

Food choice and food reward during 60 days of head-down bed rest with exercise and artificial gravity countermeasures in healthy men: The BRACE study

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30 **Highlights**

- 31 • 60 days of head-down bed rest reduced spontaneous energy intake during an *ad libitum*
- 32 buffet in healthy men.
- 33 • The relative contribution of protein to buffet meal energy intake decreased.
- 34 • Explicit liking for high-protein and foods with color decreased at the end of bed rest.
- 35 • Implicit wanting for high-fiber foods also decreased.
- 36 • No significant modifying effects of exercise, with or without artificial gravity, were detected.

Abstract

Background: Alterations in food intake have been reported during spaceflight and may be influenced by exercise countermeasures. We examined whether supine aerobic cycling, with/without artificial gravity (AG), modified energy intake, food choices, and food reward during 60 days of head-down bed rest (HDBR).

Methods: Twenty-four healthy men (29.5 ± 5.7 years; BMI: 23.8 ± 1.8 kg/m²) underwent 60 days of HDBR and were allocated to control (CNT), cycling (EX), or cycling plus AG (EX+AG). EI and food choices were assessed during an *ad libitum* multi-choice buffet, and food reward was assessed using the Leeds Food Preference Questionnaire before and after HDBR. Linear mixed-effects models tested time-by-group interactions as the primary effects and overall time effects across groups.

Results: No statistically significant time-by-group interactions were detected for any of the outcomes (all: $p \geq 0.10$). Across groups, EI from the buffet decreased by 264 kcal (LSmean; 95%CI: -476 to -52; $p=0.017$), whereas meal energy density increased (+0.34 kcal/g; 95%CI: 0.18 to 0.49; $p<0.001$). Compositional analysis showed reduced protein intake relative to carbohydrate and fat (estimate: -0.117; 95%CI: -0.201 to -0.033; $p=0.007$). *Explicit liking* bias decreased for high-protein (-6.2 a.u.; 95%CI: -11.1 to -1.4; $p=0.015$) and foods with color (-7.2 a.u.; 95%CI: -14.1 to -0.3; $p=0.043$). *Implicit wanting* bias for high-fiber foods decreased (-13.4 a.u.; 95%CI: -22.6 to -4.1; $p=0.007$).

Conclusion: Across groups, prolonged HDBR was associated with lower spontaneous EI, reduced relative contribution of protein to buffet intake, and selective changes in food reward. Neither

58 EX nor EX+AG modified these responses, although the small group sizes limit firm conclusions
59 regarding countermeasure effects.

60 **Keywords:** Bed rest, Microgravity, Food reward, HDBR, LFPQ, Exercise countermeasures

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1. Introduction

Adequate nutrition is a cornerstone of astronaut health. However, astronauts frequently fail to meet their prescribed energy requirements, with energy intake often reported at approximately 25% below estimated energy needs, resulting in negative energy balance and loss of body mass (Smith et al., 2001, 2005; Smith & Zwart, 2021; Taylor et al., 2020). Recent evidence also indicates substantial inter-individual variability, with some astronauts exhibiting positive and others negative energy balance during long-term flights on the International Space Station (ISS) (Bourdier et al., 2022). This variability suggests that energy intake does not consistently adjust to energy expenditure during spaceflight. These alterations may arise from microgravity-induced physiological adaptations, such as cephalic fluid shifts and sensory changes (Olabi et al., 2002), as well as from environmental stressors, such as confinement and monotony (Stroebele & De Castro, 2004). These alterations may also extend beyond total caloric intake. In-flight data suggest qualitative shifts in dietary composition, including a greater carbohydrate intake relative to fat compared with preflight dietary estimates (Le Roux et al., 2024).

Most available ISS and Shuttle data rely primarily on menu logs and self-reported acceptability (Douglas et al., 2025; Smith et al., 2013; Taylor et al., 2020). While these approaches describe what astronauts consume from a limited menu of ready-to-eat meals, they provide limited insight into the behavioral or motivational mechanisms driving those choices. Consequently, it remains unclear whether the observed dietary shifts reflect physiological adaptations to microgravity, alterations in food reward, and/or the restricted availability and repetitive nature of the highly processed, shelf-stable onboard food system.

Understanding these behavioral shifts requires consideration of both metabolic signals (i.e., homeostatic) and non-homeostatic reward-related processes (i.e., hedonic) involved in the control of appetite and eating behavior (J. Blundell et al., 2010; McCrickerd & Forde, 2016; Mela, 2006). These processes are closely interconnected. Nevertheless, food reward can be operationalized through two related components: *explicit liking*, which represents the conscious affective pleasure associated with consuming a food, and *implicit wanting*, which reflects the relative motivational salience of that food (Blundell et al., 2010; Finlayson et al., 2007a). While liking is relatively stable and closely linked to food palatability, wanting is more dynamic and can be modulated by metabolic state, environmental cues and physical activity (Beaulieu et al., 2020; Berridge, 2009; Finlayson et al., 2009). Accordingly, the chronic loss of ambulatory activity and mechanical unloading inherent to spaceflight may alter food reward and thereby influence spontaneous food intake and selection.

Exercise countermeasures are routinely implemented during spaceflight to mitigate physiological deconditioning, particularly musculoskeletal atrophy and cardiovascular deconditioning (Hackney et al., 2015). Beyond these somatic benefits, terrestrial evidence indicates that physical activity is an important regulator of appetite, whereas severe inactivity, characterized by a persistently low rate of overall energy turnover, may weaken the coupling between energy intake and energy requirements (Beaulieu et al., 2016; J. E. Blundell et al., 2020). This suggests that an exercise countermeasure could help re-establish this coupling by anchoring eating behavior more closely to biological energy demands rather than to environmental cues (Beaulieu et al., 2016; Finlayson et al., 2009). However, we previously observed in astronauts aboard the ISS that the

most active crewmembers—particularly those performing higher volumes of aerobic exercise—exhibited a negative energy balance and fat mass loss, whereas less active crewmembers were in a positive energy balance (Bourdier et al., 2022). This observational association suggests that exercise-related increases in energy expenditure may not always be matched by compensatory increases in energy intake. Conversely, low physical activity may not be accompanied by proportional reduction in energy intake. The effects of exercise countermeasures on appetite and energy intake regulation under microgravity conditions therefore remain to be further studied.

In this study, we took advantage of the European Space Agency (ESA)-sponsored Bed Rest with Artificial Gravity and Cycling Exercise (BRACE) study, designed to test the efficacy of aerobic exercise, with or without artificial gravity (AG), in mitigating physiological responses to 60 days of head-down bed rest (HDBR) in healthy men. AG has been proposed as an integrated countermeasure to partially restore gravitational loading through centrifugation (Clément, 2017). Initial analyses showed that aerobic exercise combined with AG preserved resting metabolism (Martin-Rodriguez et al., 2026), whereas neither countermeasure fully prevented declines in muscle mass and neuromuscular function (Mandić et al., 2026). Here, we examined whether aerobic exercise, alone or combined with AG, influenced changes in spontaneous energy intake, food choice, and food reward during 60 days of HDBR. We hypothesized that regular aerobic exercise would attenuate changes in food reward associated with HDBR and help preserve motivational drive and spontaneous energy intake during an *ad libitum* meal. We further explored whether the addition of AG provided benefits beyond exercise alone.

2. Methods

2.1 Study design and overview

This study was conducted as part of the EXENERGY protocol, one of 14 coordinated research protocols embedded within the BRACE campaign, an integrated 60-day HDBR study sponsored by the European Space Agency (ESA) and the French Space Agency (CNES) to investigate the efficacy of aerobic exercise with or without AG in mitigating physiological responses to prolonged HDBR. Our protocol was designed to comprehensively assess energy balance and its regulatory components. The present manuscript reports the food reward and food-choice outcomes. The study was conducted at the Institute for Space Medicine and Physiology (MEDES, Toulouse, France) across two campaigns (April–July 2023 and January–April 2024). The full experimental period lasted 88 days, including a 14-day baseline data collection phase (BDC), 60 days of HDBR, and a 14-day recovery phase (**Figure 1**).

During HDBR, all activities, including showering, in-bed toileting, and eating, were performed in the head-down position, with no pillow and at least one shoulder continuously in contact with the mattress. Standing or sitting was strictly prohibited, and compliance was continuously monitored via 24-hour video surveillance. Participants followed a standardized 07:00–23:00 h sleep–wake schedule throughout the campaign. Further details are available elsewhere (Hedge et al., 2025).

2.2 Participants

A total of 24 healthy men were recruited, with 12 participants enrolled in each campaign. Participants were randomly allocated to one of three parallel groups (n = 8/group): a control group (CNT) that underwent strict HDBR without countermeasures, an exercise group (EX) that performed supine interval cycling 6 days/week, and an exercise plus AG group (EX+AG) that completed the same cycling protocol while exposed to AG on a short-arm human centrifuge.

Participants aged 20–45 years were recruited through advertisements on websites, posters, and television. Eligibility was determined via multistep medical and psychological screening conducted by the MEDES medical team. To be eligible for participation, volunteers were required to be men with a body mass index (BMI) between 20 and 27 kg/m², a height of 158–190 cm, and a maximal oxygen uptake (VO₂max) of 35–55 mL/min/kg, verified during selection via a maximal graded exercise test on a cycle ergometer (Lode, Groningen, The Netherlands) using a metabolic cart (Quark CPET, Cosmed, Rome, Italy). They also had to be non-smokers, free of any chronic medical conditions and regular medication use, with no history of alcohol or drug abuse. Given the specific constraints of HDBR, additional exclusion criteria included any history of cardiovascular, musculoskeletal, or neurological disorders (including orthostatic hypotension and vestibular disorders), as well as specific risk factors for thrombosis (e.g., hereditary clotting deficiencies) or psychological intolerance to confinement (e.g., claustrophobia). A comprehensive list of inclusion and exclusion criteria is provided in the **Supplementary Table S1**.

Group allocation followed a multistep process designed to preserve both psychological compatibility within rooms and physiological balance across groups. First, participants were

paired by the MEDES clinical team based on psychological evaluations (personality and values), age, and profession. Because specific beds were pre-assigned to group conditions (CNT, EX, EX+AG) for logistical reasons, group assignment was determined through a two-step randomization process: first, each pair was randomly assigned to a room; second, each participant within a pair was randomly assigned to a specific bed (window- or door-side). Following this initial allocation, groups were checked for comparability in age, VO_{2peak} , BMI, and height, and two participant pairs were reassigned prior to study initiation to improve baseline comparability for predefined characteristics.

All participants provided written informed consent before inclusion. The study protocol was approved by the Comité de Protection des Personnes Sud-Ouest et Outre-Mer I (CPP19057-54028) and conducted in accordance with the Declaration of Helsinki. The BRACE study was registered at ClinicalTrials.gov (NCT06544213).

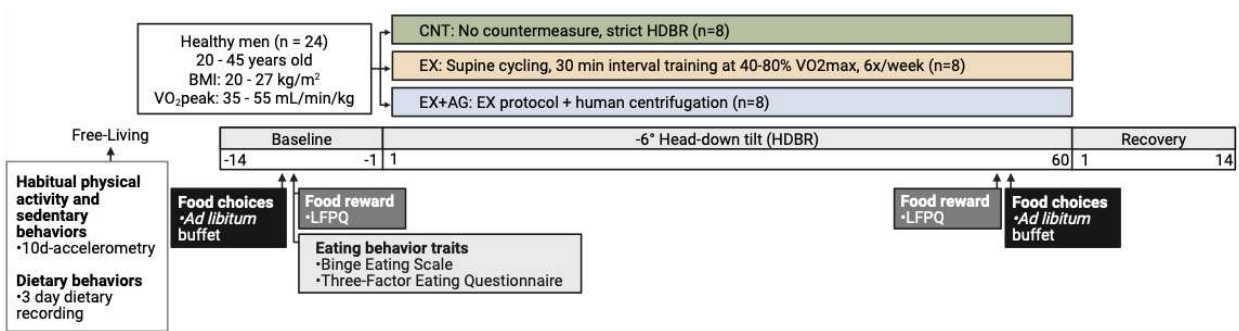


Figure 1. Schematic overview of the Bed Rest with Artificial Gravity and Cycling Exercise (BRACE) study design. Abbreviations: BMI, body mass index; CNT, control group; EX, exercise group; EX+AG, exercise plus artificial gravity group; HDBR, head-down bed rest; LFPQ, Leeds Food Preference Questionnaire; RMR, resting metabolic rate; VO_{2max} , maximal oxygen uptake.

2.3 Countermeasure protocols

Participants in the EX and EX+AG groups performed 30-minute interval cycling sessions on a supine ergometer (Lode, Groningen, The Netherlands), six days per week throughout the 60-day HDBR period, for a total of 49 sessions.

2.3.1 Exercise protocol (EX)

The exercise sessions used an interval training format designed to elicit a relatively high metabolic demand. Each session began with a 5-minute warm-up at 40% of pre-bed rest peak oxygen uptake ($\text{VO}_{2\text{peak}}$), followed by a 22-minute central block of alternating 2-minute high- and low-intensity intervals. The high-intensity intervals followed a pyramidal distribution corresponding to 65%, 70%, 80%, 80%, 70%, and 65% of $\text{VO}_{2\text{peak}}$, whereas the recovery intervals were maintained at 40% $\text{VO}_{2\text{peak}}$. Each session ended with a 3-minute cool-down at 40% of $\text{VO}_{2\text{peak}}$. When participants were unable to sustain the target intensity of 80% $\text{VO}_{2\text{peak}}$, a standardized backup protocol was implemented, in which the high-intensity intervals were capped at 70% $\text{VO}_{2\text{peak}}$ (sequence: 65%, 70%, 70%, 70%, 70%, 65%) until the participant recovered sufficient capacity to resume the standard protocol.

2.3.2 Exercise plus artificial gravity (EX+AG)

Participants in the EX+AG group performed the same cycling protocol described above, with identical duration, intensity distribution, and ergometer workload, while simultaneously experiencing AG in a short-arm human centrifuge. The AG intensity was individualized based on each participant's pre-determined orthostatic tolerance (OT).

The protocol began with a baseline AG load set at 0.15 Gz below the individual OT ($G_{\min} = OT - 0.15$). To synchronize gravitational loading with the cycling protocol, the G-level was modulated in 4-minute blocks, corresponding to the duration of one complete high-intensity and active recovery cycle. Every 4 minutes, the AG load increased by increments of one-third of the participant's AG reserve, defined as the difference between $G_{\min}$ and the maximum safety cap. The peak AG load was capped at 70% of the individual's maximum tolerance ($G_{\max}$). Following the peak intensity block, the AG load followed a symmetrical ramp-down protocol, decreasing by $(G_{\max} - G_{\min})/3$ every 4 minutes until the session concluded. Because ergometer workloads were matched between EX and EX+AG, the study design was intended to isolate the effect of the added gravitational loading (**Supplementary Figure S1**).

2.4 Baseline lifestyle and eating behavior traits

Prior to arrival at the clinical facility, participants' baseline lifestyle habits (i.e., diet and physical activity) were assessed under free-living conditions. Habitual physical activity and sedentary behaviors were quantified over a 10-day period using hip-worn accelerometers (ActiGraph GT3X, ActiGraph LLC, Pensacola, FL, USA) combined with daily activity logs. To characterize habitual dietary intake and baseline macronutrient distribution, participants completed a comprehensive dietary record over three consecutive days, including two weekdays and one weekend day. Habitual energy intake and macronutrient composition were estimated by a trained registered dietitian using the French food composition database (CIQUAL, ANSES, 2020) and Nutrilog software (Edition Standard, Nutrilog SAS, Marans, France).

During the baseline phase (BDC-8), participants also completed two validated self-report questionnaires assessing eating behavior traits. The Binge Eating Scale (BES) was administered to assess behavioral, cognitive, and emotional manifestations of binge eating characteristics (Gormally et al., 1982). The scale yields a total summed score ranging from 0 to 46, with cut-offs defined as: <17 indicating no or minimal binge eating, 17–27 indicating moderate binge eating, and >27 indicating severe binge eating characteristics. Additionally, the Three-Factor Eating Questionnaire (TFEQ-51) was used to measure three distinct dimensions of human eating behavior: cognitive restraint (conscious restriction of food intake to control body weight), disinhibition (loss of eating control in response to emotional or social cues), and susceptibility to hunger (subjective feelings of hunger and food cravings) (Stunkard & Messick, 1985).

2.5 Anthropometrics and body composition

Before and on day 56 of HDBR, body mass and composition were measured in a fasted state, with participants wearing only underwear. Body mass was recorded using one of two calibrated supine scales (Bolero 1900 mm, models CEB 6000-01 and CEB 2281-82; Malmö, Sweden). To ensure measurement reliability, each participant was weighed on the same scale throughout the study. During the baseline phase (BDC-2) and at the end of bed rest (HDT56), body composition was determined via dual-energy X-ray absorptiometry (DXA; Hologic QDR-4500C, Hologic Inc., Marlborough, MA, USA) with analyses performed using APEX software version 5.6.1.7. To account for variations in body size, body mass, fat-free mass and fat mass were also expressed relative to height squared (kg/m^2), providing size-independent indices including BMI, fat-free mass index (FFMI), and fat mass index (FMI), respectively. Daily body mass and BMI data were

smoothed using a 3-day moving average to minimize short-term variability unrelated to physiological changes.

2.6 Diet

Energy intake was standardized and monitored throughout the study. Participants received three structured meals and one snack per day, with menus designed by the MEDES clinical nutrition team and supplied by Rangueil Hospital (Toulouse, France). Main dishes were quick-frozen and accompanied by manufacturer-provided nutritional values; complementary items (e.g., starters, cheeses, desserts) were analyzed using a custom MEDES database incorporating validated European data. To allow precise quantification of actual energy and macronutrient intake, all meals and individual items were weighed before and after consumption.

Individual energy intake targets were calculated from resting metabolic rate (RMR), measured via indirect calorimetry (Quark RMR, Cosmed, Rome, Italy) at baseline (BDC-14) (Martin-Rodriguez S. et al, 2026). RMR measurements were conducted for approximately 30 minutes in the morning, approximately one hour after waking, following an overnight fast, with participants remaining in the supine position at thermoneutrality. Energy intake was prescribed at 160% of measured RMR during baseline and recovery periods. During HDBR, the daily dietary energy target was set at 142% of baseline measured RMR, with limited individual adjustments. For the EX and EX+AG groups, this requirement was supplemented with additional calories to cover the energy expenditure of the countermeasure sessions, calculated individually for each participant using their baseline VO_{2peak} test energy expenditure.

Macronutrient composition was standardized at 1.0-1.2g protein/kg/day, 30%-35% of total energy intake from fat, and the remainder from carbohydrates. Total daily liquid and electrolyte intakes were also strictly controlled. Consumption of caffeinated beverages and alcohol was prohibited.

2.7 Food choices assessment: *Ad libitum* multi-choice buffet

To evaluate the influence of prolonged HDBR on food choices, participants completed two identical test days before and at the end of the 60-day HDBR phase (**Figure 1**). On each test day, participants were required to consume a standardized breakfast at 08:00 h, providing 30% of their individual daily energy requirements (55% CHO, 30% fat, and 15% protein). At 13:00 h, a standardized *ad libitum* multi-choice lunch buffet was provided, during which participants were instructed to eat freely until comfortably full within 60 minutes. To facilitate consumption and standardize the unit of selection, all larger items (e.g., quiche, meats, buns) were served pre-cut into bite-sized portions. All items were weighed before and after consumption to precisely quantify actual intake. To evaluate food choices using standardized dietary metrics, the absolute mass consumed for each food item was converted into the number of servings. A standard reference portion size in grams was defined a priori for each of the 42 items based on established French nutritional guidelines and dietary surveys (Hercberg et al., 1994).

The *ad libitum* buffet offered 42 food items, representing a complete meal structure, including starters, main and side dishes, desserts, and condiments. A comprehensive list of all specific items provided is detailed in **Supplementary Table S2**. Energy and macronutrient composition

were computed using manufacturer values for industrial items and the French food composition database (CIQUAL, ANSES, 2020) for generic items. The overall energy density of the meal (kcal/g) was calculated as total energy intake divided by the total weight of food consumed.

Food choices were analyzed by the proportion of energy intake at the buffet (%EI) derived from specific food categories, defined by their nutritional, organoleptic, and physical modes of consumption and habitual status. Nutritionally, items were classified per 100 g according to established European and National Health Service (NHS) guidelines (see **Supplementary Table S2** for full classification). High-fat products were defined as containing >17.5 g of fat per 100 g, whereas low-fat products were defined as containing ≤ 3 g of fat per 100 g (NHS; EC Regulation No 1924/2006). Items were classified as high-carbohydrate (≥ 15 g/100 g) or low-carbohydrate (< 5 g/100 g) (Guyot, 2021) and further distinguished by sugar content into high-sugar (> 22.5 g/100 g) and low-sugar (≤ 5 g/100 g) categories (NHS). Beyond macronutrient composition, items were categorized by their organoleptic profile (sweet versus savory, hot versus cold) and their consumption mode (finger food versus utensil). Furthermore, items were classified as non-habitual (defined as foods not included in the standardized, rotational basal diet provided during the bed rest campaign) to objectively assess exploratory food choices. Finally, to prevent anticipatory regulation (i.e., intake adjustment driven by expectation of a subsequent meal), a standardized dinner providing a fixed proportion of individual daily energy requirements, independent of buffet intake, was served more than 4 h later.

2.8 Food reward measures

Food reward was assessed using the Leeds Food Preference Questionnaire (LFPQ), a validated computerized task that measures two distinct components of food reward: *explicit liking* and *implicit wanting* (Finlayson et al., 2007b). We used the French-adapted six-task version of the LFPQ (**Table 1**), which features culturally appropriate food items and translated instructions (Guyot et al., 2022). To avoid interference with the dense HDBR testing schedule, the LFPQ was administered on a dedicated day in a quiet, distraction-free environment at baseline and near the end of HDBR. The LFPQ could not be administered on the same day as the *ad libitum* buffet and was therefore scheduled on a separate but temporally proximate day under standardized individual postprandial testing conditions.

Following a brief practice session to familiarize participants with the interface, the order of the liking and wanting assessments was randomized to prevent systematic order effects. *Explicit liking* was assessed using 100-point visual analog scales (VAS) rating the anticipated pleasantness of tasting each food item. *Implicit wanting* was measured via a forced-choice task where participants selected the food they most wanted to eat, with choices and reaction times recorded using E-Prime software (v3.0; Psychology Software Tools, Sharpsburg, PA, USA). To prevent cognitive fatigue and ensure the reliability of reaction times, brief self-paced rest periods were permitted between the blocks of the forced-choice task. As detailed by Oustric et al. (2020), *implicit wanting* scores were computed for each food category using a validated frequency-weighted algorithm (Oustric et al., 2020). This algorithm integrates choice frequency and mean reaction time to yield a relative motivational score ranging approximately from -100 to 100. A positive score indicates a stronger motivational drive (faster reaction times and higher selection

frequency) for a category relative to its alternatives, whereas a negative score indicates lower relative motivation.

To quantify the relative preference for specific food attributes, preference bias scores were calculated using the established mathematical framework for the LFPQ (Finlayson et al., 2007a). Bias scores were computed as simple difference scores by subtracting the baseline attribute score from the target attribute score (e.g., High Protein minus Low Protein). Consequently, a positive score indicates a relative preference for the target attribute, whereas a negative score indicates a relative preference for the baseline counterpart. This approach was applied uniformly across all tested dichotomies to generate directional relative preference metrics (e.g., carbohydrate bias, protein bias, color bias, etc.).

2.9. Statistical analyses

Baseline characteristics are presented as means $\pm$ standard deviation (SD). All inferential analyses were performed using R statistical software (version 4.5.1; R Core Team).

Variables expressed as percentages of energy intake were analyzed using beta regression with a logit link (*glmmTMB* package), following a linear transformation to the open interval (0, 1). Count-like data with right-skew and exact zeros (e.g., number of servings) were modeled using a Tweedie distribution with a log link. Continuous variables without strict distributional bounds (e.g., total energy intake) were analyzed using linear mixed models (LMM) fitted with the lmerTest package. All mixed-effects models included group (CNT, EX, EX+AG), time (Baseline vs. end-HDBR), and their interaction as fixed effects. A subject-specific random intercept accounted

for within-participant correlation. Time-by-group interaction was the primary inference used to evaluate whether changes differed among groups. Overall time effects across groups were also estimated.

To analyze the relative macronutrient composition of the *ad libitum* buffet meal, we used compositional data analysis (CoDA) via the *compositions* package. A strictly positive three-part composition was constructed from the percentages of total energy intake (%EI) contributed by protein, carbohydrates, and fats. This composition was then transformed into two orthogonal isometric log-ratios (ILR) coordinates using a predefined sequential binary partition. The partition was defined a priori to distinguish protein from non-protein energy sources and, separately, carbohydrates from fats. The first coordinate (ILR1) contrasted protein with the geometric mean of non-protein macronutrients (carbohydrates + fats), whereas the second coordinate (ILR2) contrasted carbohydrates with fats. The corresponding ILR equations were:

$$ILR1 = \sqrt{\frac{2}{3}} \times \left[\ln(\text{protein \%EI}) - \frac{\ln(\text{carbohydrates \%EI}) + \ln(\text{fats \%EI})}{2} \right]$$

$$ILR2 = \sqrt{\frac{1}{2}} \times [\ln(\text{carbohydrates \%EI}) - \ln(\text{fats \%EI})]$$

These two ILR coordinates were stacked into a single response variable and analyzed jointly in a multivariate LMM, including time, group, ILR coordinate, and their interactions as fixed effects, with participant specified as a random intercept to account for within-subject correlation across time points and coordinates.

For LMM, homoscedasticity and residual distribution were assessed by visual inspection of residual Q-Q plots and histograms, along with Shapiro-Wilk tests. Sensitivity analyses using a rank-based inverse-normal transformation (Blom method) followed by LMMs were conducted for continuous outcomes and confirmed the direction of the main findings.

To limit the number of statistical comparisons in this small sample, formal inferential statistics for the LFPQ were restricted to the calculated bias scores, whereas individual category scores are reported descriptively in the **Supplementary Tables S3 and S4**. For all LMMs, the denominator degrees of freedom were approximated using the Kenward-Roger method and significance was assessed using Type III F-tests.

Our statistical inference focused on two model-derived contrasts: the overall estimated change from baseline and pairwise between-group differences in changes (time-by-group interaction). Results are reported as estimated least-squares means (LSMean) or contrasts with 95% confidence intervals (CIs). Pairwise countermeasure contrasts compared EX with CNT, EX+AG with CNT, and EX+AG with EX. Statistical significance was set at $p < 0.05$ (two-sided). Given the exploratory nature of the behavioral secondary outcomes, no formal correction for multiple comparisons was applied.

3. Results

3.1 Participant characteristics

Baseline participant characteristics by group are presented in **Table 2**. The cohort consisted of young, healthy male adults (mean age: $29.5 \pm [SD] 5.7$ years) with a normal BMI ($23.8 \pm 1.8 \text{ kg/m}^2$) and a good aerobic fitness level ($VO_{2\text{peak}}$: $45.2 \pm 4.6 \text{ mL/min/kg}$). Habitual moderate-to-vigorous physical activity during the free-living period prior to the study averaged $272.8 \pm 145.6 \text{ min/week}$, with substantial inter-individual variability. Baseline dietary assessments indicated a habitual diet with the following macronutrient distribution of carbohydrates ($43.3 \pm 5.3\%$), fats ($34.6 \pm 5.7\%$), and protein ($17.3 \pm 4.5\%$).

At baseline, all participants were classified as having “no” or “minimal” binge eating on the BES, except for one participant who scored at the lower threshold of the moderate category. Sensitivity analyses excluding this participant did not alter the dietary or behavioral results. TFEQ-51 scores were situated in the lower range across all subscales, indicating low levels of cognitive restraint, disinhibition, and perceived hunger within the cohort.

3.2 Changes in body composition

No statistically significant time-by-group interactions were detected for total body mass, fat-free mass, or fat mass (all interactions: $p \geq 0.13$; **Supplementary Table S5**). Across groups, the model-estimated overall change during HDBR showed a reduction in total body mass of 2 kg (95%CI: -2.4 to -1.6, $p < 0.001$) and in fat-free mass of 2.2 kg (95%CI: -2.6 to -1.7, $p < 0.001$). Fat mass did

not significantly change (0.2 kg, -0.1 to 0.4, $p = 0.209$). Body composition data, including group-specific estimates, are detailed in **Supplementary Table S5**.

3.3 Dietary intake and food choices

3.3.1 Dietary intake and composition at the buffet

No significant time-by-group interactions were detected for the dietary outcomes assessed during the *ad libitum* buffet (all interactions: $p \geq 0.82$, **Figure 2**). Across groups, total energy intake during the *ad libitum* buffet was significantly lower at the end of HDBR than at baseline (ETD: -264 kcal, 95%CI: -476 to -52, $p = 0.017$; **Figure 2A**).

However, meal energy density increased by 0.34 kcal/g (95%CI: 0.18 to 0.49, $p < 0.001$; **Figure 2B**). Consistent with the lower energy intake, absolute intakes of carbohydrate, protein and fat decreased following HDBR (all $p < 0.048$; **Figures 2D-F**). Adjustment for body mass and composition did not influence these results.

Compositional data analysis indicated that the relative macronutrient composition of the buffet meal changed during HDBR (time effect: $p = 0.027$). This compositional shift was driven by a significant decrease in the protein-to-non-protein ratio, as indicated by the reduction in IRL1 (-0.117, 95% CI: -0.201 to -0.033, $p = 0.007$, **Figure 2C**). IRL2, representing the carbohydrate-to-lipid ratio, did not significantly vary (-0.017, 95%CI: -0.101 to 0.067, $p = 0.683$). Thus, the relative contribution of dietary protein decreased, whereas the carbohydrate-to-fat balance remained unchanged.

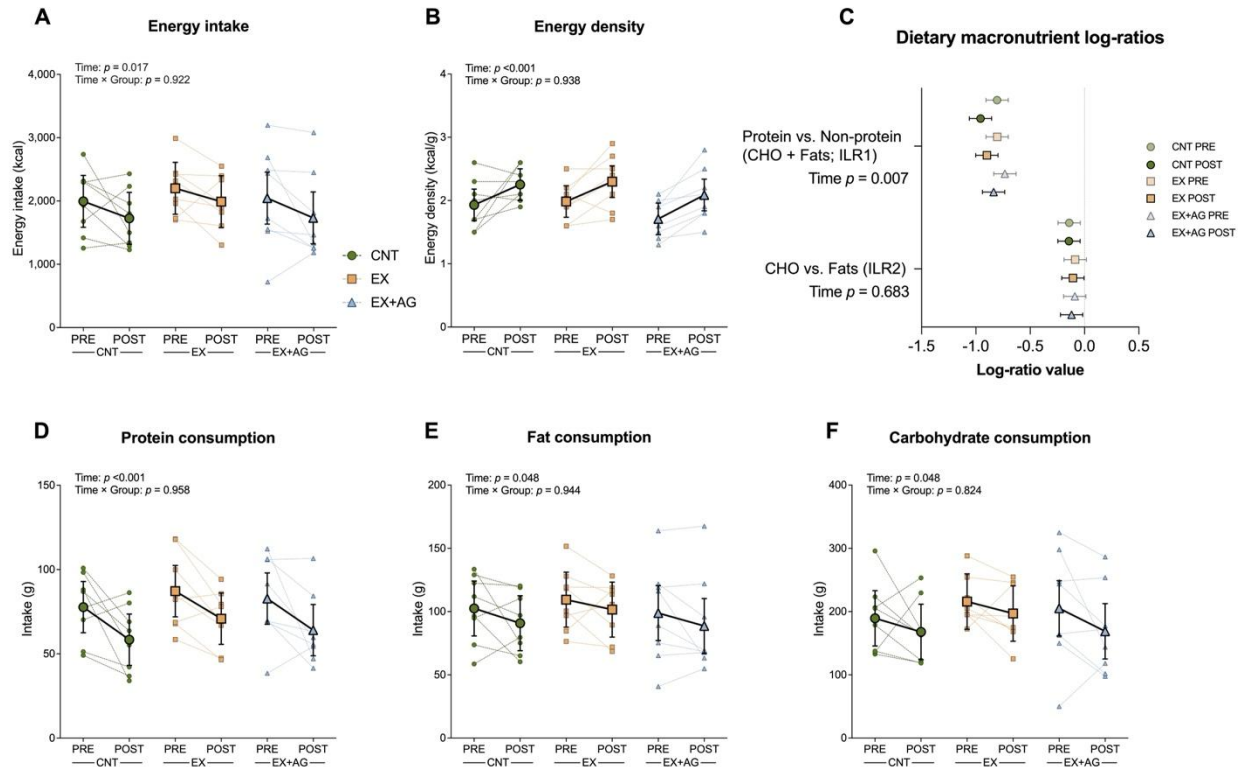


Figure 2. Impact of 60-day head-down bed rest on total energy intake, energy density and macronutrient consumption during an *ad libitum* multi-choice buffet.

Total energy intake in kcal (A), energy density in kcal/g (B), the dietary macronutrient architecture expressed as isometric log-ratios (ILR) (ILR1: Protein vs. Non-protein; ILR2: Carbohydrates vs. Fats) (C), and the absolute intake mass in g of protein (D), fat (E), and carbohydrate (F) were measured before (PRE) and after 57 days of HDBR (POST) in men randomized to strict HDBR (CNT, $n=8$), aerobic exercise training concomitantly to HDBR (EX, $n=8$) and aerobic exercise along with artificial gravity (AG) concomitant to HDBR (EX+AG, $n=8$). Statistics were derived from linear mixed models (LMM) with time, group, and their interaction as fixed effects, with p-values for main and interaction effects reported within the panels. The least-squares means (solid markers) with standard errors (error bars) are overlaid on individual participant trajectories (dashed lines with small markers) for panels A-B and D-F. Markers in panel C represent least-squares means and standard errors for the log-ratio values, with lighter shades denoting PRE and darker shades denoting POST measurements. For the multivariate compositional model (C), LMM included time, group, ILR_Coordinates, and their interactions as fixed effects.

3.3.2 Food selection by nutritional profile at the *ad libitum* multi-choice buffet

No significant time-by-group interactions were detected for buffet food selection according to food items' nutritional profiles (all interactions: $p \geq 0.16$, **Figure 3**). Overall changes across groups are reported below.

Following 60 days of HDBR, selection of high-fat products increased by 0.9 servings (95%CI: 0.3, 1.6, $p = 0.007$), and their contribution to total energy intake increased by 10.6 % (95%CI: 5.9 to 15.2, $p < 0.001$; **Figure 3A**). Selection of low-fat products decreased by 1.2 servings (95%CI: -2.2 to -0.3, $p = 0.013$) and their contribution to energy intake decreased by 3.6% (95%CI: -6.3 to -0.9, $p = 0.011$; **Figure 3B**).

The number of high-carbohydrate and high-sugar servings did not significantly change (both $p \geq 0.16$). However, the proportion of total energy derived from high-carbohydrate foods increased by 8.4 % (95%CI: 3.2 to 13.6, $p = 0.003$; **Figure 3C**), and that derived from high-sugar products increased by 6.3 % (95%CI: 2.9 to 9.7, $p = 0.001$; **Figure 3E**). Selection of low-carbohydrate foods and low-sugar foods decreased by 0.9 servings (95%CI: -1.5 to -0.4, $p = 0.002$; **Figure 3D**) and 1.9 servings (95%CI: -3.0 to -0.9, $p = 0.001$; **Figure 3F**), respectively.

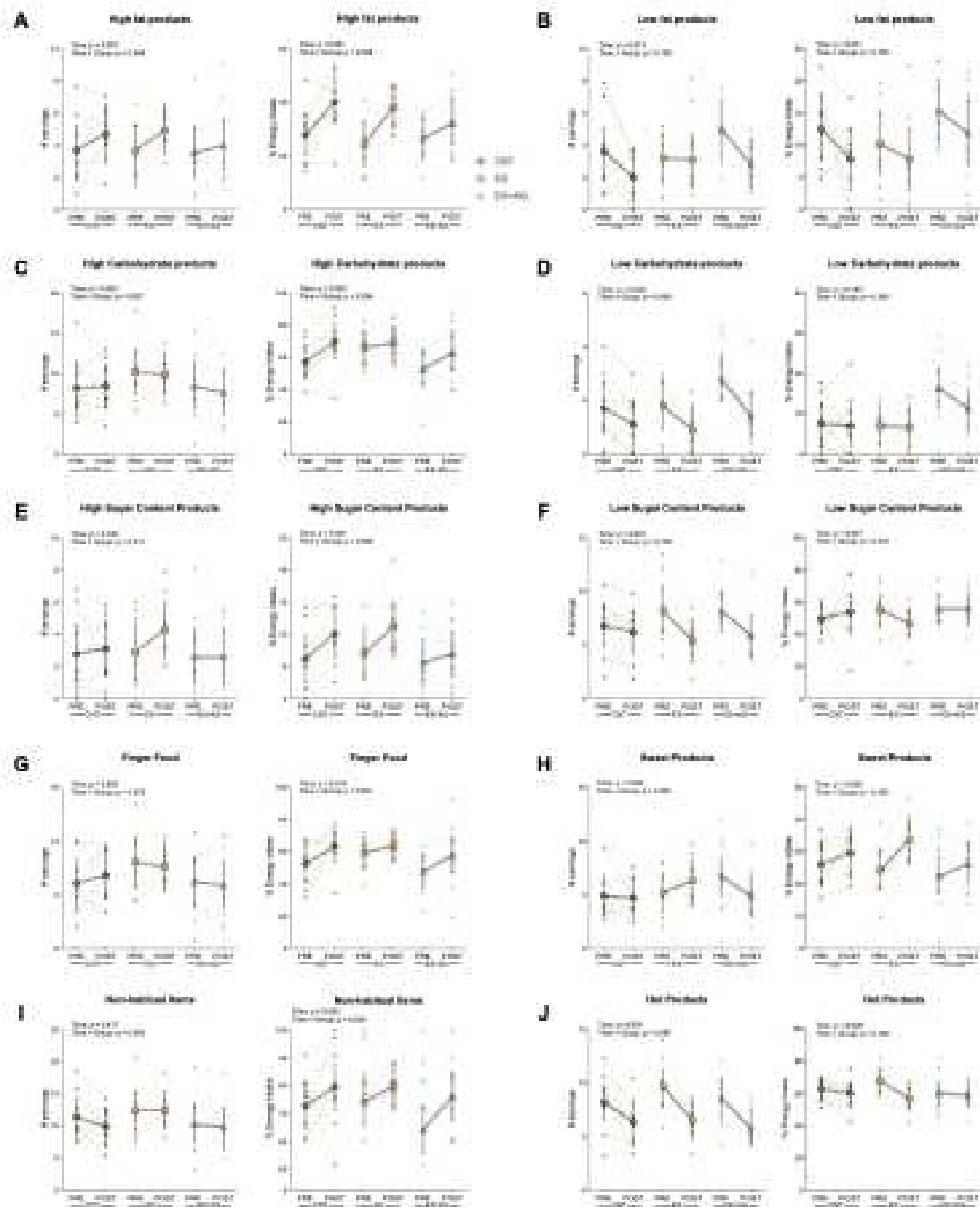


Figure 3. Impact of 60-day head-down bed rest on food selection patterns based on nutritional and organoleptic profiles.

The absolute number of servings selected (left graphs) and the proportion of energy intake in % (right graphs) for high-fat (A), low-fat (B), high-carbohydrate (C), low-carbohydrate (D), high-sugar (E), low-sugar (F), finger foods (G), sweet products (H), non-habitual items (I), and hot products (J) were measured before (PRE) and after 57 days of HDBR (POST) in men randomized to strict HDBR (CNT, n=8), aerobic exercise

training concomitantly to HDBR (EX, n=8) and aerobic exercise along with artificial gravity (AG) concomitant to HDBR (EX+AG, n=8). Statistics were derived from generalized linear mixed models utilizing a Tweedie distribution for absolute servings and Beta regression for percentages of energy intake, with time, group, and their interaction as fixed effects, with *p*-values for main and interaction effects reported within the panels. The least squares means (solid markers) with 95% Confidence Intervals (error bars) are overlaid on individual participant trajectories (dashed lines with small markers) for panels A-J.

3.3.3 Selection by food category and organoleptic traits

No significant time-by-group interactions were observed for the selection of specific food categories or organoleptic traits (all interactions: $p \geq 0.1$). The changes reported below are the main effect of HDBR across groups.

Selection of hot products decreased by 2.6 servings (95% CI: -3.7 to -1.5, $p < 0.001$), and their contribution to energy intake by 4.9 % (95% CI: -9.2 to -0.6, $p = 0.028$; **Figure 3J**). Among specific food categories (**Figure 4A**), vegetable servings decreased by 1.3 servings (95%CI: -1.9 to -0.6, $p = 0.010$; **Figure 4C**). The proportion of energy obtained from finger foods increased by 8.5 % ([1.9, 15.1], $p = 0.014$; **Figure 3G**), and the proportion obtained from non-habitual items increased by 8.2 % ([2.3, 14.1], $p = 0.009$; **Figure 3I**). Sweet-food selection did not significantly change, in either in number of servings (-0.3 servings, 95%CI: -1.6 to 1.00], $p = 0.624$), but did increase in proportion of energy intake (+0.28 % [0.07, 0.49], $p = 0.008$; **Figure 3H**). Selection of starchy products, meats and alternatives, low-fat dairy products, fast-food items, high-fat dairy products, fruits, and dressings also did not significantly change ($p \geq 0.13$, for all; **Figures 4A-B, 4D-J**).

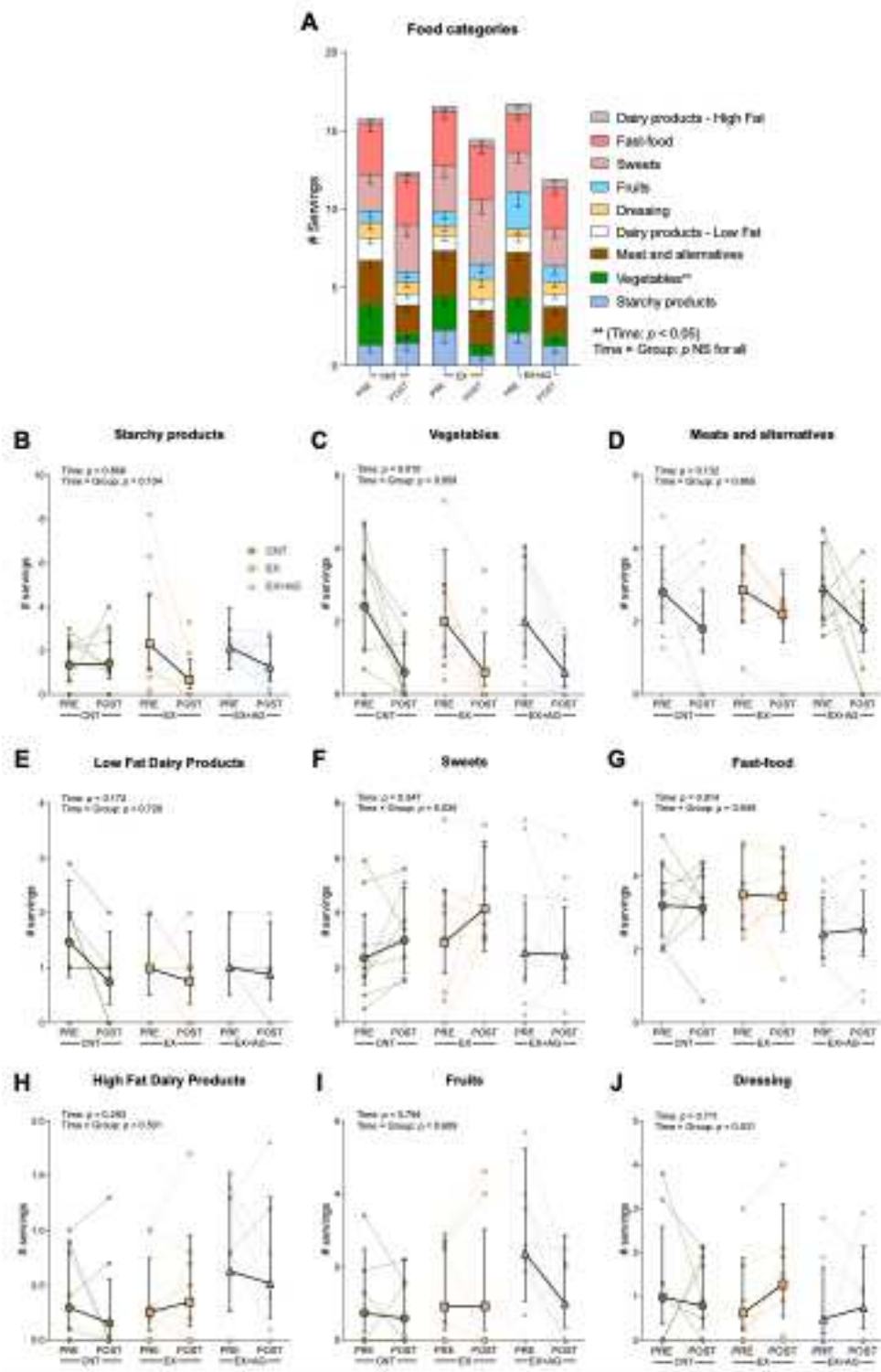


Figure 4. Impact of 60-day head-down bed rest on the overall buffet composition and selection of specific food categories.

The overall composition of the *ad libitum* buffet expressed as the stacked number of servings across all food categories (A), and the number of servings for starchy products (B), vegetables (C), meats and alternatives (D), low-fat dairy products (E), sweets (F), fast-food (G), high-fat dairy products (H), fruits (I), and dressings (J) were measured before (PRE) and after 57 days of HDBR (POST) in men randomized to strict HDBR (CNT, n=8), aerobic exercise training concomitantly to HDBR (EX, n=8) and aerobic exercise along with artificial gravity (AG) concomitant to HDBR (EX+AG, n=8). Statistics were derived from generalized linear mixed models utilizing a Tweedie distribution and a log link, with time, group, and their interaction as fixed effects, and unadjusted means with standard errors and significant main effects of time denoted by asterisks (**) are presented for the stacked bar chart (A), while least squares means (solid black markers) with 95% Confidence Intervals (gray shaded regions) overlaid on individual participant trajectories (dashed lines with open markers) are presented for the remaining categories (B-J).

3.4 Food reward

3.4.1 Explicit liking bias (pleasantness)

No statistical time-by-group interactions were noted for *explicit liking* bias scores (all interactions: $p \geq 0.25$; **Table 3**). Across groups, color bias (-7.2, 95%CI: -14.1 to -0.3, time: $p = 0.043$) and protein bias (-6.2, 95%CI: -11.1 to -1.4, $p = 0.015$) scores decreased, indicating a reduced relative liking for foods with colors and high-protein foods. Taste and fat bias scores did not significantly change (both $p \geq 0.16$).

3.4.2 Implicit wanting bias (motivational drive)

No time-by-group interactions were detected for any of the *implicit wanting* bias scores (all interactions: $p \geq 0.14$). Across groups, fiber bias score (ETD LSmean: -13.4, 95%CI: -22.6 to -4.1, $p = 0.007$; **Table 4**) decreased, indicating reduced relative wanting for high-fiber foods. Taste and fat bias scores did not significantly change (both $p \geq 0.10$).

4. Discussion

In this HDBR study in healthy men, we found no statistically significant evidence that aerobic exercise, either alone or combined with AG, modified changes in spontaneous energy intake,

food selection, or food reward following 60 days of HDBR. However, the small group sizes and wide confidence intervals limit the extent to which meaningful countermeasure effects can be excluded. Across groups, prolonged HDBR was associated with 1) reduced spontaneous energy intake during an *ad libitum* buffet, accompanied by a lower relative contribution of protein while the carbohydrate-to-fat balance remained unchanged; and 2) selective changes in food reward, including reduced *explicit liking* for foods with colors and high-protein foods and reduced *implicit wanting* for high-fiber foods.

HDBR was associated with lower ad libitum intake and a reduced relative contribution of dietary protein

The reduction in spontaneous energy intake was accompanied by lower absolute intake of all three macronutrients. This is consistent with the lower energy expenditure typically observed during prolonged HDBR (Bergouignan et al., 2010). Compositional analysis further showed that the reduction in intake was not proportional across macronutrients. The relative contribution of dietary protein decreased, whereas the carbohydrate-to-fat balance remained stable. This pattern contrasts with observations during actual spaceflight, where astronauts aboard the ISS exhibited a higher food quotient compared to their habitual diet on the ground, indicating a shift toward greater carbohydrate intake relative to fat (Le Roux et al., 2024). Direct comparison between these studies is nevertheless limited. The present study used a standardized *ad libitum* buffet meal before and at the end of HDBR along with precise measurements of the weight of all food items. In astronauts, we compared food consumption onboard the ISS from pre-made meals with a free-living habitual diet, estimated from diaries and pictures of the meal. Differences in

food availability, preparation, sensory quality, mission environment, and measurement methods could therefore contribute to the divergent macronutrient patterns.

The reduced relative protein intake was accompanied by the decline in *explicit liking* for high-protein foods. The consistency between these findings support a relative reduction in the valuation of protein-rich foods under the test conditions. However, *implicit wanting* for protein-rich foods did not significantly change. Thus, the protein-related findings were more apparent for reported pleasantness and meal composition than for the implicit motivational drive. This lower protein contribution may appear unexpected, given the loss of fat-free mass observed during HDBR in the control group and, to a lesser extent, in the countermeasure groups (Martin-Rodriguez et al., 2026). Indeed, the protein-stat and related models propose that loss or depletion of lean tissue may contribute to compensatory eating directed to tissue restoration (Dulloo et al., 2017). Several explanations are possible. The magnitude of fat-free mass loss may have been insufficient to trigger a detectable compensatory behavioral response. Another possible explanation is that the relationship between lean tissue loss and protein selection may differ between unloading and caloric restriction situations. Bed rest downregulates muscle protein synthesis (Paddon-Jones et al., 2006) and induces anabolic resistance (Biolo et al., 2004; Drummond et al., 2012), with modified postprandial amino acid handling (Ferrando et al., 1996; Glover et al., 2008), thereby potentially altering appetite-regulatory signals. However, whether these changes influence protein-specific food reward is unknown. Because amino acid kinetics, protein turnover, and central neurobehavioral responses were not measured alongside the

buffet and LFPQ, any mechanistic link between anabolic resistance and protein preference remains speculative and warrants future investigation.

The absence of statistically significant time-by-group interactions should be interpreted cautiously. Physical activity has been shown to help strengthen the coupling between energy intake and energy demands under ambulatory conditions (Beaulieu et al., 2016). We therefore hypothesized that exercise training performed concomitant to HDBR would preserve spontaneous energy intake and food reward measured at baseline. No significant modifying effect was detected. The exercise countermeasures with or without AG also provided only limited protection against losses of fat-free mass (**Supplementary Table S5**) and neuromuscular function and other musculoskeletal outcomes (Hedge et al., 2025; Mandić et al., 2026; Martin-Rodriguez et al., 2026). It is therefore possible that the duration, modality, or intermittent nature of the countermeasures was insufficient to produce detectable changes in food-related behavior. Alternatively, exercise could influence appetite through effects that were not captured by our protocol.

HDBR was associated with selective changes in food reward

The food-reward measures did not change uniformly. *Explicit liking* decreased for high-protein and foods with colors, suggesting a decline in relative pleasantness, whereas the *implicit wanting* decreased significantly only for high-fiber foods. Other bias scores remained statistically unchanged. This pattern indicates selective rather than generalized changes in food reward, as assessed by LFPQ. Under ambulatory conditions, food reward can contribute to eating beyond

immediate energy requirements, particularly when highly palatable food are readily available (Lowe & Butryn, 2007). However, the present study cannot determine whether the lower energy intake resulted from altered food reward, lower energy requirements, changes in appetite sensations, or other aspects of the HDBR environment. The observation of lower energy intake along with selective changes in liking and wanting supports further investigation of food reward as one potential contributor.

The restrictive study environment may have contributed to food selection

The highly controlled and restrictive environment represents another plausible influential factor on eating behavior. Food choice and reward valuation are influenced by sensory, contextual and social cues (Stroebele & De Castro, 2004). In confined settings, reduced sensory variety and limited food-related stimulation may influence the anticipated reward value of meals (Berridge et al., 2009). In addition, throughout the study, participants were restricted to a highly standardized menu with a rotation every 10 days, which may have induced menu fatigue and dietary monotony, although these were not measured directly. The increased contribution of non-habitual items and finger foods during the buffet is consistent with greater selection of items that differed from the standardized study diet. This pattern may reflect novelty seeking (Douglas et al., 2020, 2025) but also convenience of eating in the head-down position or differences in palatability.

A shift in the nutritional profile of the foods selected was also observed. Although total energy and absolute macronutrient intake decreased, the proportion of energy obtained from high-fat,

high-carbohydrate, and high-sugar products increased, as did the number of high-fat servings. These observations indicate that participants obtained a greater share of a smaller meal from foods classified within energy-dense categories. This is consistent with the measured increase in overall meal energy density. Studies in other confined or monotonous environments like spaceflight (Smith et al., 2021), hospital stays (Kontogianni et al., 2020), high-altitude sojourns (Karl et al., 2018), and overwintering missions in Antarctica (Klos et al., 2025) suggest that food variety, acceptability, and environmental stimulation may influence food intake and selection. Nevertheless, the direction of these associations is not uniform across settings, and boredom and sensory monotony have also been associated with increased caloric intake (Moynihan et al., 2015). Further studies are needed to clarify how unloading, inactivity, confinement, and the food environment influence eating behavior and energy balance regulation.

Strengths and Limitations

To our knowledge, this is the first study to examine eating behavior during prolonged HDBR study. Strengths include the highly standardized HDBR model, which permitted detailed assessment of food intake and selection under tightly controlled dietary and environmental conditions; the multi-choice buffet, which captured both quantitative intake and qualitative meal selection; and the use of the extended version of the LFPQ, which assessed reward across several food attributes, including protein content and visual presentation.

Several limitations should also be acknowledged. First, the cohort only included healthy males, limiting the generalizability. Because sex-based differences in appetite regulation and food reward have been reported in ambulatory conditions (Leeners et al., 2017; Rogan & Black, 2023),

responses during HDBR may differ in women. Second, the sample size was fixed by the overarching objectives of the BRACE study and was not determined for the dietary and food-reward outcomes. With eight participants per group, the time-by-group analyses had limited power. Accordingly, the absence of statistically significant interactions does not necessarily demonstrate equivalence among groups and findings should be considered exploratory. Third, the buffet and LFPQ assessments were performed at only two time points, while the diet was otherwise controlled. Spontaneous snacking, whole-day food selection and inter-meal energy compensation could not be captured.

5. Conclusion

During 60 days of HDBR, healthy men displayed lower spontaneous energy intake during an *ad libitum* meal, a reduced relative contribution of protein, and selective changes in *explicit liking* and *implicit wanting*. No statistically significant evidence was found that regular aerobic exercise, alone or combined with AG, modified these responses. However, the small group sizes limit conclusions regarding countermeasure effects. Food selection and food reward should be considered in future adequately powered countermeasure studies and in the development of nutritional strategies during spaceflight.

678 **Author contributions**

679 SB, JAN and AB designed the study. PSTM, AD, JAN and AB drafted the manuscript. PSTM, ELR,
680 NR, PB, MB, IC, AZ, PV, MPB, RBV and AB collected data. PSTM, AD, IC, AZ, LVDB, PV, JAN and
681 AB analyzed the data. PSTM and AB realized the statistical analysis. All the authors mentioned
682 significantly contributed to the realization of this study and approved the final version of the
683 manuscript.

684

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698 **Competing interests**

699 The authors declare no competing interests.

700

701 **Additional information**

702 The online version contains supplementary material

703

704 **Data availability**

705 The data that support the findings of this study are available from the corresponding author
706 upon reasonable request.

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Table 1. Dichotomous food categories assessed using the six-task version of the Leeds Food Preference Questionnaire (LFPQ)

Task	Studied Dimensions	Combined Food Categories	Bias Name	Interpretation of a Positive Score (+)
1	High carbohydrate (HC) / Low carbohydrate (LC) Solid (SO) / Fluid (FL)	HC-SO HC-FL LC-SO LC-FL	Carbohydrate Bias (HC minus LC)	Preference for high-carbohydrate
			Texture Bias (SO minus FL)	Preference for solid foods
2	Dairy (DA) / Non-dairy (ND) Color (CO) / No color (NC)	DA-CO DA-NC ND-CO ND-NC	Dairy Bias (DA minus ND)	Preference for dairy products
			Color Bias (CO minus NC)	Preference for visually colored foods
3	High fat (HF) / Low fat (LF) Savory (SA) / Sweet (SW)	HF-SA HF-SW LF-SA LF-SW	Fat Bias (HF minus LF)	Preference for high-fat foods
			Taste Bias (SW minus SA)	Preference for sweet foods
4	Fiber (FI) / No fiber (NF) Sauce (SC) / No sauce (NS)	FI-SC FI-NS NF-SC NF-NS	Fiber Bias (FI minus NF)	Preference for high-fiber foods
			Condiment Bias (SC minus NS)	Preference for foods with sauce
5	Meat (ME) / No meat (NM) High fat (HF) / Low fat (LF)	ME-HF ME-LF NM-HF NM-LF	Meat Bias (ME minus NM)	Preference for meat products
			Fat Bias (HF minus LF)	Preference for high-fat foods
6	High protein (HP) / Low protein (LP) Variation (VA) / No variation (NV)	HP-VA HP-NV LP-VA LP-NV	Protein Bias (HP minus LP)	Preference for high-protein foods
			Variation Bias (VA minus NV)	Preference for varied presentations

Table 2. Baseline characteristics of study participants

	Controls (n=8)	Ex group (n=8)	EX+AG group (n=8)	All (n=24)
Age (y)	28.9 (6.6)	29.9 (5.3)	29.6 (5.8)	29.5 (5.7)
Body mass (kg)	71.9 (8.0)	76.1 (7.8)	73.7 (7.9)	73.9 (7.7)
Height (cm)	172.6 (6.7)	178.1 (4.4)	177.4 (7.0)	176.0 (6.4)
BMI (kg/m²)	24.1 (1.5)	24.0 (2.1)	23.4 (2.0)	23.8 (1.8)
Fat-free mass (kg)	54.9 (6.6)	59.4 (4.2)	56.8 (5.12)	57.0 (5.5)
FFMI (kg/m²)	18.4 (1.1)	18.7 (1.0)	18.1 (1.3)	18.4 (1.1)
Fat mass (kg)	15.6 (3.0)	15.3 (3.8)	15.5 (4.5)	15.4 (3.7)
FMI (kg/m²)	5.25 (1.06)	4.81 (1.14)	4.90 (1.31)	4.98 (1.14)
VO₂peak (ml/min/kg)	45.5 (4.8)	45.1 (3.9)	44.9 (5.5)	45.2 (4.6)
Habitual physical activity				
Steps(n/d)	9 872 (4 185)	10 819 (5 664)	10 393 (3 999)	10 383 (4 497)
Sedentary (% wear time)	69.8 (8.4)	68.2 (11.7)	66.3 (8.5)	68.0 (9.4)
Light physical activity (% wear time)	26.2 (7.4)	27.2 (12.0)	29.9 (8.3)	27.9 (9.2)
Moderate-to-vigorous physical activity (% wear time)	4.0 (1.9)	4.6 (2.0)	3.8 (2.3)	4.1 (2.0)
Moderate-to-vigorous physical activity (min/week)	260.8 (122.6)	301.7 (153.6)	254.4 (169.3)	272.8 (145.6)
Habitual diet				
Carbohydrate (% energy intake)	41.9 (4.9)	45.6 (5.1)	42.4 (5.9)	43.3 (5.3)
Protein (% energy intake)	17.5 (6.3)	16.5 (3.5)	17.8 (4.0)	17.3 (4.5)
Lipid (% energy intake)	33.7 (4.4)	33.6 (6.4)	36.4 (6.5)	34.6 (5.7)
Binge Eating Scale	6.13 (2.90)	4.75 (5.23)	5.00 (3.30)	5.29 (3.82)
Three-Factor Eating Questionnaire				
Cognitive Restraint (/21)	5.88 (1.13)	6.50 (2.78)	5.75 (1.28)	6.04 (1.83)
Disinhibition (/16)	3.63 (1.60)	3.25 (1.98)	2.38 (1.30)	3.08 (1.67)
Hunger (/14)	3.13 (2.30)	3.50 (2.39)	3.13 (3.09)	3.25 (2.51)

Data are presented as Means (standard deviation). BMI, body mass index; FMI, fat mass index; FFMI, fat-free mass index.

Table 3. LFPQ – Explicit Liking Bias

	Baseline			End of bed rest (Changes)			ETD	Bed rest <i>p</i>	Time × group interactio n	Between-group differences in end-changes from baseline								
	CNT	EX	EX+AG	CNT	EX	EX+AG				EX vs CNT			EX+AG vs CNT			EX+AG vs EX		
										LS means (SE)	95 % CI	<i>p</i>	LS means (SE)	95 % CI	<i>p</i>	LS means (SE)	95 % CI	<i>p</i>
Task 1																		
Carbohydrate	4.9 (5.1)	5.6 (5.1)	11.1 (5.1)	3.9 (4.9)	-5.7 (5.2)	-4.3 (4.9)	-2.0 (2.9)	0.494	0.360	-9.6 (7.2)	-27.7 to 8.5	0.390	-8.2 (7.0)	-25.8 to 9.5	0.483	1.4 (7.2)	-16.7 to 19.6	0.978
Texture	14.3 (6.5)	16.6 (6.5)	13.0 (6.5)	-4.5 (7.6)	-6.9 (7.9)	-0.3 (7.6)	-3.9 (4.4)	0.393	0.830	-2.4 (11.0)	-30.0 to 25.3	0.975	4.2 (10.7)	-22.8 to 31.3	0.917	6.6 (11.0)	-21.1 to 34.2	0.821
Task 2																		
Dairy	0.6 (3.8)	11.4 (3.8)	3.5 (3.8)	-6.3 (5.4)	-2.0 (5.4)	3.0 (5.4)	-1.8 (3.1)	0.572	0.485	4.3 (7.6)	-14.8 to 23.5	0.836	9.3 (7.6)	-9.9 to 28.4	0.453	5.0 (7.6)	-14.2 to 24.1	0.793
Color	7.7 (4.4)	4.7 (4.4)	7.2 (4.4)	-6.4 (5.7)	-1.3 (5.7)	-13.8 (5.7)	-7.2 (3.3)	0.043	0.323	5.1 (8.1)	-15.4 to 25.6	0.807	-7.4 (8.1)	-27.9 to 13.1	0.641	-12.5 (8.1)	-33.0 to 8.0	0.295
Task 3																		
Fat	13.9 (5.8)	19.9 (5.8)	17.4 (5.8)	-8.1 (7.0)	-9.8 (7.0)	0.3 (7.0)	-5.9 (4.0)	0.158	0.560	-1.6 (9.8)	-26.4 to 23.2	0.985	8.4 (9.8)	-16.4 to 33.2	0.676	10.0 (9.8)	-14.8 to 34.8	0.575
Taste	12.7 (7.9)	31.1 (7.9)	12.6 (7.9)	-6.4 (8.2)	-15.8 (8.2)	1.6 (8.2)	-6.9 (4.8)	0.163	0.344	-9.4 (11.6)	-38.8 to 19.9	0.701	8.0 (11.6)	-21.4 to 37.3	0.774	17.4 (11.6)	-11.9 to 46.8	0.313
Task 4																		
Fiber	0.6 (3.9)	3.3 (3.9)	5.7 (3.9)	1.7 (4.5)	-5.7 (4.5)	-2.5 (4.5)	-2.2 (2.6)	0.417	0.518	-7.4 (6.4)	-23.6 to 8.7	0.489	-4.3 (6.4)	-20.4 to 11.9	0.786	3.2 (6.4)	-13.0 to 19.3	0.875
Condiment	-6.5 (5.4)	0.3 (5.4)	0.3 (5.4)	-2.0 (5.5)	2.5 (5.5)	-3.8 (5.5)	-1.1 (3.2)	0.735	0.709	4.5 (7.7)	-15.0 to 24.0	0.829	-1.7 (7.7)	-21.3 to 17.8	0.973	-6.3 (7.7)	-25.8 to 13.3	0.702
Task 5																		
Meat	7.3 (3.6)	12.1 (3.6)	5.2 (3.6)	-0.1 (4.4)	-4.1 (4.4)	4.8 (4.4)	0.2 (2.5)	0.950	0.374	-4.0 (6.2)	-19.7 to 11.6	0.796	4.9 (6.2)	-10.8 to 20.5	0.716	8.9 (6.2)	-6.7 to 24.5	0.343
Fat	12.8 (5.7)	14.6 (5.7)	5.0 (5.7)	-2.8 (5.7)	-6.0 (5.7)	-1.7 (5.7)	-3.5 (3.3)	0.302	0.857	-3.2 (8.0)	-23.5 to 17.1	0.917	1.1 (8.0)	-19.1 to 21.4	0.989	4.3 (8.0)	-15.9 to 24.6	0.853
Task 6																		
Protein	0.6 (2.9)	11.4 (2.9)	3.5 (2.9)	-1.8 (4.1)	-11.6 (4.1)	-5.3 (4.1)	-6.2 (2.3)	0.015	0.25	-9.8 (5.7)	-24.2 to 4.7	0.230	-3.4 (5.7)	-17.9 to 11.0	0.823	6.3 (5.7)	-8.2 to 20.8	0.525
Variation	7.7 (5.3)	4.7 (5.3)	7.2 (5.3)	1.7 (7.5)	-5.9 (7.5)	-2.8 (7.5)	-2.3 (4.4)	0.599	0.780	-7.5 (10.7)	-34.4 to 19.4	0.763	-4.4 (10.7)	-31.3 to 22.5	0.911	3.1 (10.7)	-23.8 to 30.0	0.954

Data are presented as least-square means ± SE from linear mixed models accounting for repeated measurements. CNT, Control; EX, Exercise; EX+AG, exercise and artificial gravity; ETD, Estimated Time Difference.

Table 4. LFPQ – Implicit Wanting Bias

	Baseline			End of bed rest (Changes)			ETD	Bed rest <i>p</i>	Time × group interaction	Between-group differences in end-changes from baseline								
	CNT	EX	EX+AG	CNT	EX	EX+AG				EX vs CNT			EX+AG vs CNT			EX+AG vs EX		
										LS means (SE)	95 % CI	<i>p</i>	LS means (SE)	95 % CI	<i>p</i>	LS means (SE)	95 % CI	<i>p</i>
Task 1																		
Carbohydrate	33.5 (9.9)	21.1 (9.9)	28.2 (9.9)	3.8 (8.5)	-14.1 (9.1)	-6.5 (8.5)	-5.6 (5.0)	0.278	0.371	-17.8 (12.5)	-49.3 to 13.6	0.344	-10.3 (12.1)	-40.9 to 20.3	0.677	7.6 (12.5)	-23.9 to 39.0	0.818
Texture	22.1 (11.8)	26.2 (11.8)	18.6 (11.8)	-6.7 (13.4)	-11.0 (14.0)	18.3 (13.4)	0.2 (7.8)	0.977	0.278	-4.3 (19.4)	-53.2 to 44.6	0.973	25.0 (18.9)	-22.8 to 72.8	0.400	29.3 (19.4)	-19.6 to 78.2	0.307
Task 2																		
Dairy	-0.3 (8.3)	34.9 (8.3)	8.9 (8.3)	-1.4 (9.4)	-13.6 (9.4)	10.8 (9.4)	-1.4 (5.4)	0.801	0.210	-12.2 (13.3)	-45.8 to 21.3	0.634	12.2 (13.3)	-21.4 to 45.7	0.637	24.4 (13.3)	-9.1 to 57.9	0.183
Color	15.7 (11.7)	1.5 (11.7)	-3.4 (11.7)	-2.0 (13.6)	3.0 (13.6)	-16.2 (13.6)	-5.1 (7.9)	0.525	0.591	5.0 (19.2)	-43.5 to 53.5	0.963	-14.3 (19.2)	-62.7 to 34.2	0.742	-19.3 (19.2)	-67.7 to 29.2	0.584
Task 3																		
Fat	22.7 (9.9)	32.5 (9.9)	41.5 (9.9)	5.9 (9.7)	-5.8 (9.7)	-7.2 (9.7)	-2.4 (5.6)	0.676	0.585	-11.7 (13.7)	-46.3 to 22.9	0.675	-13.1 (13.7)	-47.7 to 21.5	0.612	-1.4 (13.7)	-36.0 to 33.2	0.994
Taste	21.0 (12.1)	52.8 (12.1)	26.8 (12.1)	-14.0 (14.0)	-34.2 (14.0)	6.4 (14.0)	-13.9 (8.1)	0.100	0.148	-20.2 (19.8)	-70.1 to 29.7	0.574	20.4 (19.8)	-29.5 to 70.3	0.566	40.6 (19.8)	-9.3 to 90.5	0.125
Task 4																		
Fiber	19.7 (7.6)	17.3 (7.6)	29.8 (7.6)	-11.0 (7.7)	-12.4 (7.7)	-16.7 (7.7)	-13.4 (4.4)	0.007	0.864	-1.4 (10.9)	-28.8 to 26.0	0.991	-5.7 (10.9)	-33.0 to 21.7	0.862	-4.3 (10.9)	-31.6 to 23.1	0.919
Condiment	-15.6 (11.0)	-13.9 (11.0)	-10.6 (11.0)	1.7 (9.2)	13.7 (9.2)	7.4 (9.2)	7.6 (5.3)	0.169	0.663	12.0 (13.1)	-21.0 to 44.9	0.636	5.7 (13.1)	-27.2 to 38.7	0.900	-6.3 (13.1)	-39.2 to 26.7	0.882
Task 5																		
Meat	16.9 (7.5)	21.0 (7.5)	19.2 (7.5)	3.0 (6.4)	-4.7 (6.4)	3.5 (6.4)	0.6 (3.7)	0.879	0.601	-7.7 (9.0)	-30.4 to 15.0	0.673	0.5 (9.0)	-22.2 to 23.2	0.998	8.2 (9.0)	-14.5 to 30.9	0.639
Fat	38.0 (9.8)	19.9 (9.8)	21.8 (9.8)	-6.9 (8.9)	2.1 (8.9)	-8.2 (8.9)	-4.3 (5.1)	0.409	0.673	9.0 (12.5)	-22.6 to 40.6	0.754	-1.3 (12.5)	-32.9 to 30.3	0.994	-10.3 (12.5)	-41.9 to 21.3	0.692
Task 6																		
Protein	-0.3 (7.8)	34.9 (7.8)	8.9 (7.8)	3.6 (11.1)	-28.8 (11.1)	-14.0 (11.1)	-13.1 (6.4)	0.054	0.14	-32.5 (15.7)	-72.0 to 7.1	0.120	-17.6 (15.7)	-57.1 to 21.9	0.511	14.8 (15.7)	-24.7 to 54.4	0.617
Variation	15.7 (12.6)	1.5 (12.6)	-3.4 (12.6)	-3.9 (17.8)	9.0 (17.8)	10.4 (17.8)	5.2 (10.3)	0.620	0.822	12.9 (25.1)	-50.4 to 76.2	0.866	14.3 (25.1)	-49.0 to 77.6	0.837	1.4 (25.1)	-61.9 to 64.7	0.998

Data are presented as least-square means ± SE from linear mixed models accounting for repeated measurements. CNT, Control; EX, Exercise; EX+AG, exercise and artificial gravity; ETD, Estimated Time Difference.

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