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Influence of habitual physical activity on gastric emptying in healthy males and relationships with body composition and energy expenditure

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Abstract

Although a number of studies have examined the role of gastric emptying (GE) in obesity, the influences of habitual physical activity level, body composition and energy expenditure (EE) on GE have received very little consideration. In the present study, we compared GE in active and inactive males, and characterised relationships with body composition (fat mass and fat-free mass) and EE. A total of forty-four males (active *n* 22, inactive *n* 22; BMI 21–36 kg/m^2; percentage of fat mass 9–42 %) were studied, with GE of a standardised (1676 kJ) pancake meal being assessed by the [^{13}C]octanoic acid breath test, body composition by air displacement plethysmography, RMR by indirect calorimetry, and activity EE (AEE) by accelerometry. The results showed that GE was faster in active compared with inactive males (mean half-time ($t_{1/2}$): active 157 (SD 18) and inactive 179 (SD 21) min, $P<0{\cdot}001$). When data from both groups were pooled, GE $t_{1/2}$ was associated with percentage of fat mass (r 0·39, $P<0{\cdot}01$) and AEE (r −0·46, $P<0{\cdot}01$). After controlling for habitual physical activity status, the association between AEE and GE remained, but not that for percentage of fat mass and GE. BMI and RMR were not associated with GE. In summary, faster GE is considered to be a marker of a habitually active lifestyle in males, and is associated with a higher AEE level and a lower percentage of fat mass. The possibility that GE contributes to a gross physiological regulation (or dysregulation) of food intake with physical activity level deserves further investigation.

Key words: Body composition: Energy expenditure: Gastric emptying: Physical activity

Gastric emptying (GE) has a fundamental role in the digestion of nutrients, and is a major determinant of postprandial glycaemia[1] and gastric symptoms[2,3]. In addition, altered GE has been implicated in the pathogenesis of overconsumption, leading to weight gain and obesity[4–10]. Over the last 30 years, a number of studies have investigated this possible linkage but with conflicting outcomes, indicating that the role of GE in obesity is still unclear. Accelerated[6–8], similar[11–13] and delayed[10,14–16] emptying rates have been reported when comparing obese with lean individuals. This inconsistency has generally been attributed to methodological differences and limitations (e.g. meal size, sex)[17]. Another possibility is that inconclusive findings may be due to the influence of additional unmeasured or uncontrolled factors, for example habitual physical activity level, body composition (fat mass (FM) and fat-free mass (FFM)) and energy expenditure (EE).

When considering metabolic health, the importance of body composition[18] and physical activity level[19] is becoming increasingly apparent. Furthermore, body composition, but not BMI, has been shown to be associated with daily energy intake in obese adults[20]. However, to date, BMI or ideal body weight has been the major criterion for distinguishing obese and non-obese groups in GE studies[6–8,10–15]. To the best of our knowledge, only two studies have reported directly on body composition (FM and/or FFM)[8,13]. Vazquez Roque *et al.*[13] characterised gastric functions in normal-weight, overweight and obese individuals categorised by BMI and reported lean mass. Although no significant differences were found between groups, increased body weight was associated with faster GE. In another cross-sectional study, Mathus-Vliegen *et al.*[8] reported faster solid emptying in taller subjects with a greater FFM and in subjects with more intra-abdominal fat. These findings suggest a possible

Abbreviations: ^{13}C-OBT, [^{13}C]octanoic acid breath test; AEE, activity energy expenditure; EE, energy expenditure; FFM, fat-free mass; FM, fat mass; GE, gastric emptying; $t_{1/2}$, half-time; t_{asc}, ascension time; t_{lag}, lag time; t_{lat}, latency time.

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relationship between body composition and GE, yet further studies are clearly needed to establish this hypothesis further. Despite numerous studies examining the role of GE in obesity, body composition has received very little attention.

Differences in physical activity and EE may also influence GE. Exercise is known to improve leptin sensitivity via reducing FM[21,22], which some evidence in animals suggests may interact with gut hormones such as cholecystokinin and vagal afferent fibres to influence gastric motility[23]. It is acknowledged that habitual activity, EE and body composition are interrelated. Indeed, a higher activity EE (AEE) level can also arise in obese individuals due to the greater energy cost of activities associated with increased body weight[24]. However, the influence of resting EE or AEE on GE is unknown. Evidence that GE is faster in marathon runners[25] compared with inactive individuals arises from a single quarter-century old study by Carrio *et al.*[25]. They identified faster GE in ten marathon runners compared with ten inactive individuals; however, body surface area was the only proxy characteristic of body composition reported and EE was not measured.

Given the growing interest in targeting the gastrointestinal tract for the treatment of obesity and diabetes[4,26–28], it is pertinent that a better understanding of factors influencing GE is established. In addition, given the role of the gastrointestinal tract in satiation and satiety[16,26,29,30], understanding the associations between physical activity and GE may provide potential mechanistic insight into processes contributing to appetite regulation with exercise. The aims of the present study were to examine and compare GE in habitually active and inactive individuals across a continuum of body compositions (including lean and obese), and to determine the associations among habitual exercise, body composition, EE and GE.

Materials and methods

Participants

A total of forty-four males were studied. Inclusion criteria were as follows: male; aged 18–55 years; BMI 18–40 kg/m^2; weight stable (± 4 kg over last 6 months); no history of gastrointestinal disorder; non-diabetic; no medical conditions; not taking medication known to influence body composition, EE, GE or appetite; willing to consume the study test meal; not a heavy smoker (< 10/d); either inactive (undertaking at least one structured exercise session per week and not engaged in strenuous work) or active (undertaking four or more structured exercise sessions per week) over the last 6 months. One exercise session was defined as at least 40 min of moderate to high intensity activity[31]. Based on our previous work[32], a sample size of twenty-two participants per group was identified as sufficient to detect a 10 % difference between groups for three out of the four GE outcome measures (lag time (t_{lag}), half-time ($t_{1/2}$) and ascension time (t_{asc})). This equated to the ability to detect a mean difference of 13 min in GE $t_{1/2}$ between groups at 90 % power and a 0·5 % significance level. The present study was conducted according to the guidelines laid down in the Declaration of Helsinki, and all procedures were approved by the Queensland University of Technology Research Ethics Committee. All participants provided written informed consent.

Study design

After a 12 h overnight fast, and having avoided alcohol and strenuous exercise for 24 h, participants attended the laboratory on two separate test days 1 week apart. Participants were instructed to maintain their typical diet before the testing days, in order to be tested in their habitual state. At the first testing session, body composition and RMR were measured. At the second test session, GE was assessed. Between the two testing sessions, as described further below, participants wore an accelerometer to assess physical activity levels.

Anthropometry and body composition

Height was measured without shoes to the nearest 0·5 cm and weight to the nearest 0·01 kg. Body composition (FM and FFM) was measured using air displacement plethysmography (BodPod™; Life Measurement, Inc.).

RMR

RMR was measured by indirect calorimetry using a ventilated hood system (TrueOne 2400 Metabolic Cart; ParvoMedics). Participants lay supine in a thermoneutral environment, with oxygen uptake, CO_2 production and the respiratory quotient being measured over 30 min. The resting heart rate was measured continuously (Polar Electro Oy). RMR was calculated using the Weir formula[33], as the average resting EE over 10 min with the lowest CV[34]. The CV for resting EE was less than 5 % for all participants (mean CV: active 3·3 (SD 0·9) %; inactive 3·1 (SD 0·8) %).

Physical activity and energy expenditure

Physical activity was monitored using a triaxial GT3X accelerometer (ActiGraph) over 7 d before the GE test day, a duration estimated to result in 90 % reliability[35]. Participants were instructed to wear the device on the waist, in line with the right hip during waking hours and to remove it only during contact with water (e.g. showering). Data were processed using ActiLife software (version 6.4.5; Actigraph). Triaxial vector magnitude (VM3) counts were summed over 60 s epochs, and levels of activity were defined as counts per min according to validated recommendations[36]. Data were checked for spurious values (counts per min > 15 000). A non-wear period was defined as at least 90 min of consecutive zero counts without interruption[37]. Wear time exceeding 600 min was considered a valid day[38], and a valid dataset considered a combination of at least three weekdays and one weekend day[39,40]. Time spent in moderate and vigorous (combining vigorous and very vigorous) activities was also calculated. Activity count data were converted to AEE using the 'Freedson VM3 combination ('11)' option in ActiLife

software (version 6.4.5). Total EE (TEE) was subsequently calculated in Microsoft Excel using the following formula:

$$\text{TEE} = (\text{AEE} + \text{REE}) \times 1{\cdot}11,$$

where AEE is the activity energy expenditure; REE is the resting energy expenditure; and the thermic effect of food is fixed at 10 % of TEE[41].

Gastric emptying

GE parameters were calculated using the [^{13}C]octanoic acid breath test (^{13}C-OBT)[42], using an identical procedure to that described previously[32]. In brief, the egg yolk of a standardised pancake breakfast meal (1676 kJ (400 kcal); 15 g (15 %) protein, 17 g (37 %) fat and 48 g (48 %) carbohydrate) was labelled with 100 mg [^{13}C]octanoic acid (Cambridge Isotope Laboratories). Participants consumed the meal with a 250 ml water drink within 10 min. Breath samples were collected in 10 ml glass Exetainer tubes (Labco) before breakfast, immediately after, and subsequently every 15 min for 5 h. Participants remained in sedentary activities (reading or working on a computer) and were supervised in the laboratory throughout the test morning.

^{13}C breath test analysis

^{13}C enrichment of breath samples was measured by isotope ratio MS (Hydra 20-20; Sercon). Data were analysed according to the procedure described by Ghoos *et al.*[42]. To calculate the percentage of the ^{13}C dose recovered, enrichment values were multiplied by the estimated total CO_2 production (VCO_2) for each individual. Following the procedure outlined by Ghoos *et al.*[42], resting VCO_2 was predicted from body surface area according to the method proposed by Shreeve *et al.*[43]. Body surface area was calculated according to the method outlined by Haycock *et al.*[44]. To determine the influence of the predicted VCO_2 value on results, identical analyses were carried out using a constant value of measured VCO_2 calculated during the RMR measurement. The conventional uncorrected time-based parameters (t_{lag} and $t_{1/2}$), proposed by Ghoos *et al.*[42], and the parameters latency time (t_{lat}) and t_{asc}, proposed by Schommartz *et al.*[45], were calculated. The r^2 coefficient between the modelled and raw data was accepted if $r^2 > 0{\cdot}9$.

Statistical analysis

All parameters were tested for normality by the Shapiro–Wilk test. Data are expressed as means and standard deviations for normally distributed values, and as medians and 25th–75th percentiles for non-normally distributed values. Differences between groups were assessed by the *t* test and Mann–Whitney *U* test. Independent *t* tests were used to compare groups split by median values for body composition. Where appropriate, Pearson's or Spearman's correlations were used to determine the relationships between GE and key variables. Associations were further explored using partial correlations after controlling for group. To identify potential predictors of GE, variables of interest were included in multiple linear regression analysis, with GE $t_{1/2}$ and t_{lag} as dependent variables. Variance inflation factor was checked for multicollinearity. Statistical analysis was performed using PASW Statistics version 18.0 (SPSS, Inc.) and Graph Pad Prism version 6.0 for Mac (GraphPad Software). Statistical significance was set at $P < 0{\cdot}05$.

Results

Participant characteristics

All participants completed all the components of the study (*n* 22 per group), except for the accelerometry assessment, where there were invalid data for three participants in the inactive group. In the combined cohort, the percentage of FM and BMI ranged from 9 to 42 % and 21 to 36 kg/m^2, respectively. BMI classified eight individuals as obese (*n* 7 inactive), fourteen as overweight (*n* 9 inactive) and twenty-two as normal weight (*n* 6 inactive). The descriptive characteristics of active and inactive groups are listed in Table 1. Participants in the active group reported taking part in various types of physical activity including aerobic exercise, resistance training, field sports and combinations of different modes of exercise. As expected, significant differences were found between the two groups for a number of characteristics. Measured RMR values were within 1 % (inactive) and 5 % (active) of the predicted values[46].

Table 1. Anthropometric, body composition, physical activity and energy expenditure characteristics of the study participants

(Mean values and standard deviations; medians and 25th–75th percentiles; *n* 22 per group)

	Active group		Inactive group		
	Mean	SD	Mean	SD	*P*
Age (years)					0·56
Median	26·5		27·5		
25th–75th percentile	23·0–36·3		24·0–34·3		
Height (m)	1·80	0·07	1·78	0·08	0·55
Weight (kg)	79·2	11·7	87·1	15·8	0·07
BMI (kg/m^2)					0·02
Median	23·7		27·0		
25th–75th percentile	22·7–27·0		23·7–30·0		
BSA (m^2)	1·99	0·18	2·08	0·22	0·13
FM (%)					<0·001
Median	11·6		26·6		
25th–75th percentile	10·1–18·6		20·0–34·1		
FFM (kg)	67·7	8·9	63·3	8·2	0·10
Resting HR (bpm)	52·7	8·5	64·1	9·3	<0·001
RMR (kcal/d)	1933	244	1970	340	0·68
RMR (kJ/d)	8088	1021	8242	1423	0·68
Physical activity*					
Steps per d					0·02
Median	8474		7376		
25th–75th percentile	7663–10581		5297–8842		
AEE (kcal/d)	709	239	525	185	<0·01
AEE (kJ/d)	2966	1000	2197	774	<0·01
TEE (kcal/d)	2890	430	2665	413	0·09
TEE (kJ/d)	12 091	1799	11 150	1728	0·09

BSA, body surface area; FM, fat mass; FFM, fat-free mass; HR, heart rate; bpm, beats per min; AEE, activity energy expenditure; TEE, total energy expenditure.
* Physical activity data of nineteen participants in the inactive group.

Table 2. Gastric emptying parameters in the active and inactive groups
(Mean values and standard deviations; medians and 25th–75th percentiles; *n* 22 per group)

	Active			Inactive			
	Mean	SD	Range	Mean	SD	Range	*P*
t_{lag} (min)	95	13	76–119	110	16	85–158	<0·001
$t_{1/2}$ (min)	157	18	125–195	179	21	139–231	<0·001
t_{lat} (min)			22–46			20–60	0·01
Median	27			36			
25th–75th percentile	25–34			23–41			
t_{asc} (min)	127	15	101–162	143	19	110–179	<0·01

$t_{1/2}$, Half-time; t_{lag}, lag time; t_{asc}, ascension time; t_{lat}, latency time.

Gastric emptying

Comparison of gastric emptying in the active and inactive groups. GE was significantly faster in the active group for all parameters (Table 2). The outcome measures of GE were identical regardless of the VCO_2 value used (predicted or directly measured; data not shown).

Gastric emptying half-time in groups split by median body composition and BMI. To compare our findings with prior studies comparing GE in overweight/obese with normal-weight individuals classified by BMI, we compared GE $t_{1/2}$ between groups split by median BMI (25 kg/m^2) and body composition values (Fig. 1). There were no significant differences between the low- and high-BMI groups (P=0·17); however, GE was significantly faster in the high-FFM group and the low percentage of FM group (P=0·01 and P<0·01, respectively; Fig. 1).

Cumulative percentage of the dose recovered. There were no significant differences in the cumulative percentage of the dose recovered between the groups, except for a small significant difference when divided by the median percentage of FM (FM >20 %, 43 %; FM <20 %, 41 %; P<0·05). Adjusting for respiratory quotient did not influence the outcomes for any comparisons between the active and inactive groups or groups in Fig. 1.

Relationships between variables and determinants of gastric emptying

Simple correlation analysis between variables. When the data from the two groups were pooled (*n* 44), age was positively correlated with t_{lag} (r 0·32, P<0·05). Although BMI was not associated with GE, body composition was associated with several parameters. The GE variable t_{lag} was associated with the percentage of FM (r 0·50, P<0·01), absolute FM (r 0·46, P<0·01) and absolute FFM (r −0·32, P<0·05), while $t_{1/2}$ was associated with the percentage of FM (r 0·39, P<0·01), absolute FM (r 0·35, P<0·05) and absolute FFM (r −0·29, P=0·05).

RMR was not associated with GE. However, AEE was negatively correlated with t_{asc} (r −0·32, P<0·05), t_{lat} (r −0·37, P<0·05) and $t_{1/2}$ (r −0·46, P<0·01; Fig. 2). The average time spent in vigorous activity per d was also negatively correlated with t_{asc} (r −0·35, P<0·05), t_{lat} (r −0·50, P<0·01), t_{lag} (r −0·53, P<0·01) and $t_{1/2}$ (r −0·46, P<0·01). Similar negative correlations were observed between average time spent in moderate activity per d and GE variables (t_{lag}: r −0·42, P<0·01; $t_{1/2}$: r −0·41, P<0·01). These correlations collectively indicated that a higher amount of time spent and energy expended in physical activity were associated with faster GE.

Partial correlations controlling for activity. Partial correlations of relevant variables with GE in the pooled data (*n* 44) were performed by controlling for group (Table 3). Significant associations between adiposity and GE were then no longer evident, whereas associations between age and GE t_{lag} and between AEE/TEE and GE remained significant (Table 3).

Multiple regression analysis. When considering age, percentage of FM, activity and FFM as independent variables, activity status (active or inactive) was the only significant predictor of GE $t_{1/2}$ (model adjusted R^2 0·25, β = −0·51, P<0·01). In addition, AEE was a significant independent predictor of GE $t_{1/2}$ (β = −0·40, P<0·01). As there was no evidence of strong multicollinearity between AEE and activity

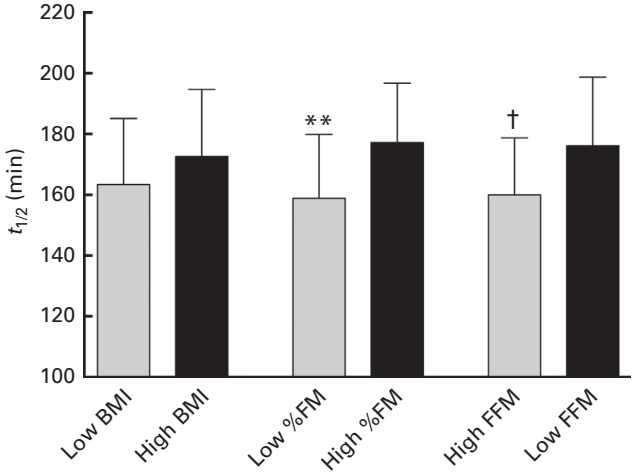

Fig. 1. Gastric emptying half-time ($t_{1/2}$) for low/high BMI, fat mass (FM) and fat-free mass (FFM) groups based on median split values of 25 kg/m^2 (BMI), 20 % (percentage of FM; %FM) and 67 kg (FFM) in pooled data from the whole cohort. Descriptive characteristics were BMI (low: 23 (SD 1) kg/m^2; high: 29 (SD 3) kg/m^2), %FM (low: 12 (SD 3); high: 28 (SD 6) %) and FFM (low: 58 (SD 4); high: 73 (SD 5) kg). Values are means (*n* 22 per group), with their standard deviations represented by vertical bars. ** Mean value was significantly different from that of the high percentage of FM group (P<0·01). † Mean value was significantly different from that of the low FFM group (P=0·01).

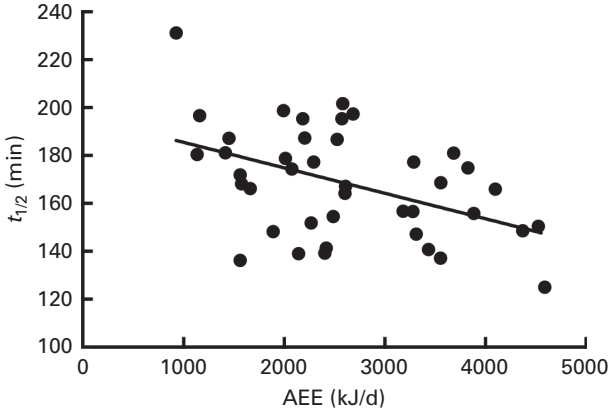

Fig. 2. Scatter plot of the relationship between activity energy expenditure (AEE) and gastric emptying half-time ($t_{1/2}$) (r −0·46, R^2 0·209, P<0·01) in the active and inactive groups (n 41).

status (variance inflation factor 1·2), these variables were included in the same model. Together, AEE and activity status accounted for the greatest variance of GE $t_{1/2}$ (model adjusted R^2 0·34, P<0·001; activity: β = −0·45, P<0·01; AEE: β = −0·28, P=0·05).

For GE t_{lag}, activity status and AEE together explained 31 % of the variance (model adjusted R^2 0·31, P<0·001; activity: β = −0·37, P=0·01; AEE: β = −0·33, P=0·03). Percentage of FM and FFM were not significant predictors of t_{lag}. However, the inclusion of age increased the model adjusted R^2 value to 0·38 (P<0·01).

Discussion

Although GE has long been implicated in the pathogenesis of obesity, findings have been inconclusive, perhaps because of the influence of additional factors such as habitual physical activity levels of participants. The findings from the present study provide evidence that GE is faster in habitually active compared with inactive males, that greater time spent in physical activity and AEE is associated with faster GE, and that body composition, but not BMI, is associated with GE. Although two studies that previously investigated GE in active and inactive individuals reported faster GE in active individuals[25,47], neither controlled for EE and body composition. The present study has involved a larger sample size, with a wider range of body compositions and activity modes, and has characterised EE, FM and FFM.

The results suggest that differences in physical activity level and associated differences in body composition (FM and FFM) and AEE between individuals may represent one explanation for the inconsistent outcomes of previous studies examining GE in obesity[6–8,10,13–15,48]. Recently, Seimon *et al.*[48] comprehensively assessed GE and other postprandial responses in normal-weight, overweight and obese males classified by BMI, and reported no differences in the GE of a nutrient drink between the groups. However, body composition and EE were not reported. In the present study, the data from the two groups were pooled and split by median BMI (25 kg/m^2) and body composition values, in order to allow comparison with previous studies. GE did not differ significantly between the groups split by BMI, but was faster in males with a lower percentage of FM and higher FFM. Previous limited evidence has shown somewhat similar findings regarding relationships between body composition and GE[8]. In addition, we examined the associations between EE and GE. While there was no association between resting EE and GE, a higher amount of time spent in physical activity and higher AEE were associated with faster GE. These data are compatible with a hypothesis that appetite signals arising from the gastrointestinal tract may be more related to AEE than to RMR[49]. Collectively, the findings demonstrate that a higher AEE, lower percentage of FM and higher FFM (but not BMI or RMR) are associated with faster GE in males.

Whereas a number of previously observed associations, including between adiposity and GE, were no longer evident after controlling for activity status (active or inactive), the associations between AEE, age and GE remained. Furthermore, the multiple regression analyses indicated that differences in body composition or BMI did not explain the faster GE observed in active individuals. Of the variables measured, habitual activity status and AEE accounted for the greatest variance in GE in males. These findings suggest that in the absence of differences in physical activity, GE may not be altered in obese individuals. Interestingly, others have shown that associations between body composition and eating frequency are mediated by physical activity[41].

The present findings have a number of possible interpretations and implications in relation to appetite control and weight management. Interactions between EE and energy intake have long been of interest in the study of energy balance. Indeed, 60 years ago (in this journal), Edholm *et al.*[50] proposed that differences in food intake originate from differences in EE. Our findings of faster GE in active individuals and in those with higher AEE are counter-intuitive to the argument that faster GE and hence reduced gastric distension contributes to overconsumption and obesity[6,9]. However, although faster GE may lead to an earlier onset of the next meal through reduced gastric distension, the influence of GE on intestinal

Table 3. Partial correlations of age, body composition, resting metabolism and energy expenditure variables with gastric emptying lag time and gastric emptying half-time after controlling for group (active or inactive; n 44)

	GE t_{lag}		GE $t_{1/2}$	
	r	P	r	P
Age (years)	0·41	<0·01	0·19	0·21
BMI (kg/m^2)	0·03	0·86	−0·05	0·77
FM (%)	0·15	0·34	0·04	0·80
FFM (kg)	−0·21	0·17	−0·19	0·23
Waist circumference	0·07	0·64	−0·06	0·70
RMR	−0·22	0·15	−0·26	0·09
RHR	0·07	0·67	0·04	0·77
AEE (n 41)	−0·35	0·03	−0·31	0·05
TEE (n 41)	−0·30	0·06	−0·31	0·05

FM, fat mass; FFM, fat-free mass; RHR, resting heart rate; AEE, activity energy expenditure; TEE, total energy expenditure.

factors must also be considered. The rate of GE plays an important role in the delivery of nutrients to the intestine[29] and hence in the release of intestinal satiation peptides[30,51] including cholecystokinin[52], glucagon-like peptide-1[53] and peptide YY[13]. Meyer-Gerspach *et al.*[16] recently demonstrated slower GE rates in obese individuals along with reduced postprandial glucagon-like peptide-1 and peptide YY secretion, reduced ghrelin suppression and reduced satiation compared with normal-weight individuals. It was suggested that the slower delivery of nutrients to the intestine could contribute to the blunted release of gut peptides and hence overconsumption[16]. Perhaps the faster GE that we observed in active individuals could lead to an earlier activation of intestinal satiety signals in response to food intake, and could mean that appetite is better regulated in response to intestinal satiety signalling between meals. Faster GE could be one contributing mechanism to an improved sensitivity of appetite control[31] and 'gross' physiological regulatory control of energy intake[54], arising from increased AEE and physical activity. Conversely, in inactive individuals, slower GE could have a role in predisposing to weight gain and a 'dysregulation' of appetite with inactivity[55] through a delayed or reduced release of gut peptides from the intestine that are involved in signalling satiety[10,16], and could mean that other factors such as sensory cues or social values may be more likely to influence food intake.

Although differences in GE between active and sedentary individuals could also be a consequence of different habitual dietary intakes[56], it is not possible to determine the causal nature of this association from cross-sectional studies and this requires additional longitudinal assessments. A slower GE might also be secondary to weight gain[14] with inactivity. However, the present results suggest that associations between body composition and GE are mediated by physical activity. Other mechanisms previously proposed to contribute to faster GE in active individuals include enhanced parasympathetic tone[25] and gastric electroactivity[47]. In the present study, active males had a significantly lower resting heart rate consistent with higher levels of parasympathetic tone[57]. Hormonal factors may also have a mechanistic role. Fasting ghrelin[58], blood glucose[59] and insulin sensitivity[60] can influence GE and are known to change in response to exercise training[61,62]. Future characterisation of blood profiles may yield further information on the underlying mechanisms. In summary, while causal inferences cannot be drawn from the present study, the findings allow for an increased understanding of factors associated with GE. Additionally, they provide insight into processes potentially contributing to meal-to-meal appetite control and energy balance with habitual physical activity, and can be used to inform prospective studies examining the efficacy of targeting GE for weight management.

It is important to acknowledge some methodological issues in the present study. The ^{13}C-OBT has many advantages[42], and has been shown to be unaffected in various medical conditions[63,64]. However, unlike scintigraphy, the ^{13}C-OBT does not permit direct imaging of gastric function, and emptying times are longer than those using scintigraphy. Although it is possible that various factors including VCO_2 predictions and respiratory quotient may influence the recovery of ^{13}C, the present analyses suggest that these factors are unlikely to have affected the results. Moreover, reports of both faster and slower GE in obese individuals using both the ^{13}C-OBT[10,65] and scintigraphy[6,14,15] have indicated that the method used is unlikely to bias the results for GE. A limitation of accelerometers placed on the hip in detecting upper body exercise may have underestimated activity in active individuals. Nevertheless, the ActiGraph accelerometer has been demonstrated to reasonably correlate with EE measured by doubly labelled water[66]. Finally, it should also be noted that only males were included so that sex and phase of the menstrual cycle were not confounding factors.

In conclusion, our findings show that GE is faster in habitually active males, and a greater time spent in physical activity and greater AEE are associated with faster GE. These results highlight the importance of considering body composition and physical activity level in studies examining GE (and parameters influenced by GE). Further investigations are needed to explore the possibility that GE contributes to a gross physiological regulation (or dysregulation) of appetite and food intake at different levels of physical activity. The potential therapeutic implications of physical activity for certain patient populations, such as those with gastroparesis, who have been characterised by low EE[67] are also relevant for future work. These findings help improve the understanding of factors that influence variability in GE, and may have relevance to both researchers and clinicians working in gastroenterology, nutrition and obesity.

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The authors declare that they have no conflicts of interest.

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