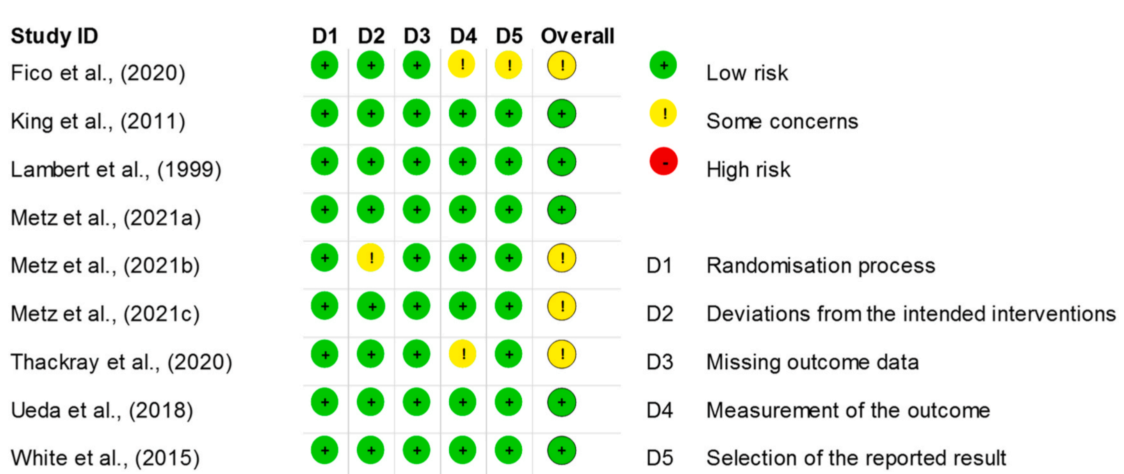

Fig. 2. Risk of bias within each study (RoB 2) Sterne et al. (2019).

Table 2
| Summary of the eligible studies.

Author(s)	Study Aim	Participant Info.	Exercise Protocol	Temp.	Measure	Outcome Data			Key Findings
							Swim	Cycling	
Fico et al. (2020)	The chronic effects of swimming on appetite related hormones in individuals with obesity	F (36); M (3)	**Conditions x 2: Independent Groups**	Swim					
		Sedentary	Exercise:	(27–28 °C)	**Total AG**		Data not available		Pre/post trial ($P = 0.381$)
Chronic		Middle aged people with obesity and osteoarthritis	3 days/week		**Total PYY**				Pre/post trial ($P = 0.290$)
		59 (1) Yrs.	20–30 min at 40–50 %HRR (Wk.1-6)	Cycling (24–26 °C)	**Insulin**				Pre/post trial ($P = 0.827$)
12 Weeks		32.5 (2.0) kg/m^2	40–45 min at 60–70 %HRR (Wk.6-12) Continuous HR & Blood: (fasting concentration, during exercise & pre/post trial)		**Leptin**				Pre/post trial ($P = 0.096$)
						Control	**Swim**		
King et al. (2011)	The influence of an acute bout of swimming on appetite and energy intake	M (14)	**Condition x 2:**	Swim	**VO_2 (L/min)**	0.32 (0.01)			
		Healthy and habitually active	Exercise:	(28.1 °C)	**HR (bpm)**		155 (5)		
Acute		22 (0.5) Yrs.	60 min (6 × 10 min blocks)		**RPE**		14 ± 0		
		23.2 (0.6) kg/m^2	at 12–14 RPE	Control	**Energy Intake (kJ)**	9161 (719)	9749 (809)		Swim vs Control ($P > 0.05$)
RCD			Intermittent	(21.6 °C)	**Energy Exp. (kJ)**		1921 (83)		
			Ad-libitum meal at 3 h (12:00)		**Relative EI (kJ)**	9163 (720)	7828 (774)		Swim vs Control ($P < 0.05$)
			Ad-libitum meal at 7.5 h (16:30)		**AG (pg/mL)**	505 (217)	473 (232)		Swim vs Control ($P < 0.001$)
			VAS (100 mm): (baseline, every 30min)		**Hunger (mm) (AUC)**	152 (19)	178 (20)		Swim vs Control ($P < 0.05$) in the hours after exercise
			Blood: (baseline, 1hr. pre-exercise, 2 h post exercise & 1 h thereafter)						Swim vs Control ($P = 0.028$) post meal at 3 h.
							Swim	**Running**	
Lambert et al. (1999)	Physiological responses and energy intake in the 2 h post exercise recovery	M (8)	**Conditions x 2:**	Running (20 °C)	**VO_2 (L/min)**		2.69 (0.11)	3.33 (0.16)	
		Well trained triathletes	Exercise:		**HR (bpm)**		134 (6)	158 (4)	
Acute		31 (8) Yrs.	45 min at 70% VO2max	Swim (29.5 °C)	**RPE**		12 (0.4)	13.2 (0.6)	
		9.5 (2.8) Fat%	Continuous		**Energy Intake (kJ)**		4383 (484)	4584 (611)	Run vs Swim ($P > 0.05$)
RCD			Ad-libitum buffet (5000 kcal)		**Energy Exp. (kJ)**		2548 (102)	3056 (143)	Run vs Swim ($P < 0.05$)
			HR & RPE: (during)		**Hunger (5-point Likert scale)**		3.4 (0.3)	3.3 (0.3)	Run vs Swim ($P > 0.05$)
			Blood sample: (during) Hunger (5-point Likert): Pre, Post, 2hr, post 2hr						
						Control	**Aqua-Cycle**	**Land-Cycle**	
Metz et al.,		M (10)	**Condition x 3:**	Control	**HR (bpm)**		Averaged 177–181 bpm: 131 (6.7)		

(*continued on next page*)

Table 2 (*continued*)

Author(s)	Study Aim	Participant Info.	Exercise Protocol	Temp.	Measure	Outcome Data				Key Findings
							Swim	Cycling		
(2021a)	Compare effects of acute HIIT cycling on land vs in water on EI, appetite sensations and RPE in healthy males	Healthy and recreationally active	Exercise:	(22 °C)	**RPE**		15.6 (1.7)	17 (1.4)		Neg. Correlation. with EI (P = 0.03)
		23.4 (1) Yrs.	5 × 3min at 85–90%: 50% VO2max recovery	Land-cycle	**Energy Intake (kJ)**	4017 (1171)	4684 (1688)	3939 (1329)		Between Trials: (P > 0.05)
Acute		21.5 (1.3) kg/m^2	Ad-libitum meal 30 min post exercise	(22 °C)	**Energy Exp. (kJ)**		Estimated 1748 (211)			
			VAS (150 mm): (fasted, post breakfast, before after lunch, 30/60min post lunch	Aqua-cycle	**Hunger (AUC)**	14.54 (6.1)	11.4 (7.9)	12.9 (9.8)		No trial effect (P > 0.05) Time x Trial: Less hungry prior to Aqua vs Control (P = 0.002)
RCD			RPE: before/after exercise,	(27 °C)						
						Control	**Aqua-Cycle**	**Land ISO-Cycle**	**Land-Cycle**	
Metz, Isacco, Fearnbach, et al. (2021)	Investigate EE and EI and appetite sensations in response to water vs land-based cycling in healthy young females	F (20)	**Condition x 4:**	Control	**VO$_2$ (mL/min^1/kg^1)**	3.75 (0.75)	15.24 (2.48)	12.5 (5)	9.4 (2.2)	All vs Control (P < 0.05)
		Healthy Inactive		(21 °C)						Aqua vs Land–ISO–cycle (P < 0.05)
Acute		27.3 (3.9) Yrs.	Exercise: 30 min at 50 RPM		**HR (bpm)**	67.6 (9.3)	105.4 (11.4)	105.2 (8.2)	88.9 (9.3)	All vs Control (P < 0.05) Land vs Aqua (P < 0.05) Land vs Land–ISO–cycle (P < 0.05)
		22.5 (2.4) kg/m^2	Continuous	Land–ISO–cycle	**Body Temp (Tympanic oC)**	36.8 (0.3)	37.3 (0.4)	37.1 (0.3)	37.0 (0.4)	Time effect (P = 0.04)
Semi-RCD			12:00: Ad-libitum lunch	(21 °C)	**Energy Intake (kJ)**	2987 (1171)	2778 (564)	2970 (631)	2815 (765)	Between all conditions (P < 0.05)
					Energy Exp. (kJ)	142 (24)	573 (111)	577 (109)	323 (89)	All vs Control (P < 0.001) Aqua vs Land-ISO (P > 0.05)
			VAS (100 mm): (fasted, post breakfast, before/after exercise, before/after lunch, 30 min post lunch)	Land-cycle						
			RPE (15 min intervals.)	(21 °C)	**Hunger (AUC)**	17.5 (6.3)	18 (8.3)	18.3 (6.4)	17.4 (4.6)	No trial effect (P = 0.58)
				Aqua-cycle (27 °C)						
						Control	**Aqua-Cycle 18 °C**	**Aqua-Cycle 27 °C**		
Metz, Isacco, Beaulieu, et al. (2021)	Examine the effect of water temperature during immersed cycling on EE, EI, appetite sessions and food reward in healthy pre-menopausal females	F (11)	**Condition x 3:**	Control	**VO2 (ml/min)**	297.7 (69.6)	1790.6 (348.1)	1478.6 (175.9)		All vs Control (P < 0.001) 18 °C vs 27 °C (P = 0.007)
		Healthy	Exercise	(22 °C)	**HR (bpm)**	72 (10)	136 (4)	133 (9)		All vs Control (P < 0.001) 18 °C vs 27 °C (P > 0.05)
Acute		Inactive	40 min at 70% VO2max		**Energy Intake (kJ)**	2681 (966)	2679 (893)	2441 (740)		Between all conditions (P > 0.05)
		21.2 (0.6) Yrs.	Continuous	Aqua-cycle	**Energy Exp. (kJ)**	238 (54)	1468 (271)	1209 (129)		All vs Control (P < 0.001) 18 °C vs 27 °C (P < 0.001)
RCD		21.7 (2.9) kg/m^2	Ad-libitum lunch at 12pm	(18 °C)	**Relative EI (kJ)**	2440 (924)	1200 (866)	1225 (769)		All vs Control (P < 0.001) 18 °C vs 27 °C (P > 0.05)
			VAS (150 mm): (Fasted, post breakfast, before/after exercise,		**Hunger mm (AUC)**	12.8 (8.9)	10.2 (8.1)	9.6 (7.5)		Less hungry before Aqua (18 °C & 27 °C) vs Control (P < 0.001)

(*continued on next page*)

Table 2 (*continued*)

Author(s)	Study Aim	Participant Info.	Exercise Protocol	Temp.	Measure	Outcome Data			Key Findings
							Swim	Cycling	
			before after lunch, 30/60 min post lunch) LFPQ: (before & after lunch) RPE: (20 & 40 min)	Aqua-cycle (27 °C)					
						Control	**Swimming**	**Cycling**	
Thackray et al. (2020)	Compare the acute effects of exertion-matched swimming and cycling on appetite, energy intake, and food preference and reward in males and females	M (17) F (15)	**Condition x 3:**	Water	**Tr. HR (bpm)**		146 (15)	143 (18)	Swim vs Cycling ($P = 0.085$)
		Healthy Active	Exercise:	(28 °C)	**RPE**		15.2 (0.7)	14.9 (0.6)	
Acute		23 (2) Yrs.	6 × 8min: 2min (60 min)		**Energy Intake (kJ)**	3259 (1265)	3857 (1611)	3652 (1619)	Swim vs Control ($P = 0.005$) Cycling vs Control ($P = 0.062$) Swim vs Cycling ($P = 0.324$)
		24 (2.6) Kg/m^2	Intermittent		**Energy Exp. (kJ)**		1087 (284)	1681 (577)	Swim vs Cycling ($P < 0.001$)
RCD			LFPQ at 11.45 a.m.		**Relative EI (kJ)**	3259 (1265)	2769 (1610)	1967 (1675)	Swim vs Control ($P = 0.045$) Cycling vs Control ($P < 0.001$) Swim vs Cycling ($P = 0.001$)
			Ad-libitum pasta at 12 p.m. VAS (100 mm): (before/after lunch, 120 min post lunch)		**Hunger (AUC)**	9.2 (10.1)	16.7 (15.5)	13.6 (15.8)	Post Swim vs Control ($P = 0.017$) Post Swim vs Cycling ($P < 0.05$)
			LFPQ: (before/after lunch, 120 min post lunch) RPE: (20 & 40 min)						
							Aqua-Walk	**Land-Walk**	
Ueda et al. (2018)	Investigate the effects of treadmill walking in water on gut hormone concentrations and appetite and compare them to those when walking on land	M (13) Healthy and habitually active	**Condition x 2** Exercise: 30 min at 50% VO2max	Aqua-walk (34 °C)	**VO2 (L/min)** **Tr. HR (bpm)**		1.64 (0.12) 111.4 (4.1)	1.67 (0.11) 118.3 (6.7)	Land vs Water ($P > 0.05$) Land vs Water ($P < 0.05$)
Acute		21.6 (2.2) Yrs. 22.7 (2.8) kg/m^2	Continuous Ad-libitum Test Meal (Pasta) at 10 a.m. Time: (60)	Land-walk	**RPE**		3.4 (1.6)	3.6 (1.3)	Land vs Water ($P > 0.05$)
RCD			Blood; RPE, 100 mm VAS	(25 °C)	**Energy Intake (kJ)**		7179 (2225)	7334 (2083)	Land vs Water. ($P > 0.05$)
			Time: fasted (0); after exercise (30); post recovery (60)				596 (141)	873 (196)	Land vs Water ($P < 0.05$)
					AG (AUC)		Data not available		Land vs Water ($P < 0.01$)
					PYY (pmol/ml)		Data not available		Land vs Water. ($P > 0.05$)
					GLP-1 (AUC)		Data not available		Land vs Water ($P < 0.05$)
					Hunger		Data not available		Less hungry during Water vs Land ($P < 0.05$)
						Control	**Aqua-Cycling CWI (20°C)**	**Aqua-Cycling NWI (33°C)**	
White et al. (2005)	Explore the effects of water temperature on EI immediately following exercise	M (11)	**Conditions x 3**	Aqua-cycling CWI (20 °C)					
					Tr. HR (bpm)		107	117	CWI vs NWI ($P < 0.05$)

(*continued on next page*)

Table 2 (*continued*)

Author(s)	Study Aim	Participant Info.	Exercise Protocol	Temp.	Measure	Outcome Data			Key Findings
							Swim	Cycling	
Acute		Healthy non-habitual exercisers 25.6 (5) Yrs.	40 min exercise at 60% VO2max	Aqua-cycling NWI (33 °C)					
		13.1 (6.3) Fat %	Continuous		**RER**	0.81	0.89	0.87	CWI & NWI vs Control (P < 0.05)
RCD			1 h (monitored food intake)		**Body Temp**		36.4	36.7	CWI vs NWI (P < 0.05)
					Energy Intake (kJ)	2585 (1158)	3669 (1912)	2543 (849)	CWI vs NWI (P < 0.005) by 44% CWI vs Control by 41%;
					Energy Exp.		517 (42)	505 (22)	CWI vs NWI (P > 0.05)

Data are presented as mean (SD).

AG: acylated ghrelin, AUC: area under the curve, BPM: beats per minute, CWI: cold water immersion, EI: energy intake, Exp: Expenditure, F: Females, GLP-1: glucagon like peptide-1, Hr.: Hours, HR: heart rate, HRR: heart rate reserve, Info: information, ISO: isoenergetic to aqua, kJ: kilojoules, Kcal: kilocalories, LFPQ: Leeds food preference questionnaire, L/min: litres per minute, M: Males, mg/dL: milligrams per decilitre, Min: minutes, Neg: Negative, Non Sig: non-significant, NWI: neutral water immersion, pg/ml: picograms per millilitre, pmol/ml: picomol/millilitre, PYY: peptide tyrosine tyrosine, RCD: randomised crossover design; RCT: randomised control trial, RER: respiratory exchange ratio, RPE: rate of perceive exertion, Temp: temperature, VAS: visual analogue scale, VO_2max: maximal oxygen consumption, Wk.: week, Yrs.: years.

4. Meta-analysis procedures

4.1. Acute exercise

It was only possible to perform a meta-analysis on the extracted energy intake data. This was due to missing data for other outcomes, measurements not included or provided by corresponding authors, or a combination of these. Therefore, data for hunger and appetite-related hormones is discussed narratively.

4.1.1. Absolute ad libitum energy intake (post-exercise)

4.1.1.1. Water-based exercise versus control. Six studies reported absolute *ad libitum* energy intake (kJ) that included a water-based activity versus a non-exercising control group (King et al., 2011; Metz et al., 2021a, 2021b, 2021c; Thackray et al., 2020, & White et al., 2005). A total of 8 study arms were included in the meta-analysis, as water-based exercise at different temperatures could be compared to the control trial separately.

The meta-analysis showed absolute *ad libitum* energy intake (kJ) was higher after water-based exercise than a non-exercise control (mean difference [95% CI], 330 [118, 542] kJ $P = 0.002$; Fig. 3). There was moderate heterogeneity among these studies ($I^2 = 56\%$). Sensitivity analysis showed that removing the one study with slight concerns relating to the measurement of energy expenditure (Thackray et al., 2020), did not alter heterogeneity ($I^2 = 56\%$), and therefore the data is included.

4.1.2. Absolute ad libitum energy intake (post-exercise)

4.1.2.1. Water-based exercise versus land-based exercise. Five studies (Lambert et al., 1999; Metz et al., 2021a, 2021b; Thackray et al., 2020 & Ueda et al., 2018) met the inclusion criteria to perform a meta-analysis to identify whether water-based exercise affected absolute *ad libitum* energy intake differently to land-based exercise.

The meta-analysis revealed there was no overall effect on absolute energy intake between water- and land-based exercise (mean difference [95% CI], 78 [−176, 334] kJ, $P = 0.55$; Fig. 4). Low heterogeneity was identified among these studies ($I^2 = 27\%$). Sensitivity analysis did not alter heterogeneity or statistical significance.

4.1.3. Absolute ad libitum energy intake (post-exercise)

4.1.3.1. Cold water exercise versus neutral water exercise. Two studies (Metz, Isacco, Beaulieu, et al., 2021 & White et al., 2005) met the inclusion criteria to analyse whether post-exercise *ad libitum* energy intake differed when exercise was undertaken in cold versus neutral water temperatures. Temperatures ranged from 18 to 20 °C (cold water) to 27–33 °C (neutral water).

Meta-analysis revealed *ad libitum* energy intake (kJ) was higher after exercise in cold water versus neutral water (mean difference [95% CI], 719 [222, 1215] kJ; $P < 0.005$; Fig. 5). Heterogeneity was rated moderate among these studies ($I^2 = 61\%$). It was not possible to carry out sensitivity analysis as only two studies compared different water temperatures.

4.1.4. Hunger

Self-reported hunger ratings were recorded over time in seven studies (King et al., 2011; Lambert et al., 1999; Metz et al., 2021a, 2021b, 2021c; Thackray et al., 2020 & Ueda et al., 2018) using a 100 mm VAS (n = 4), a 150 mm VAS (n = 2) or a 5-point Likert scale (n = 1). Due to heterogeneity amongst studies ($I^2 = 84\%$) it was not possible to undertake a meta-analysis.

When water-based exercise was compared to a no exercise control, King et al. (2011) reported that participants were less hungry during

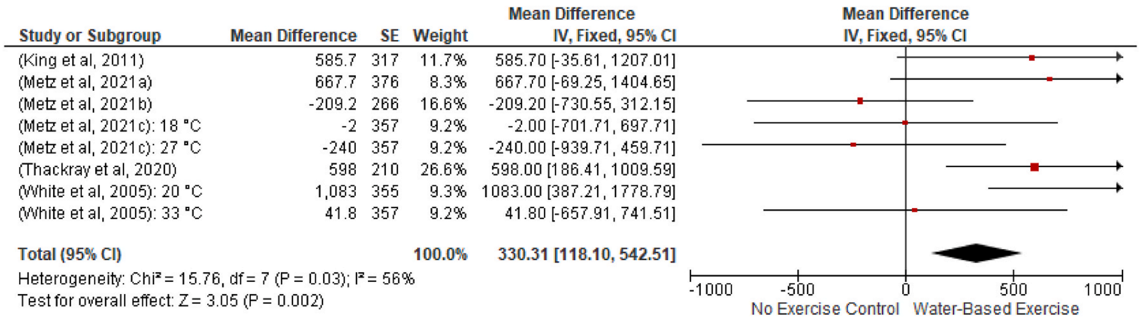

Fig. 3. Forest plot of the mean difference (±95% confidence interval [CI]) for studies comparing the influence of water-based exercise versus resting control on absolute *ad libitum* energy intake. Squares represent the relative weight of the study. Diamond represents the absolute mean difference (mean ± 95% CI) for the pooled effect.

swimming and King et al. (2011) and Thackray et al. (2020) reported participants were hungrier immediately after swimming. King et al. (2011) demonstrated hunger was higher up to and after the first ad-libitum buffet meal (0–3 h) which continued up to the second ad-libitum meal (3–7 h).

When water-based exercise was compared to a land-based exercise Lambert et al. (1999), Metz, Isacco, Miguet, et al. (2021), Metz, Isacco, Fearnbach, et al. (2021), and Ueda et al. (2018) all reported no difference between conditions. Thackray et al. (2020), reported that hunger was rated higher when swimming was compared to a land-based cycling exercise.

4.1.5. Appetite-related hormones

Two of the eligible studies included assessments of appetite-related hormones (King et al., 2011; Ueda et al., 2018). King et al. (2011) measured AG at seven time-points during an 8-hr swimming trial and a rest control trial, with biochemical data for AG available for 9 out of the 14 participants. The authors reported that AG was suppressed during swimming compared to control, but the effect was short-lived with concentrations returning to control values 1 h after exercise. In the study by Ueda et al. (2018), AG, GLP-1 and total PYY were measured before, immediately after and 30 min after a 30 min bout of water- or land-based walking. Circulating concentrations of AG and GLP-1 were lower and higher, respectively, during water-compared to land-based exercise, but no between-trial differences were identified in total PYY concentrations.

4.2. Chronic exercise

4.2.1. Appetite hormones

One study compared the effects of a 12 - week swimming or cycling intervention on circulating total ghrelin, insulin, leptin and total PYY concentration. Measurements were taken at the start and end of the study. Results showed that swimming and cycling did not alter fasting plasma concentrations of total ghrelin, insulin, leptin or total PYY. Furthermore, both cycling and swimming reduced body mass over time 87.3 (5.2) to 85.9 (5.0) kg and 88.9 (4.9) to 86.4 (4.5) kg respectively.

5. Discussion

This is the first systematic review and meta-analysis examining the effects of water-based exercise on energy intake, appetite, and appetite related hormones in adults. The key findings are that post-exercise energy intake is higher after water-based exercise versus a resting control. There was however no difference in energy intake when water-based exercise was compared with land-based exercise. When different water temperatures were analysed, post-exercise energy intake was higher in cold water versus neutral water. Finally, whilst a meta-analysis was not possible due to a paucity of data, it is posited that hunger is suppressed during and immediately after water-based exercise, but participants were hungrier in the subsequent hours when compared to control or a land-based comparator based on the available empirical literature.

Following meta-analysis of six studies (King et al., 2011; Metz et al., 2021a, 2021b, 2021c; Thackray et al., 2020, & White et al., 2005), the present review demonstrated that energy intake was higher by ~330 kJ after exercising in water versus control, supporting the notion that exercise promotes food intake, at least in the short term. This contrasts with land-based exercise where individuals tend not to over-compensate for the energy expended during the exercise bout in the immediate hours after exercise (Schubert et al., 2013). When compared to a land-based equivalent, exercising in water did not alter total energy intake markedly (Lambert et al., 1999; Metz et al., 2021a, 2021b; Thackray et al., 2020 & Ueda et al., 2018). Studies investigating the effects of cold-water immersion have focused on the energy cost of shivering due to its potential to positively influence energy balance (McInnis et al., 2020). The energy expended through shivering may contribute to or cause a person to feel hungrier or eat more subsequently (Langeveld et al., 2016 and Westerterp-Plantenga et al., 2002). According to Langeveld et al. (2016), maintaining core body temperature could reduce compensatory feeding. The studies included in the present meta-analysis all reported water temperature being comfortably warm (27–34 °C) and above the temperature that may cause shivering. Therefore, it is reasonable to suggest along with the physical activity performed, the participants remained thermoneutral. There is a lack of mechanistic studies

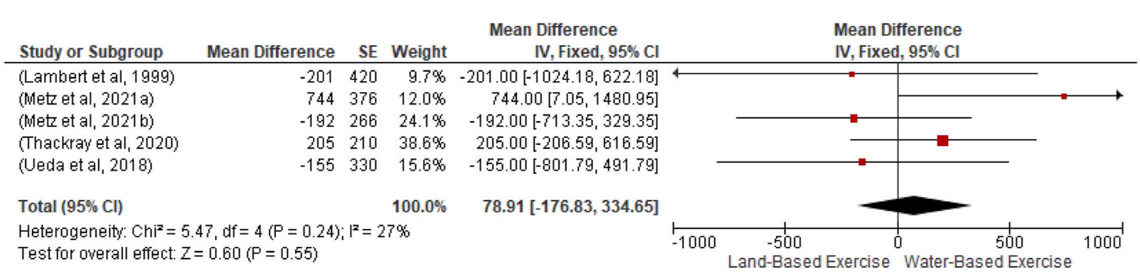

Fig. 4. Forest plot of the mean difference (±95% confidence interval [CI]) for studies comparing the influence of water-based exercise versus land-based exercise on absolute *ad libitum* energy intake. Squares represent the relative weight of the study. Diamond represents the absolute mean difference (mean ± 95% CI) for the pooled effect.

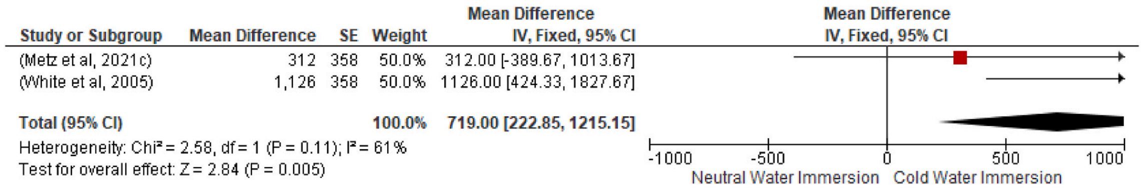

Fig. 5. Forest plot of the mean difference (±95% confidence interval [CI]) for studies comparing the influence of cold-water exercise versus neutral water exercise on absolute *ad libitum* energy intake. Squares represent the relative weight of the study. Diamond represents the absolute mean difference (mean ± 95% CI) for the pooled effect.

examining body and core temperatures as well as a wide range of gut peptide hormones and biomarkers which should be a future line of enquiry.

Two studies (Metz, Isacco, Beaulieu, et al., 2021 & White et al., 2005) compared the effects of exercising in 'cold' (defined as 18–20 °C) versus 'neutral' (defined as 27–33 °C) water temperature, and meta-analysis revealed participants tended to eat more (~719 kJ) after exercising in cold-water. There is clear disparity between published works in the temperatures used to classify the temperature of water which could influence interpretation.

White et al. (2005) reported participants aqua cycling at 60% of VO_2max for 45 min in cold (defined as 20 °C) versus neutral water (defined as 33 °C), led to a 44% increase in energy intake when presented with an *ad-libitum* meal, equivalent to 1125 kJ. Participants also chose to consume foods higher in fat content 35 (20) % versus 28 (14) %. It is likely that the duration of exercise and intensity were not sufficient for participants to remain thermoneutral which therefore caused compensatory feeding. The authors concluded the negligible decrease in body temperature of 0.3 °C during cold water cycling was unlikely to result in the marked increase in energy intake, but further studies that quantify core body temperature during water-based exercise are required to explore this possibility further. Although this meta-analysis suggests that cold water exercise may cause a person to eat more, the 95% confidence intervals for the individual studies are very large so results should be interpreted with caution. Only two studies met the inclusion criteria and were eligible for meta-analysis. This highlights the need to examine appetite and energy intake responses to water based exercise in a wide range of water temperatures. It is also important to include an immersion without exercise control to identify if being immersed in water results in increased energy intake regardless of exercise (Halse et al., 2011).

Longer term weight management interventions aimed at body mass loss must alter the balance between energy intake and expenditure. The amount and type of weight loss over time depends on initial body weight (Hall, 2010), energy partitioning (Ravussin et al., 1986) and the dynamic changes of energy expenditure that comes with weight loss (Chow & Hall, 2008). Exercise increases energy expenditure and can contribute to overall weight loss, if no compensation in energy intake occurs (Hall et al., 2011). Gwinup (1987) investigated whether the mode of exercise could influence body mass. Over a period of 6 months, fifteen females living with obesity gradually incorporated 1 h per day of swimming, cycling, or walking into their daily routine, but only the cyclists and walkers reduced their body mass by the end of the trial (12% versus 10% reduction respectively). The body mass of the swimmers didn't differ from baseline, and it was speculated the energy they expended was compensated through increased energy intake. In contrast, Lopera et al. (2016) compared 16 weeks (3 × 60 min per week) of circuit style land-based exercise, WBE and no exercise control on body composition, physical fitness, quality of life and exercise adherence in 151 children and adolescents living with obesity. Results demonstrated that there was a decrease in BMI, waist and hip circumference and an increase in strength and cardiorespiratory fitness after both land-based and WBE in comparison to the control group. Interestingly the drop-out rate was lower in the WBE (20%) versus the land-based group (36.7%) with demotivation the being the cause for drop-out for 57% of the participants in the WBE versus 94% in the land-based group.

Only one study in this review (Fico et al., 2020) analysed the longer-term effects of swimming versus cycling, on appetite and related hormones in adults living with obesity. The authors didn't monitor energy intake but similar to Lopera et al. (2016) reported an average reduction of ~2 kg in body mass after both swimming and cycling interventions, suggesting both modes of exercise facilitate body mass loss. There could be discrepancy between the findings of Fico et al. (2020) and that of Gwinup (1987) as the temperature of the pool water was 27–28 °C versus 23–25 °C. The study by Lopera et al. (2016) didn't report the temperature of the water. Chronic studies using colder water temperatures are required to investigate the longer-term effects on appetite and body mass loss. Results also showed no change in insulin, ghrelin, leptin and PYY concentrations over time between the exercising groups. However, limitations include the measurement of total ghrelin over AG, evidently less responsive to exercise (Martins et al., 2015), and total PYY which includes both $PYY_{1\text{-}36}$ and $PYY_{3\text{-}36}$, reported by Manning and Batterham (2014) to have divergent actions on appetite. It is also worth noting that the normal functioning of the appetite regulating hormones; ghrelin, glucagon-like peptide (GLP-1), and peptide YY (PYY), are altered in people with obesity due to increased adiposity (Zouhal et al., 2019). It is clear more chronic training studies are needed which measure the concentration of appetite specific hormones such as AG and $PYY_{3\text{-}36}$ along with corresponding feelings of hunger and *ad-libitum* energy intake. Based on the available evidence it cannot be stated with certainty that water-based exercise is not as effective at optimising body mass as land-based exercise.

Five of the included studies measured ratings of hunger in response to water-based exercise versus control (King et al., 2011; Metz et al., 2021a, 2021b, 2021c; Thackray et al., 2020). Hunger was suppressed more than control, prior to the start of water-based exercise in the studies by Metz, Isacco, Miguet, et al. (2021) and Metz, Isacco, Beaulieu, et al. (2021) and during and immediately after swimming in the study by King et al. (2011). However, participants rated themselves hungrier in the hours after swimming versus control in studies by King et al. (2011) and Thackray et al. (2020) which could have contributed to the increased *ad-libitum* energy intake observed in both studies. Five studies measured ratings of hunger in response to water-based versus land-based exercise (Lambert et al., 1999; Metz et al., 2021a, 2021b; Thackray et al., 2020; Ueda et al., 2018) but there was no main effect of trial reported in four of the studies (Lambert et al., 1999; Metz et al., 2021a, 2021b; Ueda et al., 2018).

It is well established that vigorous land-based exercise suppresses hunger at intensities typically >60–65% of VO_2max (Broom et al., 2007; Holliday & Blannin, 2017). In the studies by Metz, Isacco, Miguet, et al. (2021), Metz, Isacco, Fearnbach, et al. (2021) and Ueda et al. (2018) exercise was prescribed at a moderate intensity which may be why hunger was unaffected. Metz, Isacco, Fearnbach, et al. (2021) and Ueda et al. (2018) both adopted a 30 min continuous protocol where participants cycled in water or on land at a continuous 45–55% HRM, whereas Metz, Isacco, Miguet, et al. (2021) adopted a 30-min aerobic interval approach (3 min at 85–90% HRmax followed by 3 min recovery at 50% HRmax). Lambert et al. (1999) implemented a continuous and more strenuous exercise protocol (45 min at 70% of VO_2max), but since eight participants were well trained triathletes, their ability to swim at a competitive level, could mask any appetite and hunger responses. This is supported by previous research that highlights in the short-term appetite is better controlled when people are more physically active and trained (Rocha et al., 2013). Future studies are therefore encouraged towards including people who are physically inactive as well as trained at a competitive level to see if there is any influence on the hunger response to water-based exercise.

Only one included study (Ueda et al., 2018) measured GLP-1 and PYY concentration when examining the effects of aqua-walking versus land-walking in twenty habitually active healthy males. GLP-1 was significantly higher during the aqua walking trial compared to the land walking trial but there was no difference in PYY. Of all the included studies this is the only water-based exercise study where participants undertook the exercise in a fasted state. Even fewer land-based exercise studies have compared the effects of fasted versus fed exercise on gut hormone responses, but evidence indicates post prandial exercise can increase PYY (Cheng et al., 2009) but GLP-1 is unresponsive to post prandial exercise (Gonzalez et al., 2013). The paucity of evidence warrants the examination of water-based exercise in the fed vs the fasted state giving due consideration that fed exercise is atypical and advised against in swimming but could blunt the energy intake responses that have been observed through meta-analysis and hunger responses described narratively presented in this review.

6. Strengths and limitations

There are some limitations to this review. Firstly, there were only a small number of studies and due to a paucity of data and variability among studies a meta-analysis could not be undertaken for appetite or appetite related hormones. Comments on trends are therefore tenuous and speculative. Attempts were made to contact corresponding authors to glean missing data and if not forthcoming, sound methods were implemented to deal with the missing data. However, a full data set may have altered interpretation. All studies in this review predominantly recruited healthy weight status participants. As some appetite signals may be dysregulated in those living with obesity (Lean & Malkova, 2016), any interpretation cannot be generalised to other populations. Finally, we may have missed relevant data from studies that were not published in English.

7. Future methodological directions

We have presented numerous ideas for future research throughout the discussion so here we present some key methodological considerations having reviewed the body of evidence available. It is advised in future studies to include a no exercise water immersion control as Halse et al. (2011) suggest simply being submerged in water may result in increased energy intake. In their study, participants exercised for 40 min at 70% of VO_2peak, then were subsequently assigned to one of three immersion trials: no water, cold water (15 °C) and neutral water (33 °C). Although there was little difference in energy intake between cold versus neutral water immersion, more calories were consumed after both cold-water immersion (4893 ± 1554 kJ) and neutral-water immersion (5167 ± 1975 kJ) when compared to control (4089 ± 1585 kJ), equivalent to an extra 803–1075 kJ.

Future studies should give greater attention to controlling for menstrual cycle when recruiting females and use robust methods for measuring body and core temperature as well as energy expenditure. It is a priority to examine the chronic effect of water-based exercise on appetite, appetite related hormones and energy balance using valid and reliable methods.

8. Conclusion

There are many reasons why a person may prefer water-based exercise over a land-based exercise alternative, such as living with a disability, arthritis, or obesity, and some evidence suggests swimming provides health benefits such as reduced risk of injury, improved cardiorespiratory fitness, and reduced all-cause mortality. Accessible to all ages, population groups and abilities, swimming is an excellent way to reduce risks associated with sedentary behaviour. However, if body mass management is a person's primary focus for undertaking water-based exercise, they should be mindful of the tendency to eat more in the subsequent hours after the session due to this review highlighting energy intake may be increased when compared to a no exercise control. However, this needs to be examined specifically due to a lack of chronic training studies that will inform future systematic reviews and meta-analyses.

Ethical statement

As this is a systematic review, ethics is not needed.

Declaration of competing interest

JAK, AET and DJS acknowledge support from the National Institute for Health Research (NIHR) Leicester Biomedical Research Centre. The views expressed are those of the authors and not necessarily those of the NHS, the NIHR, or the Department of Health.

All other authors declare no conflict of interest.

Data availability

Data will be made available on request.

Acknowledgement

JAK, AET and DJS acknowledge support from the National Institute for Health Research (NIHR) Leicester Biomedical Research Centre. The views expressed are those of the authors and not necessarily those of the NHS, the NIHR, or the Department of Health.

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