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Post-exercise skimmed milk, but not a sucrose beverage decreases energy intake at the next meal compared to a placebo beverage in active males

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ABSTRACT

This study compared the appetite and energy intake effects of three post-exercise beverages at a subsequent post-exercise meal. On three occasions, ten active males: (mean ± sd) age 21.3 ± 1.2 y, $\dot{V}O_2$peak 58 ± 5 mL/kg/min) performed 30-min cycling at ~60% $\dot{V}O_2$peak and five 4-min intervals at 85% $\dot{V}O_2$peak. Post-exercise, placebo (PLA: 57 kJ), skimmed milk (MILK: 1002 kJ) or sucrose (CHO: 1000 kJ) beverages (615 mL) were consumed. Sixty min post-beverage, subjects consumed an *ad-libitum* pasta lunch in a 30 min eating period. Subjective appetite and plasma acylated ghrelin and plasma glucose were determined pre-exercise, post-exercise and pre-meal, with sensory characteristics of beverages rated. *Ad-libitum* energy intake in MILK (6746 ± 2035) kJ) was lower than CHO (7762 ± 1921) kJ) ($P = 0.038$; dz = 0.98; large effect) and tended to be lower than PLA (7672 (2005) kJ) ($P = 0.078$; dz = 0.76; medium effect). Including energy consumed in beverages, energy intake was greater in CHO than PLA ($P = 0.010$; dz = 1.24; large effect) or MILK ($P = 0.026$; dz = 0.98; large effect), with PLA and MILK not different ($P = 0.960$; dz = 0.02; trial effect). Plasma ghrelin, plasma glucose and appetite were not different between trials. MILK was perceived thicker than CHO ($P = 0.020$; dz = 1.11; large effect) and creamier than PLA ($P = 0.026$; dz = 1.06; large effect). These results suggest that when energy balance is important for an exerciser, post-exercise skimmed milk ingestion reduces energy intake compared to a sucrose beverage and might therefore help facilitate recovery/adaptation without affecting energy balance.

1. Introduction

Overweight and obesity develop because of a long-term positive energy balance, where energy intake is greater than energy expenditure. Rates of both overweight and obesity continue to rise globally (NCD-RisC, 2017), meaning there is a growing need to identify strategies that help to facilitate weight management. Whilst strategies to facilitate weight loss are clearly important to reduce levels of obesity, those that help facilitate weight maintenance and prevent weight gain in currently lean individuals might also help curtail the future prevalence of obesity (Ostbye et al., 2011). Structured exercise training is one such strategy, as it increases energy expenditure and facilitates weight loss (Lean et al., 2018; Myers et al., 2019). Whilst numerous studies have examined the impact of exercise on subsequent appetite (see Dorling et al., 2018; Schubert et al., 2013), only a few (Brown et al., 2016; Clayton et al., 2014; Corney et al., 2015; Desbrow et al., 2019; McCartney et al., 2019a, 2019b; Monteyne et al., 2018; Rumbold et al., 2015) have examined how post-exercise nutrition affects subsequent appetite and energy intake.

Post-exercise recovery is a multi-facetted process, but with regards to nutrition, the main goals to maximise short-term recovery are restoring glycogen and water stores, as well as optimising protein balance. Of course, the requirement for and relative importance of each of these goals will depend on the individual exercise session and the objectives of the individual. For restoration of glycogen and water stores, carbohydrate (Betts & Williams, 2010) and fluid (alongside sodium; Evans et al., 2017) intake will be required, whilst stimulation of protein synthesis requires protein (amino acid) ingestion (Phillips & Van Loon, 2011). Targeted nutritional intake after exercise can enhance recovery, but for exercisers concerned with weight management, consumption of energy containing nutrients after exercise might reduce the energy deficit created by the exercise bout. When weight management is a consideration, the impact of any post-exercise nutritional strategy on energy balance is relevant and should ideally supress appetite and subsequent energy intake (Clayton et al., 2014; Rumbold et al., 2015). Indeed, when energy balance is the primary consideration, the ingested nutrients

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would need to suppress subsequent energy intake by at least the amount of energy they supply. Consumption of bovine (cow's) milk after exercise is one nutritional strategy that might satisfy the competing goals of optimising post-exercise recovery, whilst simultaneously suppressing appetite/energy intake (James et al., 2019).

Milk is a cheap and readily available food stuff, containing a mixture of high-quality protein, carbohydrate, water and electrolytes (particularly sodium), that make it uniquely suitable for satisfying many nutritional recovery goals (James et al., 2019). Milk provides substrate to stimulate muscle (Ferguson-Stegall, McCleave, Ding, Doerner, Liu, et al., 2011) and liver (Décombaz et al., 2011) glycogen resynthesis, enhances rehydration compared to carbohydrate-based beverages (Shirreffs et al., 2007) and stimulates post-exercise protein synthesis (Wilkinson et al., 2008). Milk or milk-based beverages may increase short-term recovery of performance compared to carbohydrate (Ferguson-Stegall, McCleave, Ding, Doerner, Liu, et al., 2011; Lunn et al., 2012) and, in some studies, has been shown to facilitate better adaptation to endurance (Ferguson-Stegall, McCleave, Ding, Doerner, Liu, et al., 2011; Robinson et al., 2011) and resistance (Hartman et al., 2007; Josse et al., 2010) exercise training compared to other recovery beverages. In addition to these effects, milk ingestion may reduce subsequent energy intake at rest (Dougkas et al., 2012; Dove et al., 2009) and after exercise (Rumbold et al., 2015), potentially due to the protein (Poppitt et al., 1998; Bertenshaw et al., 2008) and/or lactose (Bowen et al., 2006) content of milk.

Rumbold et al. (2015) reported that ingestion of skimmed milk following 30 min sub-maximal exercise in a group of recreationally active females reduced energy intake 60 min later, compared to an energy-matched fruit juice beverage. Whilst this suggests skimmed milk ingestion post-exercise reduces energy intake relative to a carbohydrate-based beverage, the lack of an energy-free control beverage makes it difficult to determine the true impact of these post-exercise recovery strategies on energy intake, as both beverages provide energy, which might increase total energy intake. Furthermore, given the possible sex differences in appetite regulation (Hagobian et al., 2009), as well as energy balance responses to manipulation of dietary protein intake (Westerterp-Plantenga et al., 2009), these effects in females may not translate to males. Therefore, the purpose of this study was to compare the effects of two different energy matched recovery beverages (skimmed milk and a sucrose beverage) to a very low-energy placebo beverage on subsequent appetite regulation and energy intake in a group of active males. It was hypothesised that energy intake after the skimmed milk would be lower than after the sucrose and placebo beverages.

2. Materials and methods

2.1. Subjects

Ten healthy males (age 21.3 (1.2) years, height 1.79 (0.65) m, body mass 79.2 (9.6) kg, body mass index 23.9 (2.1), peak oxygen uptake ($\dot{V}$ O_2peak), 58 (5) mL/kg/min, body fat 16.5 (3.9) %) volunteered to participate in the present study, which was approved by the Loughborough University Ethical Advisory Committee (Ref number: R12-P126). Subjects were active, non-smokers, not currently on a weight gain/weight loss diet and had not been on any such diet during the previous 6 months. Subjects completed a health screen questionnaire and provided written informed consent.

2.2. Protocol

Subjects completed two preliminary trials followed by three experimental trials, with a different post-exercise recovery beverage ingested during each experimental trial. Experimental trials were randomised (by drawing trial orders out of a hat) and separated by 7–14 days. To minimise expectations effects related to the different beverages provided, subjects were not given any information about what the post-exercise beverages were or about the study aims/hypotheses. They were simply told the study was comparing the appetite effects of three different post-exercise recovery beverages. Furthermore, to mask the differences in beverage appearance/texture/flavour, which would otherwise have been obvious to subjects, all beverages were consumed from an opaque bottle to help mask any colour differences and were served chilled with an additional 15 mL of vanilla essence and 2 g of artificial sweetener to help mask flavour differences. The primary outcomes were total energy intake (*ad-libitum* meal energy intake + energy intake in the post-exercise drink) and *ad-libitum* energy intake, whilst subjective appetite sensations and blood-based measures were secondary outcomes.

2.2.1. Pre-trial standardisation

During the 48 h period pre-trial, subjects were asked to abstain from alcohol intake and strenuous activity. Before the first experimental trial, subjects were asked to recorded their dietary intake and any habitual low intensity physical activity in this 48 h and then replicated these diet/activity patterns in the 48 h preceding subsequent experimental trials. Additionally, a standardised breakfast of cereal and semi-skimmed milk (2693 (216) kJ) providing ~25% of estimated energy requirements (resting metabolic rate (Mifflin et al., 1990) multiplied by a physical activity level of 1.7) was provided for the subjects to consume at home 2 h before they arrived at the laboratory. Subjects confirmed compliance with all pre-trial standardisation procedures upon arrival for each trial.

2.3. Preliminary trials

At the first preliminary trial, height (Stadiometer, Seca Ltd, Germany) and body mass in underwear (Adam CFW 150 scale; Adam Equipment Co Ltd, Milton Keynes, UK) were measured. Subcutaneous skinfold measurements were obtained (Tricep, Biceps, Subscapular and Suprailiiac) and body fat percentage was estimated using the Siri equation (Durnin & Womersley, 1974). A discontinuous incremental exercise test was then performed on an electronically braked cycle ergometer (LODE Corival; Cranlea, Birmingham, UK) to volitional exhaustion to determine $\dot{V}$ O_2peak. Subjects began cycling at 100 W, with increments of 25–50 W every 4 min. During the last minute of each stage, expired gases were collected into a Douglas bag, and heart rate (Sport tester PE Polar Electro, Finland) and Rating of Perceived Exertion (RPE; 6–20 scale) were collected. In the second preliminary trial subjects were familiarised with all experimental methods by completing a trial identical to the experimental trials (described below), with the exception that water was ingested post-exercise.

2.4. Experimental trials

Subjects arrived at the laboratory 2 h after breakfast at ~9–10 a.m. Upon arrival, subjects voided their bladder, were weighed (in underwear only) and completed a subjective appetite questionnaire, before a blood sample was obtained by venepuncture of an antecubital vein. Subjective appetite was measured using 100 mm visual analogue scales. Questions were 'How full does your stomach feel?' and 'How hungry do you feel?'. Verbal anchors 'not at all' and 'very' were placed at 0 mm and 100 mm, respectively (Flint et al., 2000).

Subjects then completed 30 min moderate intensity exercise at ~60% $\dot{V}$ O_2peak (MOD), before they rested for 2 min and then completed five 4-min high intensity intervals at ~85% $\dot{V}$ O_2 peak separated by 2 min rest (HIIE). Expired gases, heart rate and RPE were collected between 14-15 min and 29–30 min of MOD and during the last min of intervals 1, 3 and 5 in HIIE. Immediately post-exercise, body mass was measured, and 10-min post-exercise, subjects completed another appetite questionnaire, and a blood sample was collected.

Subjects then consumed one of the three post exercise recovery beverages, consisting of 600 mL of test beverage (skimmed milk; an energy-matched sucrose beverage; or a low-energy placebo; Table 1) over 5 min and rated the beverage for thickness, creaminess, stickiness, sweetness, sourness and fruitiness immediately after drinking. These characteristics were rated on 100 mm visual analogue scales, with the written anchors 'not at all' and 'very' placed at 0 mm and 100 mm, respectively. To all beverages, 15 ml of vanilla essence and 2 g of an aspartame and acesulfame-K based sweetener (Canderel sweetener) were added, making the total volume 615 mL. 600 mL of beverage was chosen to match the volume provided in previous studies examining the effect of skimmed milk on appetite/energy intake (Dove et al., 2009; Rumbold et al., 2015), as well as to provide sufficient protein (>20 g) to stimulate muscle protein synthesis (Phillips & Van Loon, 2011). After beverage consumption, subjects rested for 55 min before they completed another subjective appetite questionnaire and a final blood sample was collected.

Subjects then entered an isolated eating booth for 30 min and consumed a pasta meal (fusilli pasta, Bolognese sauce, cheese and olive oil; Tesco Stores Ltd, Cheshunt UK; 14% protein, 52% carbohydrate, 34% fat). They were instructed to eat until they were 'comfortably full and satisfied'. Initially, subjects were provided with ~400 g of food in a bowl, with the bowl replaced periodically (at timings determined during the 2nd preliminary trial) to ensure warm food was continuously available and that an empty bowl did not serve as a cue for meal cessation. Water and virtually energy-free flavoured squash (Tesco, Cheshunt, UK) were available to consume ad-libitum throughout the meal. Bowls and glasses were weighed before and after the meal to determine intake. Subjective appetite measures were taken again at the end of the meal.

2.5. Sample collection and analysis

Venous blood samples (~10 ml) were taken from an antecubital vein after at least 10 min supine rest. For the determination of acylated ghrelin, 5 ml of blood was dispensed into a K_2EDTA tube (1.75 mg ml^{-1}) containing a solution (10 μl ml^{-1} blood) of potassium phosphate-buffered saline (0.05 M), *p*-hydroxymercuribenzoic acid (0.05 M) and sodium hydroxide (NaOH), (0.06 M). The tube was then centrifuged at 1800 g for 10 min at 4 °C, after which the plasma was transferred to a plain tube containing 1 M HCl (100 μl ml^{-1} plasma) and then centrifuged for a further 5 min. The resultant plasma was stored at −20 °C for 24 h and then at −80 °C until analysis using a commercially available ELISA kit (SPI BIO, Montigny le Bretonneux, France; typical CV <12%). For the determination of plasma glucose (colorimetric assay; Randox Laboratories Ltd, Crumlin, UK; typical CV <1%), 5 ml blood was dispensed into a K_2EDTA tube, the plasma was separated by centrifugation and stored at −80 °C until analysis. Due to sample storage issues, only 9 subjects' samples were analysed for plasma glucose concentration. Expired gas samples were analysed for O_2 and CO_2 concentrations (Servomex 1400 Oxygen and Carbon Dioxide Gas Analyser; Servomex, Crowborough, UK), gas volume (Harvard dry gas meter; Harvard Apparatus Ltd., Edenbridge, UK) and gas temperature (RS Pro digital thermometer; RS Components, Corby, UK) and corrected to standard temperature and pressure, dry.

Table 1
Energy and macronutrient composition of the post-exercise recovery beverages.

	PLA	MILK	CHO
Energy (kJ)	57	1002	1000
Protein (g)	0.0	21.6	0.0
Carbohydrate (g)	2.5	32.5	58.0
Fat (g)	0.4	2.2	0.4

2.6. Statistical analysis

Data were analysed using SPSS 20 (Chicago, USA), and initially checked for normality of distribution using the Shapiro Wilk test. Data were then analysed using one-way or two-way repeated measures ANOVA, followed by Holm-Bonferroni-adjusted t-tests for normally distributed data and Holm-Bonferroni-adjusted Wilcoxon Signed Rank tests for non-normally distributed data. Data are presented as mean ± SD, unless otherwise stated. Effect sizes (Cohen's dz) were calculated for paired comparisons and interpreted as trivial ($dz < 0.2$), small ($dz \geq 0.2$), medium ($dz \geq 0.5$) and large ($dz \geq 0.8$). Data sets were accepted as being significantly different when $P < 0.05$. At the time of data collection, there were no similar studies to inform sample size calculation, but sample size was similar to those with similar methodology (Clayton et al., 2014; Rumbold et al., 2015).

3. Results

3.1. Exercise session

There were no differences between trials for heart rate during MOD (PLA 151 ± 16; MILK 148 ± 11; CHO 149 ± 16; P = 0.646) or HIIE (PLA 177 ± 12 beats/min; MILK 178 ± 7 beats/min; CHO 178 ± 1 beats/min; P = 0.931), RPE during MOD (PLA 13 ± 1; MILK 13 ± 2; CHO 13 ± 2; P = 0.305) or HIIE (PLA 16 ± 2; MILK 17 ± 2; CHO 17 ± 2; P = 0.282) or $\dot{V}O_2$ during MOD (PLA 2.65 ± 0.35; MILK 2.60 ± 0.38; CHO 2.59 ± 0.38; P = 0.075) or HIIE (PLA 3.92 ± 0.37; MILK 3.78 ± 0.46; CHO 3.88 ± 0.40; P = 0.287).

3.2. Energy intake

There was a main effect for energy intake at the ad-libitum meal (P = 0.011; Fig. 1a), with energy intake reduced for MILK compared to CHO (P = 0.039; dz = 0.98; large effect) and although there was a medium effect size for MILK compared to PLA, the corrected P value did not reach significance (P = 0.078; dz = 0.76; medium effect). There was no difference between CHO and PLA (P > 0.999; dz = 0.11; trivial effect). There was also a main effect for total energy intake (energy intake at the ad-libitum meal plus energy in the post-exercise beverage; P = 0.008; Fig. 1b), with greater total energy intake during CHO compared to both PLA (P = 0.010; dz = 1.24; large effect) and MILK (P = 0.026; dz = 0.98; large effect), with no difference between PLA and MILK (P = 0.960; dz = 0.02; trivial effect).

3.3. Subjective ratings of appetite and beverage sensory characteristics

For fullness (Table 2), there was a time effect (P < 0.001), but no trial (P = 0.245) or interaction effects (P = 0.114). For hunger (Table 2) there was a time effect (P < 0.001), as well as trial (P = 0.011) and interaction (P = 0.008) effects, however, after correction for multiple comparisons, there were no post-hoc differences between trials (P > 0.102).

For the beverage characteristics (Table 3), there were main effects of trial for thickness (P = 0.014), creaminess (P = 0.007) and sweetness (P = 0.001), but not for stickiness (P = 0.516), sourness (P = 0.699) or fruitiness (P = 0.510). MILK was perceived to be thicker than CHO (P = 0.020; dz = 1.11; large effect) and creamier than PLA (P = 0.026; dz = 1.06; large effect), but the difference did not reach statistical significance for thickness compared to PLA (P = 0.118; dz = 0.76; medium effect) or creaminess compared to CHO (P = 0.071; dz = 0.78; medium effect), despite medium effect sizes. For sweetness, MILK was perceived as sweeter than PLA (P = 0.041; dz = 0.89; large effect), whilst CHO was perceived as sweeter than both PLA (P = 0.015; dz = 1.26; large effect) and MILK (P = 0.033; dz = 0.81; large effect).

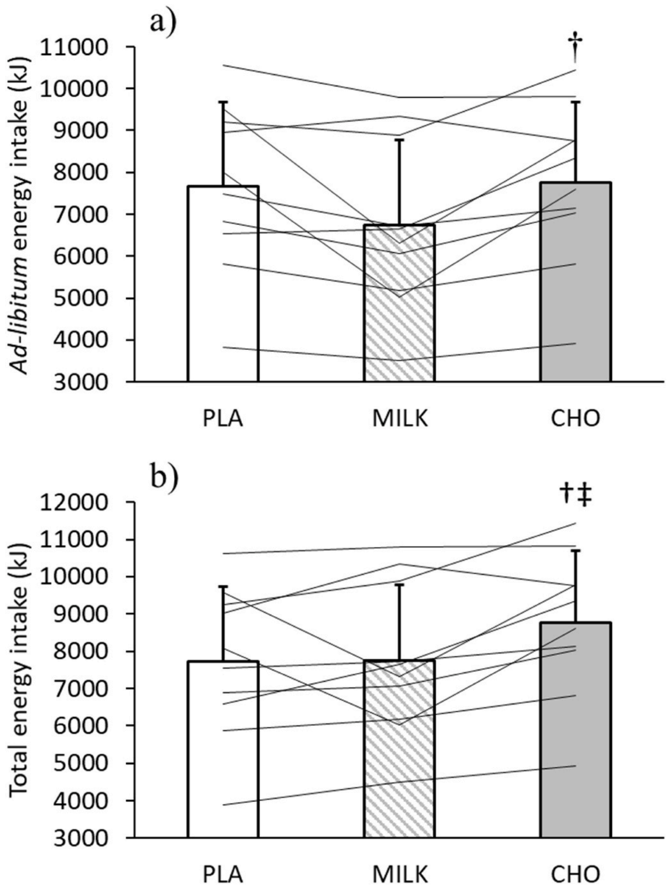

Fig. 1. Energy intake (kJ) consumed at the *ad-libitum* meal (a) and cumulative energy intake (kJ) from post-exercise beverage and *ad-libitum* meal (b). Bars are mean and error bars are SD, with lines representing individual subject data. †‡ˆ Significantly different from the CHO.

Table 2
Subjective ratings of appetite throughout trials. Data are Mean ± SD (range).

	Pre-exercise	Post-exercise	Pre-meal	Post-meal
Hunger (0–100 mm)				
PLA	33 ± 15 (16–61)	41 ± 26 (8-79)	85 ± 9 (74–98)	10 ± 4 (0-28)
MILK	31 ± 16 (13–63)	50 ± 24 (2-82)	80 ± 13 (53–90)	9 ± 12 (1-32)
CHO	42 ± 23 (9-74)	66 ± 11 (50–80)	81 ± 6 (70–96)	8 ± 6 (0-22)
Fullness (0–100 mm)				
PLA	61 ± 26 (12–84)	54 ± 24 (22–82)	21 ± 20 (0-61)	84 ± 15 (60–97)
MILK	54 ± 16 (31–83)	37 ± 12 (13–86)	23 ± 12 (13–44)	86 ± 15 (57–98)
CHO	57 ± 22 (25–90)	41 ± 14 (14–69)	23 ± 15 (11–52)	90 ± 6 (81–97)

3.4. Blood measures

For plasma glucose concentration, there were no time (P = 0.121), trial (P = 0.543) or interaction (P = 0.730) effects. For acylated ghrelin concentration (Table 4), there was a main effect of time (P = 0.015), with an increase from post-exercise to pre-meal (P = 0.006), but no trial (P = 0.643) or interaction (P = 0.264) effects.

Table 3
Subjective ratings of beverage characteristics. Data are Mean ± SD (range). † signifies significantly different from MILK ($P < 0.05$). ‡ signifies significantly different from PLA ($P < 0.05$).

	PLA	MILK	CHO
Thickness	24 ± 19 (6-58)	41 ± 18 (17–69)	23 ± 14 † (2-44)
Creaminess	25 ± 20 † (3-58)	56 ± 31 (25–85)	44 ± 26 (3-86)
Stickiness	30 ± 19 (9-67)	31 ± 20 (11–66)	35 ± 19 (9-66)
Sweetness	50 ± 18 (19–71)	71 ± 16 ‡ (35–94)	80 ± 18 †‡ (35–98)
Sourness	12 ± 12 (0-28)	9 ± 14 (0-35)	14 ± 18 (0-45)
Fruitiness	26 ± 21 (0-69)	27 ± 26 (0-84)	21 ± 20 (0-71)

Table 4
Plasma glucose (A) and acylated ghrelin concentrations (B). Values are mean ± SD or mean ± SD (range).

	Pre-exercise	Post-exercise	Pre-meal
Plasma glucose concentration (mmol/L)			
PLA	4.43 ± 0.47	4.70 ± 0.47	4.67 ± 0.55
MILK	4.50 ± 0.77	4.71 ± 0.44	4.60 ± 0.40
CHO	4.93 ± 0.64	5.15 ± 1.05	4.76 ± 0.50
Plasma acylated ghrelin concentration (pg/mL)			
PLA	109 ± 84 (31–307)	88 ± 81 (11–211)	150 ± 109 (37–393)
MILK	129 ± 88 (40–323)	104 ± 126 (18–420)	129 ± 82 (30–317)
CHO	125 ± 110 (37–424)	121 ± 131 (6–452)	143 ± 100 (33–385)

Plasma glucose data are n = 9.

4. Discussion

This study aimed to examine the effect of different post-exercise recovery beverages on subsequent appetite and energy intake, comparing skimmed milk and an energy-matched carbohydrate (sucrose) beverage to a low-energy placebo in active males. The main finding was that *ad-libitum* energy intake 60 min after beverage ingestion was reduced following skimmed milk compared to a sucrose beverage and tended to be reduced for skimmed milk compared to the placebo beverage. This meant that total energy intake (*ad-libitum* energy intake plus the energy provided in the post-exercise beverage) was lower following skimmed milk and placebo compared to after ingestion of the sucrose beverage, with no difference between skimmed milk and placebo, at least when a fixed volume of fluid is provided. Interestingly, despite these differences in energy intake, there were no between-trial differences for subjective appetite ratings or acylated ghrelin concentrations, suggesting the mechanisms of action for the observed effect lie elsewhere.

These results support the findings of another study (Rumbold et al., 2015), in which ingestion of 600 mL skimmed milk after 30 min submaximal cycling decreased energy intake at a subsequent *ad-libitum* meal compared to a carbohydrate-based orange juice beverage in recreationally active females. The present study demonstrates that a similar effect is apparent in males, but additionally demonstrates that total energy intake, including the energy in the post-exercise beverage, is similar when skimmed milk or an almost energy-free placebo are ingested. These results are important, as they suggest that if the exercise session is being used to facilitate a negative energy balance, consumption of skimmed milk will not reduce the energy deficit created by the exercise. An important consideration here is that a fixed volume of beverage was provided. Studies (Baguley et al., 2016; Campagnolo et al., 2017; McCartney et al., 2019a, 2019b) suggest that milk-based beverages are consumed in lower volumes than carbohydrate beverages or water, which could influence subsequent eating behaviour responses and should be explored in future studies.

At rest, milk has been shown to increase satiety (Dove et al., 2009; Dougkas et al., 2012; Maersk et al., 2012) and subsequent energy intake at the next eating opportunity (Dove et al., 2009; Dougkas et al., 2012), although not universally (Soenen & Westerterp-Plantenga, 2007; Maersk et al., 2012). Dove reported that consumption of 600 mL skimmed milk with breakfast reduced energy intake by ~8.5% at lunch 4 h later compared to consumption of 600 mL of a carbohydrate fruit beverage, whilst Dougkas et al. (2012) reported that 410 mL semi-skimmed milk as a mid-morning snack reduced lunch energy intake 90 min later by 12% compared to water. Like this previous work (Dougkas et al., 2012; Dove et al., 2009), the present study observed that energy intake at lunch after the MILK beverage was ~12% and ~13% lower compared to the PLA and CHO beverages, respectively. Interestingly, there were no differences in subjective appetite in the present study, a finding that is consistent with the results after exercise in females (Rumbold et al., 2015), but contrasts with previous work performed at rest (Dove et al., 2009; Dougkas et al., 2012; Maersk et al., 2012). Given the inclusion of exercise in the present study, it is possible that the effects of exercise on subjective appetite/satiety (Dorling et al., 2018) masked the effects of different post-exercise beverages on subjective appetite or we may have been underpowered to detect these effects. Furthermore, it is not uncommon for studies to observe no difference between trials for appetite, but to observe differences in *ad-libitum* food intake (e.g. Dougkas et al., 2012), particularly with combined exercise-nutrition interventions (e.g. Clayton et al., 2014; Monteyne et al., 2018; Rumbold et al., 2015).

These findings have important implications for athletes and other exercisers who are concerned with weight management. Consumption of carbohydrate and protein post-exercise will increase glycogen resynthesis (Betts & Williams, 2010) and protein synthesis (Phillips & Van Loon, 2011), respectively, potentially augmenting recovery from and/or adaptation to exercise training. However, the additional energy consumed in a post-exercise beverage may reduce the energy deficit created by the exercise session, potentially attenuating weight/fat loss in the long-term. Thus, in this setting, post-exercise recovery goals requiring energy intake (i.e. carbohydrate and protein intake) may conflict with goals focusing on energy balance/weight loss. Milk is a natural beverage that can satisfy many recovery goals, enhance short-term recovery, in some situations, and facilitate beneficial adaptive responses to exercise training (James et al., 2019). In this context, the present study importantly demonstrates that consumption of skimmed milk after exercise may offer a nutritional recovery strategy that can enhance exercise recovery and/or adaptation, without compromising the energy deficit created by exercise. Studies have suggested decreases in daily energy intake of ~700 kJ are clinically relevant for weight control (Hill et al., 2003; Wynne et al., 2005), suggesting that the ~1000 kJ decrease in total energy intake in the MILK trial vs the CHO trial might be relevant for long-term weight maintenance in active populations. Indeed, in support of this hypothesis, long-term resistance (Hartman et al., 2007; Josse et al., 2010) and endurance (Ferguson--Stegall, McCleave, Ding, Doerner, Liu, et al., 2011) training studies suggest that consuming milk or milk-based beverages after exercise increases fat mas reduction, suggesting a more negative energy balance. However, clearly further work to explore the energy balance responses, with careful measurement of energy intake and expenditure are required to confirm this.

Whilst the present study does not identify the mechanisms, there are several plausible explanations related to the differences in beverage composition and/or sensory characteristics that might account for the observed effects. Milk contains high quality protein, that can stimulate post-exercise muscle protein synthesis (Wilkinson et al., 2008), as well as possibly suppressing appetite. At rest, protein-containing beverages have been shown to increase satiety and/or decrease subsequent energy intake (Poppitt et al., 1998; Bowen et al., 2006; Bertenshaw et al. 2008, 2009; Astbury et al., 2010). These effects of protein are believed to be caused by effects on appetite-regulatory hormones (Bowen et al., 2006). Similar effects have been reported after exercise, with protein addition to beverages consumed in this context reducing subsequent energy intake relative to low-energy placebo (Clayton et al., 2014) or iso-energetic carbohydrate (Monteyne et al., 2018) beverages. Although we were only able to measure acylated ghrelin in the present study, there were no differences observed between trials, which contrasts previous work at rest (Bowen et al., 2006). Given exercise has been shown to alter acylated ghrelin concentrations (Dorling et al., 2018), it may be that, similar to our subjective appetite data, these exercise effects mitigate differences produced by nutrient intake or we may have been underpowered to detect these effects. Future studies should seek to determine the responses of other appetite-related hormones, that may help to elucidate potential mechanisms.

Additionally, the lactose and calcium content of milk might also help to explain the findings. Compared to an isoenergetic amount of glucose, lactose increases satiety and decreases subsequent energy intake 3 h later (Bowen et al., 2006), with the degree of change like those induced by protein. Lactose is made up of the monosaccharides galactose and glucose. Galactose may be more slowly absorbed in the intestines and decreases hunger relative to glucose (Duckworth et al., 2013), effects that might account for the suppression of energy intake reported following lactose ingestion. The skimmed milk also contained calcium, which may influence appetite responses. Calcium in a meal has been shown to increase GLP-1 and GIP concentrations (Gonzalez et al., 2013) and to decrease subsequent energy intake (Gonzalez et al., 2015). Therefore, it is possible that the protein, lactose and/or calcium content of the skimmed milk acted alone or in combination to suppress energy intake at the post-exercise meal.

Finally, the effects might not have been a direct result of the compositional differences between the beverages, but rather caused by the influence these compositional factors had on the beverages sensory properties. The sensory characteristics of a beverage appear to have a powerful effect on appetite and energy intake, with beverages of greater perceived thickness and creaminess being shown to modify subsequent energy intake (Yeomans & Chambers, 2011; Bertenshaw et al., 2013). These are sensory characteristics associated with milk protein-containing, beverages. Indeed, previous work that has reported protein-containing beverages to decrease subsequent energy intake has either observed differences in these sensory characteristics (Bertenshaw et al. 2008, 2009; Astbury et al., 2010; Monteyne et al., 2018) or used beverages that would be expected to differ sensorially (Bowen et al., 2006; Dougkas et al., 2012; Dove et al., 2009; Rumbold et al., 2015). Therefore, it seems likely that the increased perceived thickness or creaminess of the skimmed milk might, at least partially, account for the reduced energy intake in the MILK trial.

Of course, this study is not without limitations. Firstly, the acute, single-meal nature of the study, makes firm extrapolation of the findings to long-term training difficult. Secondly, we imposed fixed restrictions on the volume of post-exercise beverage and the timing of the post-exercise meal. These were necessary to test our hypothesis, but future studies should seek to determine effects under more free-living situations, by example allowing ad-libitum intake of post-exercise beverages and self-selection of meal start times to better reflect real world scenarios. Finally, the population studied were young, healthy males, but given an appetite suppressive effect of post-exercise skimmed milk (vs a carbohydrate drink) has already been demonstrated in young healthy females (Rumbold et al., 2015), it is good to see similar result in a male population. Clearly further studies will be needed to explore the effects in children, older adults and clinical populations, including those with overweight/obesity.

This study has important practical implications for athletes and recreational exercisers for whom weight management is important. For these individuals, managing post-exercise energy balance is possibly as important, if not more important, than other post-exercise recovery goals and in this context, post-exercise nutritional intake should be carefully considered. This study shows that consumption of skimmed milk after exercise reduces subsequent energy intake, such that total energy intake is not different from a low-energy placebo beverage and reduced relative to a sucrose beverage. Therefore, we conclude that in situations where weight management (weight reduction or maintenance) is an important consideration, but that rapid intake of nutrients post-exercise might benefit short-term recovery or long-term adaptation, consumption of skimmed milk post-exercise may offer a practical and cost-effective strategy to achieve these goals.

Ethical statement

Ten healthy males (age 21.3 (1.2) years, height 1.79 (0.65) m, body mass 79.2 (9.6) kg, body mass index 23.9 (2.1), peak oxygen uptake ($\dot{V}O_2$peak), 58 (5) mL/kg/min, body fat 16.5 (3.9) %) volunteered to participate in the present study, which was approved by the Loughborough University Ethical Advisory Committee **(**Ref number: R12-P126**)**. Subjects were active, non-smokers, not currently on a weight gain/weight loss diet and had not been on any such diet during the previous 6 months. Subjects completed a health screen questionnaire and provided written informed consent.

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Declaration of competing interest

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Data availability

Data will be made available on request.

References

Astbury, N. M., Stevenson, E. J., Morris, P., Taylor, M. A., & Macdonald, I. A. (2010). Dose-response effect of a whey protein preload on within-day energy intake in lean subjects. *British Journal of Nutrition, 104*, 1858–1867.

Baguley, B., Zilujko, J., Leveritt, M. D., Desbrow, B., & Irwin, C. (2016). The effect of ad libitum consumption of a milk-based liquid meal supplement vs. a traditional Sports drink on fluid balance after exercise. *International Journal of Sport Nutrition and Exercise Metabolism, 26*, 347–355.

Bertenshaw, E. J., Lluch, A., & Yeomans, M. R. (2008). Satiating effects of protein but not carbohydrate consumed in a between-meal beverage context. *Physiology & Behavior, 93*, 427–436.

Bertenshaw, E. J., Lluch, A., & Yeomans, M. R. (2009). Dose-dependent effects of beverage protein content upon short-term intake. *Appetite, 52*, 580–587.

Bertenshaw, E. J., Lluch, A., & Yeomans, M. R. (2013). Perceived thickness and creaminess modulates the short-term satiating effects of high-protein drinks. *British Journal of Nutrition, 110*, 578–586.

Betts, J. A., & Williams, C. (2010). Short-term recovery from prolonged exercise: Exploring the potential for protein ingestion to accentuate the benefits of carbohydrate supplements. *Sports Medicine, 40*, 941–959.

Bowen, J., Noakes, M., Trenerry, C., & Clifton, P. M. (2006). Energy intake, ghrelin, and cholecystokinin after different carbohydrate and protein preloads in overweight men. *The Journal of Cinical Endocrinology and Metabolism, 91*, 1477–1483.

Brown, M. A., Green, B. P., James, L. J., Stevenson, E. J., & Rumbold, P. L. (2016). The effect of a dairy-based recovery beverage on post-exercise appetite and energy intake in active females. *Nutrients, 8*, Article E355.

Campagnolo, N., Iudakhina, E., Irwin, C., Schubert, M., Cox, G. R., Leveritt, M., & Desbrow, B. (2017). Fluid, energy and nutrient recovery via ad libitum intake of different fluids and food. *Physiology & Behavior, 171*, 228–235.

Clayton, D. J., Stensel, D. J., Watson, P., & James, L. J. (2014). The effect of post-exercise drink macronutrient content on appetite and energy intake. *Appetite, 82*, 173–179.

Corney, R. A., Sunderland, C., & James, L. J. (2015). The effect of hydration status on appetite and energy intake. *Journal of Sports Sciences, 33*, 761–768.

Décombaz, J., Jentjens, R., Ith, M., Scheurer, E., Buehler, T., Jeukendrup, A., & Boesch, C. (2011). Fructose and galactose enhance postexercise human liver glycogen synthesis. *Medicine & Science in Sports & Exercise, 43*, 1964–1971, 2011.

Desbrow, B., Barnes, K., Cox, G. R., Iudakhina, E., McCartney, D., Skepper, S., Young, C., & Irwin, C. (2019). Calorie-containing recovery drinks increase recreational runners' voluntary energy and carbohydrate intake, with minimal impact on fluid recovery. *International Journal of Sport Nutrition and Exercise Metabolism, 29*, 359–363.

Dorling, J., Broom, D. R., Burns, S. F., Clayton, D. J., Deighton, K., James, L. J., miyashita, M., Thackray, A. E., Betterham, R. L., & Stensel, D. J. (2018). Acute and chronic effects of exercise on appetite, energy intake, and appetite-related hormones: The modulating effect of adiposity, sex, and habitual physical activity. *Nutrients, 10*, Article E1140.

Dougkas, A., Minihane, A. M., Givens, D. I., Reynolds, C. K., & Yaqoob, P. (2012). Differential effects of dairy snacks on appetite, but not overall energy intake. *British Journal of Nutrition, 108*, 2274–2285.

Dove, E. R., Hodgson, J. M., Puddey, I. B., Beilin, L. J., Lee, Y. P., & Mori, T. A. (2009). Skim milk compared with a fruit drink acutely reduces appetite and energy intake in overweight men and women. *American Journal of Clinical Nutrition, 90*, 70–75.

Duckworth, L. C., Backhouse, S. H., & Stevenson, E. J. (2013). The effect of galactose ingestion on affect and perceived exertion in recreationally active females. *Appetite, 71*, 252–258.

Durnin, J. V. G. A., & Womersley, J. (1974). Body fat assessed from total body density and its estimation from skinfold thickness: Measurements on 481 men and women aged from 16 to 72 years. *British Journal of Nutrition, 32*, 77–97.

Evans, G. H., James, L. J., Shirreffs, S. M., & Maughan, R. J. (2017). Optimizing the restoration and maintenance of fluid balance after exercise-induced dehydration. *Journal of Applied Physiology, 122*, 945–951.

Ferguson-Stegall, L., McCleave, E., Ding, Z., Doerner, P. G., Iii, Liu, Y., Wang, B., Healy, M., Kleinert, M., Dessard, B., Lassiter, D. G., Kammer, L., & Ivy, J. L. (2011a). Aerobic exercise training adaptations are increased by postexercise carbohydrate-protein supplementation. *J. Nutr. Metab*, Article 623182, 2011.

Ferguson-Stegall, L., McCleave, E. L., Ding, Z., Doerner, P. G., 3rd, Wang, B., Liao, Y. H., Kammer, L., Liu, Y., Hwang, J., Dessard, B. M., & Ivy, J. L. (2011b). Postexercise carbohydrate-protein supplementation improves subsequent exercise performance and intracellular signaling for protein synthesis. *The Journal of Strength & Conditioning Research, 25*, 1210–1224.

Flint, A., Raben, A., Blundell, J. E., & Astrup, A. (2000). Reproducibility, power and validity of visual analogue scales in assessment of appetite sensations in single test meal studies. *International Journal of Obesity, 24*, 38–48.

Gonzalez, J. T., Green, B. P., Brown, M. A., Rumbold, P. L., Turner, L. A., & Stevenson, E. J. (2015). Calcium ingestion suppresses appetite and produces acute overcompensation of energy intake independent of protein in healthy adults. *Journal of Nutrition, 145*, 476–482.

Gonzalez, J. T., Rumbold, P. L., & Stevenson, E. J. (2013). Appetite sensations and substrate metabolism at rest, during exercise, and recovery: Impact of a high-calcium meal. *Applied Physiology Nutrition and Metabolism, 38*, 1260–1267.

Hagobian, T. A., Sharoff, C. G., Stephens, B. R., Wade, G. N., Silva, J. E., Chipkin, S. R., & Braun, B. (2009). Effects of exercise on energy-regulating hormones and appetite in men and women. *American Journal of Physiology - Regulatory, Integrative and Comparative Physiology, 296*, 233–242.

Hartman, J. W., Tang, J. E., Wilkinson, S. B., Tarnopolsky, M. A., Lawrence, R. L., Fullerton, A. V., & Phillips, S. M. (2007). Consumption of fat-free fluid milk after resistance exercise promotes greater lean mass accretion than does consumption of soy or carbohydrate in young, novice, male weightlifters. *American Journal of Clinical Nutrition, 86*, 373–381.

Hill, J. O., Wyatt, H. R., Reed, G. W., & Peters, J. C. (2003). Obesity and the environment: Where do we go from here? *Science, 299*, 853–855.

James, L. J., Stevenson, E. J., Rumbold, P. L. S., & Hulston, C. J. (2019). Cow's milk as a post-exercise recovery drink: Implications for performance and health. *European Journal of Sport Science, 19*, 40–48.

Josse, A. R., Tang, J. E., Tarnopolsky, M. A., & Phillips, S. M. (2010). Body composition and strength changes in women with milk and resistance exercise. *Medicine & Science in Sports & Exercise, 42*, 1122–1130.

Lean, M. E. J., Astrup, A., & Roberts, S. B. (2018). Making progress on the global crisis of obesity and weight management. *BMJ*, 361, 2018.

Lunn, W. R., Pasiakos, S. M., Colletto, M. R., Karfonta, K. E., Carbone, J. W., Anderson, J. M., & Rodriguez, N. R. (2012). Chocolate milk and endurance exercise recovery: Protein balance, glycogen, and performance. *Medicine & Science in Sports & Exercise, 44*, 682–691.

Maersk, M., Belza, A., Holst, J. J., Fenger-Gron, M., Pedersen, S. B., Astrup, A., & Richelsen, B. (2012). Satiety scores and satiety hormone response after sucrose-sweetened soft drink compared with isocaloric semi-skimmed milk and with non-caloric soft drink: A controlled trial. *European Journal of Clinical Nutrition, 66*, 523–529.

McCartney, D., Irwin, C., Cox, G. R., & Desbrow, B. (2019a). The effect of different post-exercise beverages with food on ad libitum fluid recovery, nutrient provision, and subsequent athletic performance. *Physiology & Behavior, 201*, 22–30.

McCartney, D., Irwin, C., Cox, G. R., & Desbrow, B. (2019b). Fluid, energy, and nutrient recovery via ad libitum intake of different commercial beverages and food in female athletes. *Applied Physiology Nutrition and Metabolism, 44*, 37–46.

Mifflin, M. D., St Jeor, S. T., Hill, L. A., Scott, B. J., Daugherty, S. A., & Koh, Y. O. (1990). A new predictive equation for resting energy expenditure in healthy individuals. *American Journal of Clinical Nutrition, 51*, 241–247.

Monteyne, A., Martin, A., Jackson, L., Corrigan, N., Stringer, E., Newey, J., Rumbold, P. L. S., Stevenson, E. J., & James, L. J. (2018). Whey protein consumption after resistance exercise reduces energy intake at a post-exercise meal. *European Journal of Nutrition, 57*, 585–592.

Myers, A., Dalton, M., Gibbons, C., Finlayson, G., & Blundell, J. (2019). Structured, aerobic exercise reduces fat mass and is partially compensated through energy intake but not energy expenditure in women. *Physiology & Behavior, 199*, 56–65.

NCD Risk Factor Collaboration (NCD-RisC). (2017). Worldwide trends in body-mass index, underweight, overweight, and obesity from 1975 to 2016: A pooled analysis of 2416 population-based measurement studies in 128·9 million children, adolescents, and adults. *Lancet, 390*, 2627–2642.

Ostbye, T., Malhotra, R., & Landerman, L. R. (2011). Body mass trajectories through adulthood: Results from the national longitudinal survey of youth cohort (1981-2006). *International Journal of Epidemiology, 40*, 240–250.

Phillips, S. M., & Van Loon, L. J. (2011). Dietary protein for athletes: From requirements to optimum adaptation. *Journal of Sports Sciences, 29*(Suppl 1), S29–S38.

Poppitt, S. D., McCormack, D., & Buffenstein, R. (1998). Short-term effects of macronutrient preloads on appetite and energy intake in lean women. *Physiology & Behavior, 64*, 279–285.

Robinson, M. M., Turner, S. M., Hellerstein, M. K., Hamilton, K. L., & Miller, B. F. (2011). Long-term synthesis rates of skeletal muscle DNA and protein are higher during aerobic training in older humans than in sedentary young subjects but are not altered by protein supplementation. *The FASEB Journal, 25*, 3240–3249.

Rumbold, P., Shaw, E., James, L., & Stevenson, E. (2015). Milk consumption following exercise reduces subsequent energy intake in female recreational exercisers. *Nutrients, 7*, 293–305.

Schubert, M. M., Desbrow, B., Sabapathy, S., & Leveritt, M. (2013). Acute exercise and subsequent energy intake. A meta-analysis. *Appetite, 63*, 92–104.

Shirreffs, S. M., Watson, P., & Maughan, R. J. (2007). Milk as an effective post-exercise rehydration drink. *British Journal of Nutrition, 98*, 173–180.

Soenen, S., & Westerterp-Plantenga, M. S. (2007). No differences in satiety or energy intake after high-fructose corn syrup, sucrose, or milk preloads. *American Journal of Clinical Nutrition, 86*, 1586–1594.

Westerterp-Plantenga, M. S., Lejeune, M. P. G. M., Smeets, A. J. P. G., & Luscombe-Marsh, N. D. (2009). Sex differences in energy homeostatis following a diet relatively high in protein exchanged with carbohydrate, assessed in a respiration chamber in humans. *Physiology & Behavior, 97*, 414–419.

Wilkinson, S. B., Phillips, S. M., Atherton, P. J., Patel, R., Yarasheski, K. E., Tarnopolsky, M. A., & Rennie, M. J. (2008). Differential effects of resistance and endurance exercise in the fed state on signalling molecule phosphorylation and protein synthesis in human muscle. *Journal de Physiologie, 586*, 3701–3717.

Wynne, K., Stanley, S., McGowan, B., & Bloom, S. (2005). Appetite control. *Journal of Endocrinology, 184*, 291–318.

Yeomans, M. R., & Chambers, L. (2011). Satiety-relevant sensory qualities enhance the satiating effects of mixed carbohydrate-protein preloads. *American Journal of Clinical Nutrition, 94*, 1410–1417.