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Associations of physical activity and sedentary behavior with appetite sensations and eating regulation behaviors before and during the initial year following bariatric surgery

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Abstract

Background: Bariatric surgery produces weight loss in part by impacting appetite and eating behavior. Research suggests physical activity (PA) assists with regulation of appetite and eating during non-surgical weight loss, although whether PA carries similar benefits in the context of bariatric surgery is unknown.

Objective: Evaluate associations of moderate-to-vigorous intensity PA (MVPA) and sedentary time (ST) with appetite sensations (hunger [homeostatic/hedonic], satiety) and eating regulation behaviors (restraint, disinhibition) before and during the initial year following bariatric surgery.

Method: Adult bariatric patients received an accelerometer to measure MVPA/ST and a smartphone to complete appetite/eating ratings at four semi-random times daily for 10 days at pre- and 3-, 6-, and 12-months post-surgery. Data were analyzed using generalized linear mixed models.

Results: Higher MVPA levels related to more satiety across time ($p = 0.045$) and more restraint at 3-months post-surgery ($p < 0.001$). At pre-surgery, higher MVPA levels also related to more disinhibition (p's < 0.01), although participants reported more disinhibition on days they performed less MVPA than usual ($p = 0.017$). MVPA did not relate to hunger. Lower ST levels related to more hedonic hunger ($p = 0.003$), especially at 12-months post-surgery ($p < 0.001$), and participants reported more homeostatic hunger on days they accumulated more ST than usual ($p = 0.044$). Additionally, higher ST levels related to more disinhibition at 3-months post-surgery (p's < 0.01) and lower restraint at pre-surgery (p's < 0.05). ST did not relate to satiety.

Conclusions: This study is the first to show that MVPA and ST each associate with appetite and eating regulation in daily life before and during post-surgical weight loss. Results, while preliminary and requiring experimental confirmation, highlight potential for targeting bariatric patients' activity behaviors to enhance modulation of appetite, control of food intake, and resistance to overeating.

KEYWORDS
appetite, bariatric surgery, eating, physical activity, sedentary behavior

1 | INTRODUCTION

Bariatric surgery is a first-line treatment for people with severe obesity.[1-3] Compared to other weight loss treatments, bariatric surgery is superior in terms of efficacy and sustainability of weight loss and resolution of obesity-related comorbidities.[4-7] While understanding of weight loss mechanisms after bariatric surgery is still evolving,[8] there is consensus that reduced appetite and enhanced regulation of eating behavior are two important proximal drivers.[9] Indeed, research shows appetite and eating regulation improve overall after bariatric surgery and greater improvements favor more successful weight loss trajectories.[9-16] However, little is known about patient-level factors that underlie variability in postoperative appetite and eating regulation changes, especially ones that could be leveraged to help patients achieve greater improvements in appetite and eating regulation to optimize surgical outcomes.

Physical activity (PA) can have a positive influence on regulation of appetite and eating behavior via both homeostatic and non-homeostatic pathways.[17-19] Higher levels of PA, while increasing the drive to eat, also improve post-meal satiety, resulting in tighter coupling between energy intake and energy expenditure in response to hunger and satiety signals.[17-19] Additionally, higher PA levels are related to greater conscious restriction of food intake (i.e., higher dietary restraint)[20] and resistance to cues in the obesogenic environment that promote eating in the absence of hunger (hedonic hunger) and overeating (i.e., lower disinhibition),[21] possibly due to strengthened executive functions (i.e., inhibitory control).[22,23] By contrast, lower levels of PA are associated with dysregulated appetite, greater tendency toward overeating, and higher fat mass.[17,19]

Effects of PA on appetite and eating regulation may be particularly important during weight loss. Metabolic adaptations that occur with weight loss are hypothesized to create an “energy gap” where hunger is increased, total daily energy expenditure is decreased, and the amount of energy desired is more than what is required.[18,19] Higher PA levels may counter these adaptations by enabling individuals to eat more in response to hunger while remaining in energy balance, thereby facilitating better weight loss outcomes.[17-19] Additionally, research shows that larger PA increases during behavioral weight loss treatment are favorably associated with eating regulation (e.g., dietary restraint, emotional overeating, self-efficacy for control of eating)[24-27] and dietary habits (i.e., energy intake, dietary quality).[26] Moreover, mechanistic studies suggest that higher PA levels contribute to greater consumption of healthy foods and weight loss via improved eating regulation.[24,25,28] Taken together, the above findings suggest that engagement in higher PA levels could both serve as a buffer against biological adaptations during weight loss that contribute to increased appetite and strengthen cognitive control of eating. However, whether PA carries similar benefits in the context of surgical weight loss is unknown. Conversely, no study has evaluated whether more sedentary time (ST) adversely associates with appetite and eating regulation before and/or during surgical weight loss.

Therefore, this study sought to evaluate associations of moderate-to-vigorous intensity PA (MVPA) and ST with appetite sensations (hunger [homeostatic/hedonic], satiety) and eating regulation behaviors (dietary restraint, disinhibition) before and during the initial year (at 3-, 6-, and 12-months) following bariatric surgery (i.e., Roux-en-y gastric bypass [RYGB] or sleeve gastrectomy [SG]). Both between- and within-subject associations were investigated to understand whether there existed a range of participants for whom appetite and eating regulation related to average daily MVPA and/or ST levels and if regulation of appetite and eating differed for individual participants on days when they engaged in more or less MVPA and/or ST. Analyses focused on MVPA given that it is emphasized as part of guidelines to optimize and maintain weight loss, including after bariatric surgery.[3,29,30] Additionally, total daily accumulation of MVPA (i.e., MVPA performed in ≥1-min bouts) rather than bouted MVPA (i.e., MVPA performed in ≥10-min bouts) was of interest given daily performance of bouted MVPA is rare among bariatric surgery patients[31,32] thus yielding insufficient variability to evaluate relations of MVPA with appetite and eating regulation on a daily level. ST was also examined to enhance understanding of how behaviors at the opposite ends of the energy expenditure spectrum (i.e., MVPA vs. ST) differentially relate to appetite sensations and eating regulation behaviors during weight loss. The study combined accelerometry and smartphone ecological momentary assessment (EMA) to enable simultaneous measurement of activity behaviors, appetite sensations, and eating regulation in near real-time during patients' daily lives, thereby advancing previous research in this area that has relied on retrospective questionnaires. It was hypothesized that higher MVPA levels would be favorably associated, and higher ST levels adversely associated, with appetite sensations and eating regulation behaviors at pre- and/or post-surgical timepoints.

2 | METHODS

2.1 | Participants

The present study involves analysis of data collected as part of a parent prospective cohort study that aimed to evaluate multiple behavioral and psychosocial predictors of outcomes after bariatric surgery using different digital assessment tools (e.g., accelerometry, smartphone EMA).[33] Eligibility required participants to have a body mass index (BMI) ≥35.0 kg/m^2, be ≥21 years old, and be scheduled to undergo Roux-en-Y gastric bypass (RYGB) or sleeve gastrectomy (SG) at one of two university-based hospitals in the Northeastern United States. Participants were excluded if they were receiving weight management treatment outside the context of standard surgical care, or reported presence of a condition (e.g., uncontrolled severe mental illness) or factors (e.g., plans to geographically relocate) that could preclude adherence to the study protocol. A total of 92 participants consented to participate at baseline, 71 of whom completed both EMA and PA assessment at baseline (details below). All participants who provided valid EMA and accelerometry data at the 3-, 6-, and 12-month post-surgical visits were included in analysis.

2.2 | Procedure

All aspects of the parent study protocol relevant to the present analyses are described below; a full description of the protocol is published elsewhere.[33] Participants were recruited between May 2017 and April 2018 using a study recruitment brochure that clinic staff provided to patients between 3- and 8-weeks pre-surgery during a regularly scheduled clinic visit. Interested individuals provided their contact information to clinic staff and were then contacted by research staff to complete an eligibility phone screen. Participants deemed initially eligible completed an in-person screen/baseline assessment at the bariatric clinic or affiliated research center. During this pre-surgery baseline visit, participants provided informed consent, had their height and weight measured, and completed questionnaires. Participants were provided with[1]: an accelerometer to complete 10 days of activity monitoring, and[2] a smartphone configured with an EMA application to complete 10 days of near real-time assessment of appetite sensations and eating regulation behaviors. Compliance was monitored for both devices, and participants were able to view their EMA compliance and earned compensation in real-time on the smartphone. Although participants were asked to complete EMA ratings and accelerometry for 10 days, participants were allowed to extend the assessment period to achieve the adequate compliance threshold and participants who experienced technical or other difficulties with the accelerometer or EMA protocol were allowed additional days to provide data. Participants were compensated $75 for completing the baseline assessment, plus $0.50 per completed EMA survey. These assessment procedures were repeated at 3-, 6-, and 12-months post-surgery. The parent study was approved by the institutional review boards of The Miriam Hospital (TMH) and Beth Israel Deaconess Medical Center (BIDMC) in Providence, RI and Boston, MA respectively and registered at www.clinicaltrials.gov (NCT02777177).

2.3 | Measures

2.3.1 | Accelerometer-determined moderate-to-vigorous intensity PA and sedentary time

Total daily time spent in MVPA and ST were assessed with an ActiGraph GT9X Link wrist-worn accelerometer (ActiGraph, LLC). A valid wear day was defined as ≥10 h and ≥4 days of valid wear at each assessment was required to be included in analyses. Sleep and non-wear (i.e., ≥90 min without movement using vector magnitude counts and with allowance of interruptions of ≤2 min of non-zero counts) periods were identified and removed using the validated algorithms within ActiLife 6 software.[34,35] Vector magnitude counts per minute thresholds shown to minimize the mean difference between estimates of ST and MVPA when using wrist- versus hip-worn ActiGraph accelerometers were used to categorize 60 s epochs as follows: <2000 counts/min = ST and ≥7500 counts/min = MVPA.[36,37]

2.3.2 | EMA of appetite sensations and eating regulation behaviors

Participants were provided an Android smartphone (Samsung Galaxy S7; Samsung Electronics) configured with a smartphone application (PiLR Health™, developed by MEI Research Ltd) to complete EMA at each assessment. The PiLR application communicated with a study server that allowed the research team to implement the EMA protocol and to receive and view data from completed EMA surveys. Participants received four semi-random smartphone prompts daily. Participants responded to approximately 10–60 questions per prompt, depending on whether certain behaviors (e.g., eating) were endorsed. Restraint, disinhibition and hunger (homeostatic and hedonic) were assessed at each survey with a total of 16 items. Restraint and disinhibition were each assessed with five, Likert-type items (1 = never, 5 = always) adapted from the Restraint (e.g., *I am conscious of what I eat*) and Disinhibition (e.g., *When I feel upset, I overeat*) subscales of the Three Factor Eating Questionnaire.[38] Homeostatic hunger (i.e., desire to eat driven by biological needs) was assessed via a single item (*I feel hungry*) and hedonic hunger (i.e., desire to eat driven by sensory perception or pleasure/reward) was assessed via five items adapted from the Power of Food Scale[39] (e.g., *It's very important to me that the foods I eat are as delicious as possible*) or created de novo (e.g., *I want to eat even though I am not hungry*). All hunger items were assessed on a 1 = strongly disagree to 5 = strongly agree Likert-type scale. At each semi-random prompt, participants were asked if they had eaten since the last prompt. If "yes," satiety was assessed with four items (e.g., *I am full*) with anchors 1 = strongly disagree and 5 = strongly agree. Means for all appetite- and eating-related items were calculated for analysis. The semi-random smartphone prompts, anchored at 11:00 AM, 2:00 PM, 5:00 PM, and 8:00 PM, were delivered with an audible tone, vibration, and notification on the screen. To be included in analysis, participants had to meet a minimum threshold of EMA adherence (≥10 observations of each variable at a given assessment period). This threshold was selected to ensure adequacy of the data and minimize potential bias resulting from participants completing a minimal number of ratings (e.g., due to social desirability concerns).

2.3.3 | Body mass index, sociodemographic characteristics, and surgery type

Research staff measured participants' height (in mm) with a wall-mounted Harpenden stadiometer and their weight to the nearest 0.1 kg with a calibrated digital scale. Participants self-reported their age, sex, race, ethnicity, and educational attainment. Surgery type was self-reported by patients and confirmed with the surgeon and the clinical team.

2.4 | Analytic approach

Descriptive statistics were calculated for all study variables. One-way repeated measures analysis of variance (RM ANOVA) models were used to assess changes in BMI and EMA variables, as averaged within each assessment wave, across time points. One-way repeated measures analysis of covariance (RM ANCOVA) models were used to assess changes in MVPA and ST variables across time points, controlling for accelerometer wear time. Corresponding effect sizes were assessed as partial η^2 (small = 0.01, medium = 0.06, large = 0.14). Greenhouse–Geisser corrections were applied when the assumption of sphericity was violated (as indicated by significant Mauchly's test of sphericity). Significant main effects of time were followed up with pairwise comparisons between pre-surgery and each follow-up assessment (i.e., 3-, 6-, and 12-months post-surgery). Associations between demographic characteristics (i.e., age, BMI, sex, race/ethnicity), EMA compliance (operationalized as the mean number of completed signals at each assessment timepoint), and attrition (operationalized as the number of assessment timepoints completed) were assessed using Pearson correlations and chi-square tests. Generalized linear mixed models (GLMMs) examined the relationships of daily time spent in MVPA and ST with EMA-measured appetite sensations (i.e., homeostatic/hedonic hunger, satiety) and eating regulation behaviors (i.e., restraint, disinhibition), and the extent to which time since surgery moderated these relationships. Separate models were conducted for MVPA and ST, and effects of these variables were partitioned into between- and within person components (centered within assessment timepoint [pre- and 3-, 6-, and 12-months post-surgery]). Between-person effects (grand-mean centered) reflected the degree to which a participant's average level of MVPA or ST during the assessment timepoint differed from other participants in the sample. Within-person effects (person-mean centered) reflected the degree to which a person's daily MVPA or ST differed from his/her usual level during the assessment timepoint.

Each GLMM included fixed effects of MVPA or ST (between and within-person components), months since surgery (pre-surgery [0] and 3-, 6-, and 12-months post-surgery), and their interactions, in addition to a random intercept effect to model individual variability in outcomes. Assessment timepoint (i.e., months since surgery) was treated as a categorical rather than continuous variable to examine potential non-linear associations between time and appetitive behaviors (the pre-surgery assessment timepoint was treated as a reference category). All models also included age, sex, body mass index (BMI; kg/m^2) at each assessment timepoint, surgery type (SG or RYGB), race/ethnicity, educational attainment, and daily accelerometer wear time as covariates. GLMMs specified an AR1 covariance structure to account for dependencies within the data and linear functions given that outcome variables were normally distributed. Analyses were conducted using IBM SPSS Statistics for Windows, version 27.0 (IBM Corp.), and marginal effects of significant interaction terms were plotted using the sjPlot package in R 4.0.2.[40,41]

3 | RESULTS

3.1 | Participant characteristics

Of 170 patients initially screened, 92 consented to participate, and 71 participants had surgery (SG or RYGB) and provided sufficient accelerometer and EMA data at pre-surgery baseline to be included in analysis. Participants were predominantly female (91.5%) and had a mean age of 44.3 ± 11 years (range: 21–64). A majority (83.1%) of participants reported attending at least some college, with 38.0% having a college degree or higher. Approximately half (56.3%) identified as White, with the remaining identifying as Black or African American (23.9%), “other” race (16.9%), and Native Hawaiian or other Pacific Islander (2.8%). Before surgery, participants had a mean BMI of 45.91 ± 6.96 kg/m^2. Most participants (74.6%) had SG, whereas 25.4% had RYGB.

3.2 | Measurement protocol compliance

Of the 71 participants who had surgery and provided sufficient accelerometer and EMA data at pre-surgery baseline to be included in the analysis, 54 (76%) provided sufficient data at 3-months post-surgery; 50 (70%) at 6-months post-surgery; and 45 (63%) at 12-months post-surgery. On average, participants completed 3.1 ± 1.1 out of four assessments. Pre-surgery age and BMI did not significantly correlate with attrition (i.e., the number of completed assessments; *rs* = 0.06–0.10; *ps* = 0.393–0.640). Chi-square tests indicated no significant associations of sex, race/ethnicity, or surgery type with attrition (*ps* = 0.111–0.954).

The mean (±SD) number of completed EMA signals and daily hours of accelerometer wear time at each timepoint was: pre-surgery baseline—34.97 (15.91) and 16.93 (1.96); 3-months post-surgery—39.85 (15.47) and 16.73 (1.80); 6-months post-surgery—40.96

(14.84) and 16.81 (2.23); and 12-months post-surgery—37.64 (14.93) and 16.10 (2.23). Pre-surgery age and BMI did not significantly correlate with accelerometer/EMA compliance (*rs* = 0.16–0.23; *ps* = 0.051–0.185). Chi-square tests did not indicate significant associations of sex, race/ethnicity, or surgery type with EMA signals and accelerometer wear time compliance (*ps* = 0.635–0.887).

3.3 | Pre- to postoperative changes in activity behaviors, appetite sensations, eating regulation behaviors, and weight

Table 1 shows that participants spent 39 min in MVPA per day on average before surgery and made small yet statistically significant increases in MVPA after surgery; with the results of the RM ANOVA showing a main effect of time after adjusting for average daily wear time averaged across assessment waves ($F[3] = 4.59$, $p = 0.022$, partial $\eta^2 = 0.11$). However, follow-up pairwise comparisons were not statistically significant (*ps* = 0.160–0.880). Participants accumulated 636 ST min/day on average before surgery; the change in ST across time was not statistically significant after adjusting for average daily wear time ($F[3] = 1.79$, $p = 0.154$, partial $\eta^2 = 0.05$). Participants reported significant changes in restraint, with a main effect of time showing a medium to large effect size ($F[3] = 3.98$, $p = 0.020$, partial $\eta^2 = 0.10$). Pairwise comparisons showed that restraint was greater at the 3- and 6-month follow-ups compared to pre-surgery ($p = 0.018$ and 0.014, respectively), but did not differ from pre-surgery levels at the 12-month follow-up ($p = 0.109$). Across time participants showed significant decreases in BMI and reported significantly less disinhibition, homeostatic hunger, and hedonic hunger, with large effect sizes (BMI: $F[3] = 274.46$, $p < 0.001$, partial $\eta^2 = 0.86$; disinhibition: $F[3] = 21.73$, $p < 0.001$, partial $\eta^2 = 0.38$; homeostatic hunger: $F[3] = 13.31$, $p < 0.001$, partial $\eta^2 = 0.27$; hedonic hunger: $F[3] = 12.42$, $p < 0.001$, partial $\eta^2 = 0.26$). Pairwise comparisons showed that levels of these variables were lower at all follow-ups compared to pre-surgery levels (*ps* < 0.001–0.005). There were not statistically significant changes in levels of satiety across time ($F[3] = 1.65$, $p = 0.197$, partial $\eta^2 = 0.05$). According to BMI categories, participants had extreme or class III obesity (BMI ≥ 40 kg/m^2) on average before surgery and reduced to class I obesity (BMI = 30–34.9 kg/m^2) at 12-months post-surgery.

3.4 | Associations of MVPA and ST with appetite sensations and eating regulation behaviors before and during the initial year after bariatric surgery

Tables 2 and 3 show GLMM models of independent and interactive effects of each of the activity variables (MVPA, ST) and time (months) as predictors of appetite sensations (homeostatic and hedonic hunger, satiety) and eating regulation behaviors (restraint, disinhibition) at pre- and post-surgical timepoints. Random intercept effects were significant across all models, indicating significant interindividual variability in outcomes. Regarding covariates, there were main effects of BMI (*ps* < 0.001) predicting hedonic hunger, such that participants with lower BMI reported higher levels of hedonic hunger. Additionally, participants who identified as Black or African American reported lower disinhibition and satiety relative to those who identified as White (*ps* = 0.015–0.047). There were no significant effects of age, sex, educational attainment, surgery type, or daily accelerometer wear time.

3.4.1 | MVPA as a predictor of appetite sensations

Main effects of time predicting homeostatic and hedonic hunger indicated participants reported lower levels of both types of hunger across post-surgical timepoints compared to pre-surgery (*ps* < 0.001). In addition, there was a main effect of BMI predicting hedonic hunger ($p < 0.001$), such that participants with higher BMI reported less hedonic hunger ($p < 0.001$). However, there were no significant relationships between MVPA and homeostatic or hedonic hunger, or interactions between time and MVPA in predicting hunger.

For satiety, there were main effects of time at 3-months post-surgery ($p = 0.002$) and between-person MVPA ($p = 0.045$), but no interactive effects. That is, participant had lower satiety at 3-months post-surgery compared to pre-surgery, and those who performed more MVPA reported higher satiety levels across time relative to those who performed less MVPA.

3.4.2 | Moderate-to-vigorous intensity physical activity as a predictor of eating regulation behaviors

For restraint, there were main effects of time predicting restraint, such that restraint was higher at all post-surgical timepoints compared to pre-surgery (*ps* < 0.001). There was also a significant interaction of time and between-person MVPA predicting restraint at 3-months post-surgery ($p < 0.001$). Figure 1A shows that participants who performed more MVPA at this timepoint reported higher restraint levels compared to those who performed less MVPA.

For disinhibition, there were significant main effects of time (*ps* < 0.001), between-person MVPA ($p < 0.001$), and within-person MVPA ($p = 0.017$), as well as interactions of time and between-person MVPA ($p < 0.0010.006$) and time and within-person MVPA ($p = 0.028$). Figure 1B displays the interaction of time and between-person MVPA. Participants who performed more MVPA at pre-surgery reported more disinhibition relative to persons who performed less MVPA. By contrast, within-person interactive effects (Figure 1C) indicate that before surgery, participants reported greater disinhibition on days when they performed less MVPA than their usual levels. Relationships between MVPA and disinhibition were minimal at post-surgical timepoints.

TABLE 1 Activity behaviors, appetite sensations, eating regulation behaviors and weight at pre- and postoperative assessment timepoints

	Pre-surgery ($n = 71$)		3-month post-surgery ($n = 54$)		6-month post-surgery ($n = 50$)		12-month post-surgery ($n = 45$)	
	M	SD	*M*	SD	*M*	SD	*M*	SD
MVPA (min/d)	38.98	26.50	41.86	34.37	45.64	37.30	46.66	42.39
ST (min/d)	634.26	129.19	629.85	115.28	610.55	128.61	573.82	109.93
Homeostatic hunger (1–5)	2.23	0.65	1.75	0.47	1.88	0.54	1.91	0.63
Hedonic hunger (1–5)	2.38	0.73	1.97	0.58	2.09	0.65	2.05	0.67
Satiety (1–5)	2.97	0.27	2.90	0.23	2.93	0.19	2.96	0.17
Restraint (1–5)	2.96	0.47	3.23	0.55	3.27	0.55	3.21	0.55
Disinhibition (1–5)	2.39	0.83	1.78	0.57	1.91	0.58	1.88	0.64
Body mass index	45.91	6.96	38.21	6.19	35.24	6.04	33.53	5.73

Note: MVPA, moderate-to-vigorous intensity physical activity; ST, sedentary time; appetite sensations and eating regulation behavior variables measured via Ecological Momentary Assessment (i.e., hunger [homeostatic, hedonic], satiety, restraint, disinhibition) were aggregated within persons.

3.4.3 | Sedentary time as a predictor of appetite sensations

Similar to MVPA findings, there were main effects of time predicting homeostatic and hedonic hunger (*ps* < 0.001), as well as BMI predicting hedonic hunger ($p < 0.001$). In addition, there was a main effect of within-person ST predicting homeostatic hunger ($p = 0.044$), indicating participants reported homeostatic hunger on days they accumulated more ST than usual. There was also a main effect of between-person ST predicting hedonic hunger ($p = 0.003$), as well as interactions of time and between-person ST predicting hedonic hunger ($p < 0.001$). Figure 2A shows that hedonic hunger was lower at all post-surgical timepoints compared to pre-surgery and the relationship between ST and hedonic hunger was greatest at 12-months post-surgery, such that participants who engaged in less ST reported more hunger relative to participants who engaged in more ST.

For satiety, there was a main effect of time at 3-months post-surgery ($p = 0.004$) indicating participants' satiety levels were lower at this timepoint compared to pre-surgery. However, ST was not significantly associated with satiety levels.

3.4.4 | Sedentary time as a predictor of eating regulation behaviors

There were main effects of time (*ps* < 0.001), between-person ST ($p = 0.021$), and interactions of time and between-person ST predicting restraint ($p = 0.027$–0.032). Figure 2B shows that before surgery participants who had lower ST levels reported higher restraint compared to those who had lower ST levels, although this difference was minimal at post-surgical timepoints.

For disinhibition, there were significant main effects of time (*ps* < 0.001) and the interactions of time and between-person ST ($p < 0.001$ to $p = 0.010$). Figure 2C indicates that relationship between ST and disinhibition was greatest at 3-months post-surgery, such that participants who engaged in more ST reported higher levels of disinhibition compared to participants who engaged in less ST.

4 | DISCUSSION

This study uniquely combined accelerometry and smartphone EMA to evaluate relationships of activity behaviors with appetite and eating regulation in daily life among bariatric surgery patients before and during rapid weight loss. Overall, results provide novel evidence to suggest activity behaviors at the opposite ends of the energy expenditure spectrum (i.e., MVPA and ST) may each play a role in modulating components of appetite (hunger, satiety) and eating (restraint, disinhibition) systems that regulate energy intake—that is, the main driver of post-surgical weight loss. Additionally, despite lack of clinically meaningful pre- to post-surgery changes in MVPA and ST among the sample as a whole, results suggest that day-to-day variations in participants' performance of these behaviors may hold importance in relation to appetite and eating regulation both before and during weight loss after bariatric surgery.

Results showed that MVPA and ST both related to appetite regulation, but to different components. ST, but not MVPA, related to hunger driven both by biological needs (homeostatic hunger) and pleasure/reward (hedonic hunger). Specifically, participants reported more homeostatic hunger on days they accumulated more ST than usual. It is possible that engaging in higher levels of ST enhanced participants' awareness of actual energy needs. Alternatively, higher levels of ST may disrupt the brain's ability to balance energy intake with energy needs, increasing drive to eat when the body does not require food. Support for these hypotheses is derived from studies involving rigorous laboratory protocols. For example, one study found that women participants' hunger increased in response to a 24-hour sitting condition, but only when energy intake was reduced to achieve an energy balance,[42] whereas another study in men found that an imposed 7-day sedentary routine was not accompanied by a compensatory reduction in energy intake resulting in a substantial energy surplus.[43]

TABLE 2 Generalized linear mixed models examining independent and interactive effects of moderate-to-vigorous physical activity (MVPA) and time (months) as predictors of appetite sensations and eating regulation behaviors before and following bariatric surgery

	Homeostatic hunger			Hedonic hunger			Satiety			Restraint			Disinhibition		
	ß	SE	*p*	ß	SE	*p*	ß	SE	*p*	ß	SE	*p*	ß	SE	*p*
Intercept	2.29	0.55	<0.001	2.82	0.61	<0.001	2.74	0.18	<0.001	3.27	0.50	<0.001	3.04	0.65	<0.001
Covariates															
Age	−0.01	0.01	0.144	0.01	0.01	0.454	<0.01	<0.01	0.499	<−0.01	0.01	0.477	<−0.01	0.01	0.798
Sex	0.16	0.25	0.518	−0.31	0.28	0.268	0.04	0.08	0.564	−0.21	0.22	0.338	−0.33	0.28	0.243
Education	0.02	0.06	0.788	−0.05	0.07	0.452	0.02	0.02	0.421	0.04	0.05	0.492	<−0.01	0.07	0.954
Race (other)	0.13	0.20	0.521	−0.19	0.23	0.402	0.08	0.06	0.200	−0.10	0.17	0.561	−0.35	0.21	0.106
Race (Hawaiian)	−0.07	0.17	0.669	−0.34	0.19	0.069	−0.31	0.21	0.127	0.47	0.56	0.400	−1.14	0.72	0.117
Race (AA)	0.28	0.43	0.524	−0.44	0.48	0.361	**−0.10**	**0.05**	**0.047**	−0.20	0.14	0.143	**−0.44**	**0.18**	**0.015**
Surgery type (RYGB)	0.13	0.17	0.446	−0.02	0.19	0.921	0.02	0.06	0.765	−0.17	0.15	0.269	−0.13	0.19	0.520
BMI	<−0.01	0.01	0.603	**−0.02**	**0.00**	**<0.001**	<0.01	<0.01	0.514	**0.01**	**<0.01**	**0.049**	<0.01	0.01	0.857
Wear time	<0.01	<0.01	0.313	0.00	<0.01	0.821	<0.01	<0.01	0.183	<0.01	<0.01	0.556	<0.01	<0.01	0.970
Effect of time															
3-month post-surgery	**−0.46**	**0.04**	**<0.001**	**−0.38**	**0.02**	**<0.001**	**−0.05**	**0.02**	**0.002**	**0.20**	**0.02**	**<0.001**	**−0.61**	**0.03**	**<0.001**
6-month post-surgery	**−0.37**	**0.04**	**<0.001**	**−0.28**	**0.02**	**<0.001**	−0.02	0.02	0.355	**0.24**	**0.02**	**<0.001**	**−0.52**	**0.03**	**<0.001**
12-month post-surgery	**−0.28**	**0.04**	**<0.001**	**−0.36**	**0.03**	**<0.001**	<0.01	0.02	0.988	**0.16**	**0.02**	**<0.001**	**−0.48**	**0.03**	**<0.001**
Between-person effects															
MVPA GMC	<−0.01	<−0.01	0.451	<−0.01	<0.01	0.324	**<0.01**	**<0.01**	**0.045**	<−0.01	<0.01	0.353	**<0.01**	**<0.01**	**<0.001**
MVPA GMC × 3-month post-surgery	<−0.01	<0.01	0.173	<0.01	<0.01	0.882	<0.01	<0.01	0.228	**<0.01**	**<0.01**	**<0.001**	**<−0.01**	**<0.01**	**0.006**
MVPA GMC × 6-month post-surgery	<−0.01	<0.01	0.618	<−0.01	<0.01	0.413	<0.01	<0.01	0.154	<0.01	<0.01	0.156	**<−0.01**	**<0.01**	**<0.001**
MVPA GMC × 12-month post-surgery	<0.01	<−0.01	0.147	<0.01	<0.01	0.186	<0.01	<0.01	0.170	<0.01	<0.01	0.158	**<−0.01**	**<0.01**	**<0.001**
Within-person effects															
MVPA PMC	<0.01	<−0.01	0.652	<−0.01	<0.01	0.125	<0.01	<0.01	0.385	<0.01	<0.01	0.826	**<−0.01**	**<0.01**	**0.017**
MVPA PMC × 3-month post-surgery	<0.01	<0.01	0.644	<0.01	<0.01	0.408	<0.01	<0.01	0.177	<−0.01	<0.01	0.341	<0.01	<0.01	0.028[a]
MVPA PMC × 6-month post-surgery	<−0.01	<0.01	0.235	<0.01	<0.01	0.791	<0.01	<0.01	0.448	<−0.01	<0.01	0.382	<0.01	<0.01	0.471
MVPA PMC × 12-month post-surgery	<0.01	<0.01	0.978	<0.01	<0.01	0.241	<0.01	<0.01	0.810	<−0.01	<0.01	0.997	<0.01	<0.01	0.081
Random effect (intercept)	**0.31**	**0.06**	**<0.001**	**0.40**	**0.07**	**<0.001**	**0.03**	**0.01**	**<0.001**	**0.23**	**0.04**	**<0.001**	**0.39**	**0.07**	**<0.001**

Note: The pre-surgery assessment was coded as the reference category. Bolding is used to denote statistically significant associations. Significant interactive effects indicate that the relationship between MVPA and the outcome variable differed from the relationship at pre-surgery. Participants completed assessments at pre- and 3-, 6-, and 12-months post-surgery. Education, educational attainment (1 [grade school] to 7 [graduate education]); Race (AA), African American race; Surgery type (RYGB), Roux-en-gastric bypass; BMI, body mass index; Wear time, accelerometer wear time; MVPA, moderate-to-vigorous intensity physical activity; GMC, grand-mean centered (between-person) variable; PMC, person-mean centered (within-person) variable; Sex was coded such that male was the reference category; race/ethnicity was coded such that White was the reference category; surgery type was coded such that sleeve gastrectomy was the reference category.

[a] Omnibus interaction effect was not significant.

TABLE 3 Generalized linear mixed models examining independent and interactive effects of sedentary time (ST) and time (months) as predictors of appetite sensations and eating regulation behaviors before and following bariatric surgery

	Homeostatic hunger			Hedonic hunger			Satiety			Restraint			Disinhibition		
	ß	SE	p	ß	SE	p	ß	SE	p	ß	SE	p	ß	SE	P
Intercept	2.14	0.57	<0.001	2.85	0.62	<0.001	2.72	0.19	<0.001	3.21	0.51	<0.001	3.12	0.65	<0.001
Covariates															
Age	−0.01	0.01	0.119	0.01	0.01	0.458	<0.01	<0.01	0.479	<−0.01	0.01	0.463	<−0.01	0.01	0.648
Sex	0.17	0.26	0.514	−0.35	0.29	0.223	0.03	0.08	0.646	−0.21	0.22	0.334	−0.31	0.28	0.269
Education	0.01	0.06	0.882	−0.04	0.07	0.554	0.01	0.02	0.473	0.04	0.05	0.446	<0.01	0.07	0.985
Race (other)	0.13	0.21	0.538	−0.20	0.23	0.375	0.08	0.06	0.195	−0.09	0.17	0.592	−0.37	0.21	0.081
Race (Hawaiian)	−0.07	0.17	0.699	−0.32	0.19	0.084	−0.33	0.21	0.114	0.47	0.56	0.400	−1.10	0.72	0.124
Race (AA)	0.26	0.44	0.557	−0.41	0.49	0.397	−0.10	0.05	0.052	−0.20	0.14	0.142	**−0.42**	**0.18**	**0.018**
Surgery type (RYGB)	0.14	0.18	0.424	−0.03	0.19	0.889	0.01	0.06	0.800	−0.16	0.15	0.280	−0.11	0.19	0.583
BMI	−0.01	0.01	0.371	**−0.02**	**<0.01**	**<0.001**	<0.01	<0.01	0.409	0.01	<0.01	0.101	<0.01	0.01	0.529
Wear time	**<0.01**	**<0.01**	**0.023**	<0.01	<0.01	0.344	<0.01	<0.01	0.195	<0.01	<0.01	0.751	<−0.01	<0.01	0.307
Effect of time															
3-month post-op	**−0.45**	**0.04**	**<0.001**	**−0.39**	**0.02**	**<0.001**	**−0.05**	**0.02**	**0.004**	**0.20**	**0.02**	**<0.001**	**−0.63**	**0.03**	**<0.001**
6-month post-op	**−0.36**	**0.04**	**<0.001**	**−0.29**	**0.02**	**<0.001**	−0.01	0.02	0.480	**0.24**	**0.02**	**<0.001**	**−0.54**	**0.03**	**<0.001**
12-month post-op	**−0.27**	**0.04**	**<0.001**	**−0.37**	**0.02**	**<0.001**	<0.01	0.02	0.918	**0.16**	**0.02**	**<0.001**	**−0.49**	**0.03**	**<0.001**
Between-person effects															
ST GMC	<0.01	<0.01	0.145	**<−0.01**	**<0.01**	**0.003**	<0.01	<0.01	0.931	**<−0.01**	**0.00**	**0.021**	<−0.01	<0.01	0.355
ST GMC × 3-month post-surgery	<0.01	<0.01	0.159	**<0.01**	**<0.01**	**<0.001**	<0.01	<0.01	0.917	**<0.01**	**<0.01**	**0.032**	**<0.01**	**<0.01**	**<0.001**
ST GMC × 6-month post-surgery	<0.01	<0.01	0.281	**<0.01**	**<0.01**	**<0.001**	<0.01	<0.01	0.607	**<0.01**	**<0.01**	**0.027**[a]	**<0.01**	**<0.01**	**0.010**
ST GMC × 12-month post-surgery	<0.01	<0.01	0.686	<0.01	<0.01	0.289	<0.01	<0.01	0.133	<0.01	<0.01	0.203	<0.01	<0.01	0.138
Within-person effects															
ST PMC	**<0.01**	**<0.01**	**0.044**	<0.01	<0.01	0.192	<0.01	<0.01	0.484	<−0.01	<0.01	0.425	<0.01	<0.01	0.407
ST PMC × 3-month post-surgery	<0.01	<0.01	0.498	<0.01	<0.01	0.458	<0.01	<0.01	0.593	<−0.01	<0.01	0.690	<−0.01	<0.01	0.318
ST PMC × 6-month post-surgery	<0.01	<0.01	0.668	<0.01	<0.01	0.282	<0.01	<0.01	0.756	<0.01	<0.01	0.225	<0.01	<0.01	0.596
ST PMC × 12-month post-surgery	<0.01	<0.01	0.640	<0.01	<0.01	0.511	<0.01	<0.01	0.494	<0.01	<0.01	0.978	<0.01	<0.01	0.879
Random effect (intercept)	**0.32**	**0.06**	**<0.001**	**0.40**	**0.07**	**<0.001**	**0.03**	**0.01**	**<0.001**	**0.23**	**0.04**	**<0.001**	**0.39**	**0.07**	**<0.001**

Note: The pre-surgery assessment was coded as the reference category. Bolding is used to denote statistically significant associations. Significant interactive effects indicate that the relationship between ST and the outcome variable differed from the relationship at pre-surgery. Participants completed assessments at pre- and 3-, 6-, and 12-months post-surgery. Education, educational attainment (1 [grade school] to 7 [graduate education]); Race (AA), African American race; Surgery type (RYGB), Roux-en-gastric bypass; BMI, body mass index; Wear time, accelerometer wear time; ST, sedentary time; GMC, grand-mean centered (between-person) variable; PMC, person-mean centered (within-person) variable; Sex was coded such that male was the reference category; race/ethnicity was coded such that White was the reference category; surgery type was coded such that sleeve gastrectomy was the reference category.

[a] Omnibus interaction effect was not significant.

Interestingly, for hedonic hunger, the pattern of findings was reversed. Participants with lower levels of ST reported more hedonic hunger or desire to consume highly palatable foods compared to those with higher levels of ST, particularly at 12-months post-surgery. While this finding seems counterintuitive, it is possible that participants who sat less experienced exposure to a greater number or variety of palatable food cues (e.g., seeing or smelling food, observing people eating, and advertisements) via more movement between different environmental and social situations where such cues were present (e.g., different rooms at home or the workplace, gatherings with friends or family, and walking past neighborhood food establishments). Future evaluation of the contexts (e.g., location) and times (e.g., weekends) in which participants reported elevated hedonic hunger and whether this corresponds with

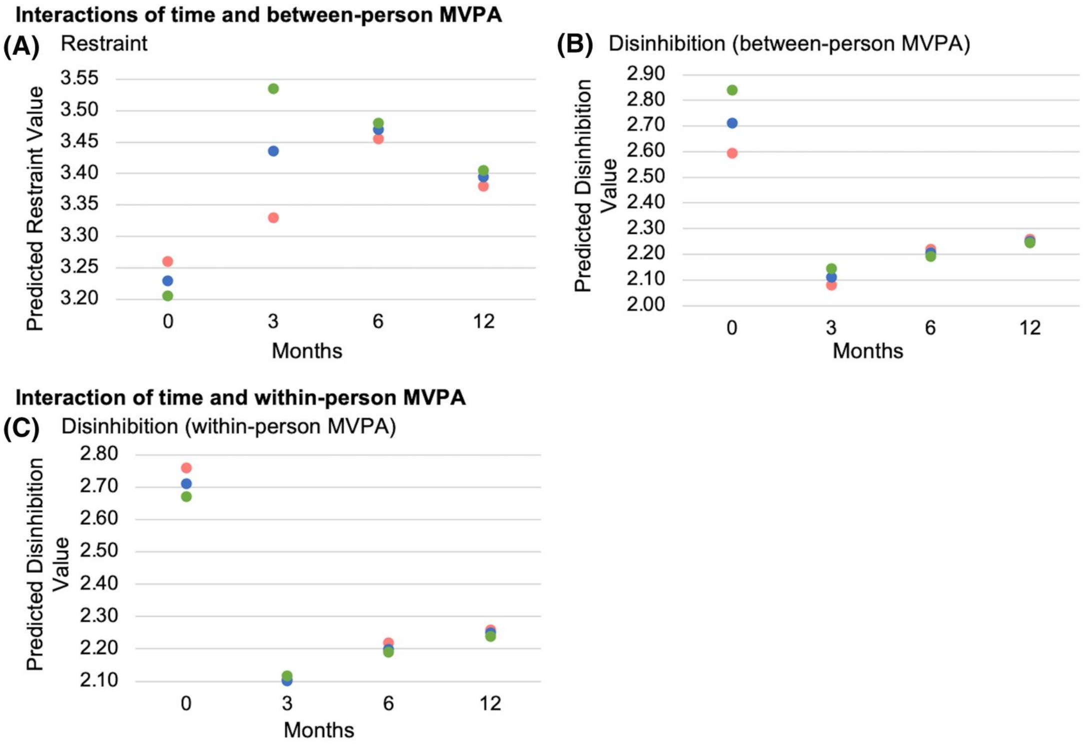

FIGURE 1 Interaction of time since surgery and between- or within-participant MVPA predicting restraint (A) and disinhibition (B-C). MVPA, moderate-to-vigorous intensity physical activity; Red, blue, and green dots indicate low (−1 SD), mean, and high (+1 SD) of MVPA (respectively)

movement patterns could help elucidate this possibility. It is also possible that greater behavioral changes (i.e., reductions in ST) along with greater weight loss could contribute to greater experiencing of hedonic hunger, or that some participants interpreted some of the items assessing hedonic hunger (e.g., “I want to eat even though I am not hungry”) in relation to adherence to post-surgery recommendations to eat regularly rather than hedonically-driven eating. While this latter concern is attenuated by use of multiple items to assess hedonic hunger, including items from previously validated scales, further assessment of motives for eating in the absence of homeostatic hunger is warranted. Notably, because the protocol did not ask participants whether they acted on their hedonic hunger, future studies are also needed to determine whether hedonic hunger results in problematic eating behavior.

By contrast, MVPA, but not ST, was related to satiety, such that participants who performed more MVPA reported greater feelings of fullness (or post-meal suppression of hunger) compared to those who performed less MVPA. This finding is also consistent with previous observational and interventional research showing that higher levels of MVPA associate with enhanced post-meal satiety[44-46] possibly by interacting with food ingested to improve hormonal satiety signaling or via other exercise-related physiological adaptations (e.g., improved insulin and leptin sensitivity) thought to influence food intake and eating behavior.[17,47] Taken together, the above findings carry potentially important clinical implications as they raise potential for targeting bariatric patients' MVPA and ST to augment surgical effects on gut hormones and appetite regulation[8,9] to effect greater changes in energy intake and clinical outcomes.

Additionally, MVPA and ST differentially associated with eating regulation behaviors and that the strength of these associations varied across assessment timepoints. For example, higher MVPA levels related to more restraint, although this difference was most pronounced at 3-months post-surgery and minimal at other timepoints. Lower ST levels related to less restraint, although this relationship was most evident before surgery and less so after surgery. Although reasons for these findings are not entirely clear, it is possible that engaging in higher levels of MVPA during the early post-surgical period may help to strengthen cognitive control over food intake. Alternatively, individuals who are exerting greater efforts to control food intake during this period might also simultaneously undertake efforts to be more active. Similarly, participants who are less sedentary may be more able to regulate food intake or vice versa, especially before surgery. Given that higher levels of dietary restraint before surgery are associated with greater weight loss after bariatric surgery,[16,48] additional research is needed to understand mechanisms underlying ST and restraint and whether reducing ST can be a strategy to increase restraint and improve clinical eating and weight outcomes.

For disinhibition, participants prior to surgery reported higher disinhibition on days that they performed less MVPA than usual. Yet, interestingly, higher MVPA levels overall associated with higher levels of disinhibition, also before surgery. While the direction of this relationship cannot be determined, it is possible that participants reporting more disinhibition may generally perform more MVPA to help control dysregulated eating. This hypothesis aligns with previous research showing that acute exercise can reduce motivation to eat

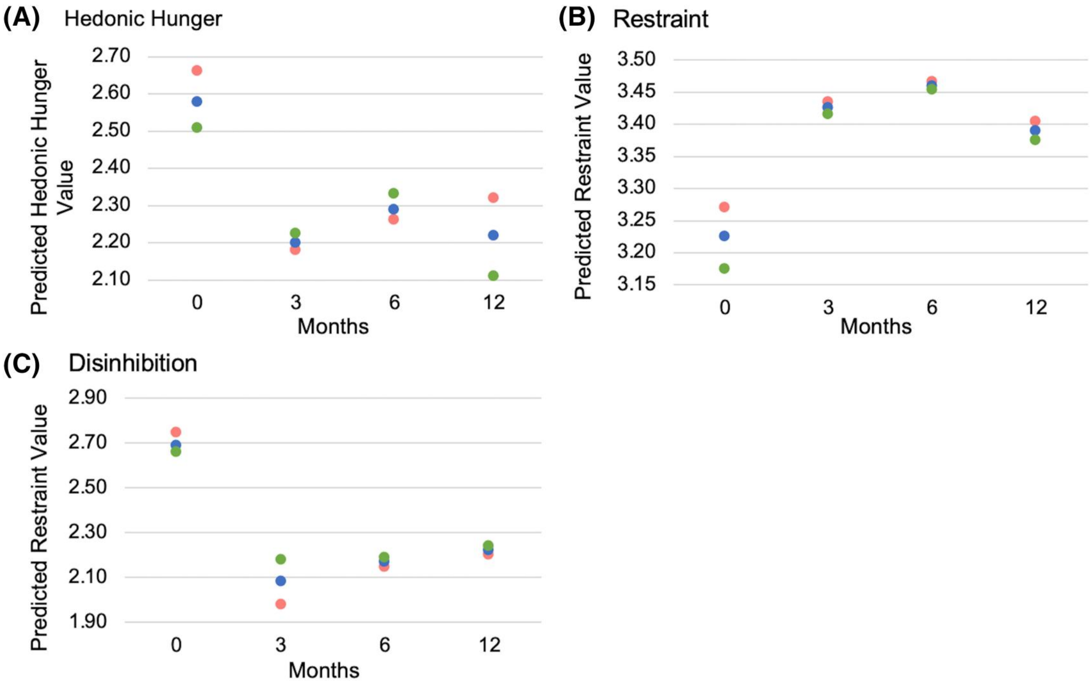

FIGURE 2 Interaction of time since surgery (months) and between-person sedentary time predicting (A) Hedonic hunger, (B) restraint, and (C) disinhibition. Red, blue, and green dots indicate low (−1 SD), mean, and high (+1 SD) of sedentary time (respectively)

and wanting for high-fat foods among women with high disinhibition, and chronic exercise training reduces disinhibition among individuals with overweight/obesity.[49,50]

By contrast, participants who engaged in higher levels of ST reported higher disinhibition relative to those who engaged in lower levels of ST, with this difference being greatest at 3-months post-surgery and minimal at other timepoints. Thus, it appears that both ST and MVPA could play important roles in eating regulation during the early post-surgical period, with higher levels of ST related to greater susceptibility to overeating in the presence of palatable foods or other stimuli and higher levels of MVPA related to greater conscious efforts to restrict or control food intake. Additional research is needed to understand whether these relationships also influence post-surgical weight trajectory.

This study has important strengths. This study uniquely integrated accelerometry and smartphone EMA to evaluate how bariatric surgery patients' objectively measured participation in different activity behaviors relate to appetite and eating regulation in near real-time in their natural environment before and during active weight loss. It should also be noted this study is the first to use this methodology to evaluate these relationships during any form of weight loss treatment. Participants also exhibited high levels of compliance with the accelerometer and EMA protocols within each assessment wave. Given the rigorous and burdensome nature of the protocol, it is possible that patients who chose to participate may have been more motivated, active, or conscientious than the average patient, resulting in a potential selection bias. It is also possible that the intensive protocol may have partially contributed to 37% reduction in the number of participants who completed assessment waves from pre- to 12-months post-surgery, which may reduce the internal validity of our findings. To partially offset this limitation, statistical methods were used that maximized use of all available data from the 71 participants at baseline who fulfilled data integrity requirements. Because analyses did not correct for multiple comparisons due to the exploratory nature of both this study and the parent project, results should be viewed as preliminary and for hypothesis-generating purposes. Appetite and eating regulation behaviors were not assessed in response to meal and exercise challenges, and there may be additional factors (e.g., habitual level of physical activity, type and timing of PA, macronutrient content of diet) that impact the associations between PA, appetite sensations, and eating behavior regulation that were not evaluated in this study.[17,51] Future studies should consider the moderating role of these factors. This study focused on total daily MVPA rather than bouted MVPA, a proxy for exercise which might associate differently with components of appetite and eating regulation. While low daily engagement in bouted MVPA among bariatric surgery patients[31,32] undermines ability to investigate associations with appetite and eating regulation overall in daily life, future studies conducted in larger samples with greater number of active patients or in the context of interventions targeting bouted MVPA are needed to examine whether these associations vary by pattern of MVPA accumulation. Some measures like restraint and disinhibition reflect a self-perception and not necessarily actual eating behavior. Thus, future studies that combine laboratory and ecological assessments, along with measurement of energy intake and appetite-regulating hormones, are needed to elucidate directionality and biobehavioral mechanisms of relationships between activity behaviors and regulation of appetite and eating after bariatric surgery. These relationships were assessed only during the initial year after bariatric surgery when most weight loss occurs. It is equally or more important to understand how activity behaviors may influence appetite and eating regulation beyond the initial post-surgical year after weight has stabilized and weight regain begins to occur.[1,52] Finally, randomized controlled trials are needed to determine whether targeting greater changes in patients' free-living activity patterns effect larger changes in appetite and eating regulation above and beyond the effects of bariatric surgery.

5 | CONCLUSIONS

This study is the first to evaluate associations of MVPA and ST with appetite sensations (hunger and satiety) and eating regulation behaviors (restraint and disinhibition) in the context of bariatric surgery. Regarding appetite sensations, MVPA did not relate to hunger, but higher MVPA levels associated with higher satiety levels over time. Conversely, ST did not relate to satiety, but participants recorded more homeostatic hunger on days they had higher levels of ST than usual and lower levels of ST associated with more hedonic hunger, especially at 12-months post-surgery. Regarding eating regulation behaviors, higher MVPA levels related to more restraint at 3-months post-surgery and more disinhibition, especially before surgery; however, the highest levels of disinhibition were recorded on days when participants performed less MVPA than usual. Finally, lower ST levels associated with less restraint, particularly before surgery, and higher ST levels related to more disinhibition, especially at 3-months post-surgery. Although preliminary, these data provide support that activity behaviors at the opposite end of the energy expenditure spectrum could influence appetite and eating systems that regulate energy intake, the proximal driver of post-surgical weight loss. Additional research combining naturalistic assessment methods with laboratory-based activity/meal challenges and measurement of energy intake and appetite-related gut hormones are needed to confirm these relationships, identify mechanisms, and provide foundation for targeting PA and ST to augment surgical effects on appetite and eating regulation and improve clinical outcomes.

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Dale S. Bond and J. Graham Thomas conceived the study and design. Dale S. Bond and J. Graham Thomas acquired the data. Kathryn E. Smith and Dale S. Bond analyzed and interpreted the data. Dale S. Bond, Kathryn E. Smith, and Leah M. Schumacher drafted the manuscript. All authors revised the manuscript for intellectual content and approved the final version of the completed manuscript. The study was supported by the National Institute of Diabetes and Digestive and Kidney Diseases (R01 DK108579; principal investigators: Dale S. Bond & J. Graham Thomas). Dr. Schumacher is supported by a grant from the National Heart, Lung, and Blood Institute (T32-HL076134; PI: Wing). We thank study participants for their commitment to this study.

CONFLICT OF INTEREST

Dale S. Bond, J. Graham Thomas, Sivamainthan Vithiananthan, Daniel B. Jones, and Leah M. Schumacher report funding from NIH during the course of the study. Kathryn E. Smith and Jennifer Webster have nothing to disclose.

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