



Moderate continuous versus high-intensity interval training on gut dysbiosis and glucagon-like peptide hormone in irritable bowel syndrome

Marwa Saeed Mohamed Mansour Salama^{*1,A-D},
Donia Mohamed El Masry^{1,A,C,E}, Alaa Mohamed El-Moatasem^{1,B-C,E},
Reham Assem Zeyada^{2,B-C,E-F}, Mona Ahmed Mohamed Abouelhassan^{3,B,E},
Nesreen Ghareeb Elnahas^{1,E-F}

¹ Faculty of Physical Therapy Cairo University, Cairo, Egypt

² Faculty of Medicine Cairo University, Cairo, Egypt

* **Corresponding author:** Marwa Saeed Mohamed Mansour Salama; Faculty of Physical Therapy Cairo University, Cairo, Egypt; e-mail: marwasaeed1989@gmail.com

Received: 2025-06-25

Accepted: 2025-11-07

Published: 2026-03-31

- A – Research concept and design
B – Collection and/or assembly of data
C – Data analysis and interpretation
D – Writing the article
E – Critical revision of the article
F – Final approval of article



This is an Open Access journal, all articles are distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0). License (<http://creativecommons.org/licenses/by-nc-sa/4.0/>).

ABSTRACT

Introduction: Regular physical activity is critical in maintaining or restoring gut microbiota equilibrium, potentially ameliorating gut dysbiosis (GD) associated with obesity. Our objective is to evaluate and compare the impacts of moderate-intensity interval training (MICT) and high-intensity interval training (HIIT) on GD and glucagon-like peptide-1 (GLP-1) levels in patients with irritable bowel syndrome (IBS).

Materials and methods: Sixty-six participants diagnosed with IBS of both sexes with a body mass index (BMI) of 30–34.9 kg/m², 30–39 years, prediabetic status and a sedentary lifestyle were randomly and equally assigned into groups A (MICT + low FODMAP diet [LFD]), B (HIIT + LFD) and C (control; LFD only). The intervention lasted for 12 weeks, and training was performed on a treadmill. All groups underwent pre- and post-treatment assessments measuring serum GLP-1 concentrations, faecal short-chain fatty acids (SCFAs), IBS symptom severity (IBS severity scoring system [IBSSS]), quality of life (IBS-QoL questionnaire) and anthropometric parameters, including weight and height.

Results: Significant improvements in BMI, SCFA levels (acetate, propionate and butyrate), IBSSS and IBS-QoL scores (for all $p < 0.001$) were observed in Group A. In contrast, Group B exhibited significant increases in GLP-1 levels compared to the other groups ($p < 0.001$).

Conclusions: Both MICT and HIIT, when combined with an LFD, confer distinct benefits in managing IBS. MICT demonstrated superior effects on reducing BMI, improving SCFA profiles and alleviating symptom severity, while HIIT was more effective in enhancing GLP-1 secretion. These findings support the use of tailored exercise interventions based on individual therapeutic goals in IBS management.

Keywords: irritable bowel syndrome, gut microbiota, glucagon-like peptide-1, exercise therapy, high-intensity interval training

How to cite this article: Salama MSMM, El Masry DM, El-Moatasem AM, Zeyada RA, Abouelhassan MAM, Elnahas NG. Moderate continuous versus high-intensity interval training on gut dysbiosis and glucagon-like peptide hormone in irritable bowel syndrome. Adv Rehab. 2026; 40(1): 69-86. doi: 10.2478/advrehab-2026-0005

INTRODUCTION

The gastrointestinal (GI) tract hosts an intricate and diverse microorganism ecosystem called the gut microbiota (GM), including bacteria, fungi, archaea and viruses. A balanced GM contributes to host health by maintaining epithelial integrity, preventing pathogenic invasion and producing essential micronutrients. Among its metabolic functions, the GM generates short-chain fatty acids (SCFAs), primarily acetate, propionate and butyrate, through anaerobic fermentation of dietary carbohydrates¹⁻³. SCFAs serve as primary energy sources for colonocytes and exert multiple physiological effects, including preservation of intestinal barrier functionality, immunomodulation, anti-inflammatory activity and regulation of appetite through stimulation of satiety hormones, such as leptin, peptide YY (PYY) and glucagon-like peptide-1 (GLP-1). Furthermore, GM influences appetite and satiety through the gut-brain axis, involving vagal nerve signalling and immune-neuroendocrine pathways⁴⁻⁶.

Gut dysbiosis (GD) represents an imbalance in GM composition or function, typically characterised by diminished microbial diversity, loss of beneficial species or overgrowth of pathogenic organism^{7,8}. This disruption is related to heightened ROS production and participates in the development of inflammation, insulin resistance, diabetes, obesity, NAFLD, atherosclerosis, hypothyroidism and irritable bowel syndrome (IBS)^{9,10}. In IBS, GD exacerbates visceral hypersensitivity, mucosal immunity alteration, increased gut permeability and low-grade inflammation, often leading to comorbidities such as fatigue, anxiety and depression¹¹.

Physical activity (PA) has become a potent GM composition and function modulator. Studies demonstrate that physical exercise enhances microbial diversity, particularly associated with cardiorespiratory fitness, promoting SCFA production and improving metabolic and inflammatory profiles^{12,13}. PA exerts beneficial effects on obesity and related metabolic disorders by favourably altering the Firmicutes-to-Bacteroidetes ratio, enhancing gut barrier function and regulating appetite through modulation of GLP-1, PYY and pancreatic polypeptide (PP)^{14,15}. Additionally, exercise regulation reduces systemic inflammation and lipid peroxidation, lowering cardiovascular disease risk and type 2 diabetes¹⁶. Microbial remodelling may be influenced by physiological adaptations induced by endurance exercise, such as altered splanchnic blood flow, transient intestinal hypoxia and changes in gut motility¹⁷. Notably, exercise increases the abundance of butyrate-producing taxa, which are linked to improved colonic epithelial integrity and reduced inflammation. Regular moderate-intensity exercise activates the gut-brain axis, potentially mitigating central sensitisation and visceral pain perception in GI disorders¹⁸. Moreover, PA stimulates the production of metabolites such as N-lactoyl-phenylalanine, which inhibits food intake and body weight gain¹⁹. These mechanisms underpin the concept of 'exercise-induced anorexia', associated with elevated PYY, GLP-1 and PP levels during physical exertion.

Different modalities and intensities of exercise influence microbial metabolism and host physiology²⁰. Exercise intensity, classified based on the maximal heart rate (HR) or VO₂max percentage, significantly affects haemodynamic responses, muscle metabolism, oxidative stress, mood and cognitive function^{21,22}. Both moderate-intensity interval training (MIIT) and high-intensity interval training (HIIT) have been shown to enhance SCFA production, particularly butyrate, which may explain their beneficial effects on GI health and risk reduction in conditions such as IBS and colorectal cancer²³.

Exercise therapy has demonstrated efficacy in managing IBS symptoms²⁴, with outcomes comparable or superior to pharmacological interventions and the low FODMAP diet (LFD)²⁵. Its benefits extend beyond symptom relief to include improvements in psychological well-being, such as reduced anxiety, depression and perceived stress. Given the involvement of the gut–brain axis in IBS pathophysiology, exercise offers a promising, holistic approach with fewer adverse effects²⁶ compared to conventional treatments^{27,28}.

While both MICT and HIIT have been shown to modulate GM and metabolic hormones, direct comparative studies in populations with IBS are scarce. Furthermore, the combined effects of structured exercise and the LFD, which is a cornerstone of IBS management, on gut-derived metabolites such as SCFAs and GLP-1 remain underexplored. To our knowledge, no prior study has simultaneously evaluated the differential impact of MICT versus HIIT on SCFA profiles and GLP-1 levels in obese individuals with IBS. This study aims to fill this gap by comparing the efficacy of MICT and HIIT, both combined with LFD, in modulating GD and metabolic signalling in this high-risk population. We hypothesised that there would be a significant difference between the MICT and HIIT on GD and GLP-1 in IBS.

MATERIALS AND METHODS

Study design

This prospective, randomised, pre-test–post-test controlled trial was conducted between May 2024 and May 2025 on 66 patients with IBS, including 43 women and 23 men aged 30–39 years, enrolled in the Healthy Life Nutrition Outpatient Clinic. All participants received a detailed explanation of the study's purpose, procedures and potential risks, and informed consent was obtained before participation. The Ethical Committee of the Faculty of Physical Therapy authorised the study (Approval No. P.T.REC/012/004224). The study was retrospectively registered on Clinicaltrials.gov (NCT06408610).

Participants

Participants were selected when meeting the following inclusion criteria: fulfillment of the Rome IV diagnostic criteria for IBS, a body mass index (BMI) of 30–34.9 kg/m² (indicative of obesity), age range of 30–39 years, prediabetic status defined by HbA1c levels of 5.7%–6.4% and a sedentary lifestyle, operationalised as fewer than 5000 daily steps measured via pedometer. Obese individuals with IBS were selected for this study due to the high prevalence of metabolic-GI comorbidity in this population. Obesity and IBS share common pathophysiological mechanisms, including GD, low-grade systemic inflammation, impaired gut barrier function and dysregulation of appetite-related hormones such as GLP-1. By focusing on this subgroup, we aimed to evaluate the synergistic effects of structured exercise and dietary intervention on both GI and metabolic outcomes. Furthermore, this population may benefit most from non-pharmacological interventions that simultaneously target weight management and IBS symptomatology²⁹.

Exclusion criteria included recent (within the past 2 months) use of antibiotics or probiotics; GI bleeding; history of colorectal cancer or other terminal diseases; presence of palpable abdominal mass; recent surgery within 6 months; uncontrolled arrhythmia or hypertension; recent myocardial injury; active respiratory infections; current smoking; diagnosis of fibromyalgia or multiple sclerosis; musculoskeletal injuries limiting exercise capacity and communication disorders that could interfere with study compliance.

Randomisation and allocation

Participants were randomly assigned by a blinded, independent research assistant into one of three groups ($n = 22/\text{group}$), Group A (MICT + LFD), Group B (HIIT + LFD) and Group C (control group; LFD only), using computer-generated randomisation cards sealed in opaque envelopes in a ratio of 1:1:1. Once assigned, all participants completed the study protocol without withdrawal (Figure 1).

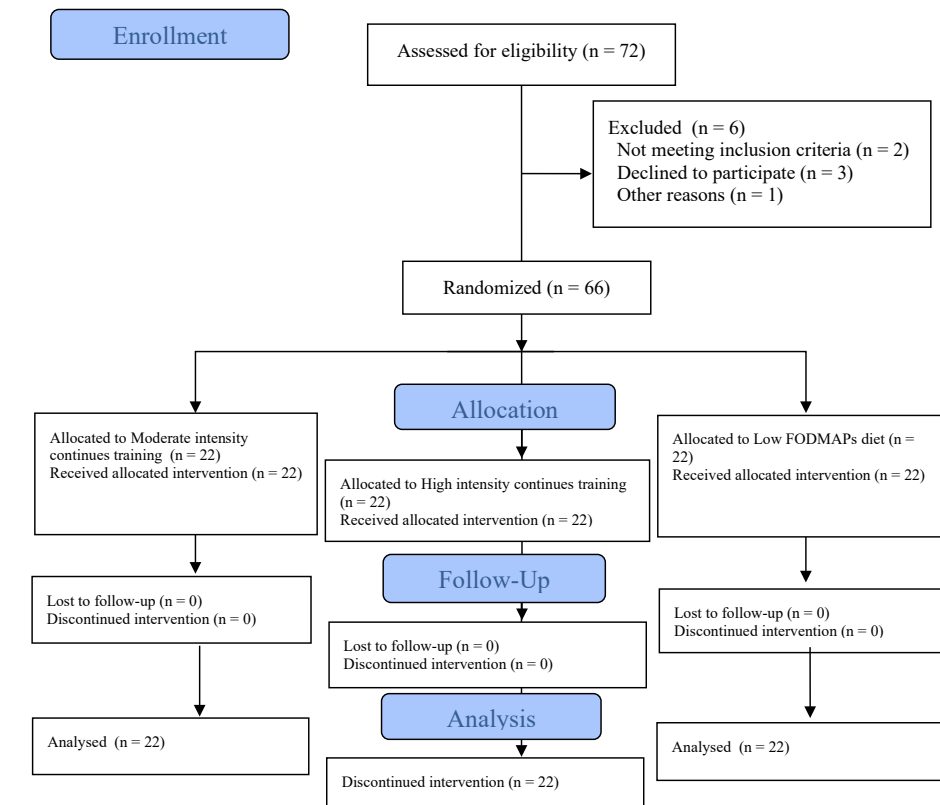


Figure 1. CONSORT flow diagram of participant progress through the trial

Of the 72 individuals assessed for eligibility, 66 were randomised into three groups ($n = 22$ each). All received their allocated interventions with no loss to follow-up or exclusions.

Intervention

Participants were randomly allocated into three groups and assessed pre-and post-intervention. Group A underwent an MICT programme on a treadmill for 12 weeks. Each session lasted 40 minutes, consisting of a 5-minutes warm-up at low intensity, followed by 30 minutes of continuous walking or jogging at 65%–75% of the target HR and concluded with a 5-minutes cool-down period. Participants also adhered to a structured LFD throughout the intervention period. Group B participated in HIIT sessions on a treadmill for 12 weeks. Each session lasted 30 minutes, beginning with 5-minutes warm-up, followed by 10 cycles of 1 minute at 90% of the target HR, interspersed with 1 minute of active recovery at 50% of the target HR (totalling 20 minutes of interval training) and ending with 5-minutes cool-down. Participants also followed the LFD during the study. Group C received

only dietary management in the form of an LFD for the entire 12-week period without any structured exercise intervention.

Primary outcomes

Short-chain fatty acid

Stool faecal samples were gathered and immediately processed for SCFA analysis. Sample preparation involved four analytical steps to ensure proper extraction and quantification. Briefly, faecal specimens were homogenised, centrifuged, filtered and finally derivatised to prepare for injection into a GC-MS system (GC-TSQ Mass Spectrometer, Thermo Scientific, Austin, TX, USA) having a TG-5MS capillary column. Analyses were conducted at Nawah Scientific Laboratories. The three primary SCFAs, acetate, propionate and butyrate, were quantified using internal standard calibration and expressed in $\mu\text{mol/g}$. Standardised techniques and validated predictive approaches were employed throughout the analytical process to ensure the accuracy, reproducibility and comparability of the results across samples.

GLP-1 hormone blood serum level

Blood samples were collected at the Hormonal Unit, Clinical Pathology Department, Kasr Al-Ainy Medical School. Venous blood was drawn into chilled 3-mL EDTA vacutainer tubes containing protease inhibitors to prevent peptide degradation. The serum was separated after allowing the blood to clot for 10–20 minutes at room temperature. Serum GLP-1 concentrations were quantified using a commercially available ELISA kit following the instructions. Briefly, the microplate wells were precoated with a monoclonal antibody specific to human GLP-1. GLP-1 in the serum samples bound to the immobilised antibodies following sample addition. A biotinylated detection antibody against human GLP-1 was introduced and bound to the captured GLP-1 antigen, forming a sandwich complex. Subsequently, Streptavidin-HRP was introduced, binding specifically to the biotinylated detection antibody. After incubation, unbound Streptavidin-HRP was eliminated by washing. A chromogenic substrate solution was added, resulting in a colorimetric reaction proportional to the GLP-1 level in the sample. The enzymatic reaction was terminated using an acidic stop solution, and absorbance was measured at 450 nm using a microplate reader. Standard curves were used to determine GLP-1 concentrations in the serum samples.

Secondary outcomes

IBS Severity Scoring System

The IBS severity scoring system (IBS-SSS) is a validated, five-item questionnaire to assess IBS symptom severity. It evaluates key domains, including abdominal pain frequency and intensity, bloating, satisfaction with bowel habits and the impact of symptoms on daily activities. Each item is scored on a scale of 0–100, with higher scores reflecting greater symptom severity. The total score is calculated by summing all five domain scores, with the following clinical classifications: 75–175 indicating mild IBS, 176–300 indicating moderate IBS and >300 representing severe IBS³⁰.

IBS Quality of Life Questionnaire

The IBS quality of life (IBS-QoL) questionnaire is a validated, disease-specific instrument designed to evaluate IBS impact on health-related QoL and assess

treatment outcomes. The questionnaire comprises 34 items distributed across eight domains: dysphoria, activity interference, body image, health worry, food avoidance, social reaction, sexual functioning and relationship satisfaction. Each item is rated on a 5-point Likert scale ranging from 'not at all' to 'extremely'. Raw scores are calculated by summing responses across all items, then averaged and transformed into a standardised total score of 0–100, with higher values reflecting better IBS-specific QoL³¹.

Weight and height measurements

Height was measured using a manually calibrated wall-mounted stadiometer set at 200 cm from a flat, level surface. Weight and body composition parameters were assessed using a bioelectrical impedance analysis device (InBody 720) at the Healthy Life Nutrition Clinic. The device employs a three-compartment model to estimate body composition by differentiating total body water (including intracellular and extracellular compartments), dry lean mass (comprising protein and mineral content) and adipose tissue. Additional derived indices included BMI, waist-to-hip ratio, fat-free mass index and visceral fat area. These metrics were utilised to assess overall body composition and estimate the relative risk of metabolic and cardiovascular health complications associated with obesity.

Intervention and exercise management

Participants were randomised into either a non-exercise control group (Group C), instructed to follow an LFD only, or one of two supervised exercise training groups. Following randomisation, all participants underwent baseline assessments. Group A engaged in a 12-week MICT programme, while Group B participated in a HIIT regimen of the same duration.

Resting HR was measured in all participants assigned to Groups A and B using a fingertip pulse oximeter (Smart Care FS10A). Measurements were obtained after participants had rested in a seated position for 10 minutes in a quiet, temperature-controlled environment to ensure standardised conditions.

An exercise stress test was conducted using the Stex 8020T treadmill to determine individual exercise tolerance and guide the training intensity prescription before initiating the intervention programme³². Participants were instructed to begin with a 5-minute warm-up phase, followed by a gradual increase in treadmill speed until reaching their maximal exertion level, under direct supervision by a physician. The inability to speak comfortably (talk test) was used as a secondary, supportive indicator of near-maximal exertion but not as the primary criterion. The test was terminated upon reaching maximal HR, volitional exhaustion or physician-determined safety limits. HR was continuously monitored via the treadmill's integrated sensors and cross-verified using the pulse oximeter employed for baseline resting HR measurements. The stress test was performed thrice: once during the initial assessment and twice during re-evaluations. Re-evaluation occurred after 1 month of adherence to the exercise programme, allowing for adjustment of training intensity based on updated performance metrics. All test results were systematically documented in the participants' clinical records for ongoing monitoring and programme modification.

All exercise sessions were supervised by certified physical therapists with expertise in metabolic and GI disorders. Supervision ensured protocol fidelity, safety and real-time HR monitoring. Attendance was recorded for each session,

and adherence was defined as completion of $\geq 80\%$ of scheduled sessions (≥ 29 of 36 sessions over 12 weeks).

While the total session duration differed (40 minutes for MICT vs 30 minutes for HIIT), the design aligns with standard exercise guidelines. MICT included 30 minutes of continuous effort, whereas HIIT involved 10 minutes of high-intensity intervals. This structure reflects the time-efficient nature of HIIT, which has been shown to elicit similar or greater physiological adaptations compared to longer-duration MICT, despite reduced total exercise time³³.

MICT protocol

Frequency: Three sessions per week for 12 weeks, conducted at the Healthy Life Nutrition Clinic using a Stex 8020T treadmill.

Intensity: Exercise intensity was maintained at 65%–75% of the individual's target HR, determined based on baseline assessments.

Duration: Each session lasted 40 minutes: 5-minutes warm-up, 5-minutes cool-down period and 30 minutes of continuous treadmill walking or jogging at the prescribed intensity.

HIIT protocol

Frequency: Three sessions per week for 12 weeks, performed at the Healthy Life Nutrition Clinic using the Stex 8020T treadmill.

Intensity: Each session consisted of 10 cycles of high-intensity intervals (1 minute at 90% of target HR) alternated with 1 minute of active recovery at 50% of target HR.

Duration: Total session time was 30 minutes: 5-minutes warm-up and 5-minutes cool-down period.

LFD Intervention

All 66 participants, regardless of group assignment, followed an LFD as part of the dietary intervention. Each participant received individual counselling and a detailed dietary guide outlining foods to eliminate (including fermentable carbohydrates and dairy products) and suitable alternatives. The elimination phase lasted 6 weeks, after which a reintroduction phase commenced in week 7. During this phase, previously excluded foods were gradually reintroduced into the diet to assess individual tolerance levels and identify specific symptom triggers. Dietary adherence was monitored through weekly dietary logs and bi-weekly counselling sessions with a registered dietitian. Participants recorded all food and beverage intake using a standardised food diary, which was reviewed during counselling to assess compliance with LFD principles. Adherence was defined as $>80\%$ avoidance of high-FODMAP foods during the elimination phase and structured reintroduction during weeks 7–12. Any deviations were discussed, and personalised strategies were provided to improve compliance.

Statistical analysis

Data analysis was performed through SPSS (v25, IBM, Chicago, IL, USA). Categorical variables are reported as frequencies and percentages (n [%]) and compared between groups using the Chi-square test (χ^2) or Fisher's exact test, as appropriate. The sample size was determined using G*Power 3.1.9.7 software, with

the primary outcome being the change in IBS-SSS. With an alpha of 0.05, a power of 0.80 and an effect size of 0.35 (based on previous studies), the required sample size was 18 participants per group. To account for potential dropouts, we recruited 22 participants per group, resulting in a total sample size of 66. We have added this information to the 'Statistical analysis' section for transparency.

The Shapiro–Wilk test was initially performed to assess the normality of continuous variables. Parametric tests were applied based on these findings. Pair *t*-tests were applied to evaluate within-group changes from pre- to post-intervention. Mean differences between baseline and post-intervention values and 95% CI were calculated for each group. Inter-group comparisons across the three study groups were conducted using one-way ANOVA, followed by Tukey's post hoc test for pairwise comparisons when a significant overall effect was detected. A mixed-model repeated-measures ANOVA was employed to determine the interaction effects of time and group assignment throughout the intervention. Effect sizes were estimated using partial eta-squared (η^2), with the following thresholds: small = 0.01, medium = 0.06 and large = 0.14. Statistical tests were two-tailed, with $p < 0.05$ indicating statistical significance.

RESULTS

The participants' baseline demographic and clinical characteristics (Table 1) revealed that the mean age was 34.0 years, with an age range of 30.0– 39.0 years; the majority were female ($n = 43$, 65.2%). At baseline, no significant differences were observed among the groups in age, sex, BMI, SCFAs (acetate, propionate and butyrate), GLP-1 concentrations, IBS-SSS or IBS-QoL scores ($p > 0.05$).

A significant reduction in BMI from pre- to post-intervention was observed in MICT and HIIT groups, with no significant change in the control. Post-intervention, the MICT group demonstrated the greatest decrease in BMI ($\Delta = 2.96 \text{ kg/m}^2$, 9.07%) compared to the HIIT ($\Delta = 3.61\%$) and control groups ($\Delta = 1.68\%$). The BMI did not significantly differ between the HIIT and control groups after intervention. A significant main effect of time ($F = 12.296$, $p < 0.001$, $\eta^2 = 0.281$), treatment ($F = 12.296$, $p < 0.001$, $\eta^2 = 0.281$) and time $\times$ treatment interaction ($F = 12.296$, $p < 0.001$, $\eta^2 = 0.281$) were observed (Figure 2).

The levels of acetate (Figure 3A), propionate (Figure 3B) and butyrate (Figure 3C) significantly diminished from baseline to post-intervention across all groups, with the most pronounced reductions observed in the MICT group (acetate: 18.83%, propionate: 10.42% and butyrate: 25.00%), followed by HIIT (acetate: 14.48%, propionate: 1.25% and butyrate: 17.30%) and control (acetate: 11.36%, propionate: 1.26% and butyrate: 7.81%). Propionate levels did not significantly differ between the HIIT and control groups. Significant main effects of time and treatment were observed for all SCFAs: acetate (time: $F = 4637.447$, $p < 0.001$, $\eta^2 = 0.987$; treatment: $F = 77.478$, $p < 0.001$, $\eta^2 = 0.711$); propionate (time: $F = 116.814$, $p < 0.001$, $\eta^2 = 0.650$; treatment: $F = 73.988$, $p < 0.001$, $\eta^2 = 0.701$) and butyrate (time: $F = 5309.939$, $p < 0.001$, $\eta^2 = 0.988$; treatment: $F = 450.303$, $p < 0.001$, $\eta^2 = 0.935$). Additionally, a significant time $\times$ group interaction was found for each SCFA (acetate: $F = 98.278$, $p < 0.001$, $\eta^2 = 0.757$; propionate: $F = 69.256$, $p < 0.001$, $\eta^2 = 0.687$ and butyrate: $F = 472.515$, $p < 0.001$, $\eta^2 = 0.938$).

Moreover, GLP-1 levels increased significantly from pre- to post-intervention in all groups, with the HIIT group displaying the largest increase (MD = 93.12 pg/mL, 774.71%), followed by the control (MD = 11.80 pg/mL, 92.99%) and MICT group

Table 1. Baseline characteristics of participants in the MICT, HIIT and control groups (*n* = 66)

Variables	Total (<i>n</i> = 66)	MICT group (<i>n</i> = 22)	HIIT group (<i>n</i> = 22)	Control group (<i>n</i> = 22)	Test of significance	<i>p</i> value
Age (Years)	34.00 ± 2.44 30.00–39.00	33.95 ± 2.92 30.00–39.00	34.50 ± 2.35 31.00–38.00	33.55 ± 1.97 30.00–37.00	<i>F</i> = 0.846	0.434
Sex, <i>N</i> (%)					χ^2 = 3.737	0.154
Male	23 (34.8)	5 (22.7)	11 (50.0)	7 (31.8)		
Female	43 (65.2)	17 (77.3)	11 (50.0)	15 (68.2)		
BMI (kg/m ²)	32.48 ± 1.44 30.00–35.00	32.64 ± 1.65 30.00–35.00	32.73 ± 1.39 30.00–35.00	32.09 ± 1.23 30.00–34.00	<i>F</i> = 1.270	0.288
Acetate	32.68 ± 0.19 32.22–32.93	32.71 ± 0.17 32.38–32.93	32.67 ± 0.18 32.38–32.92	32.67 ± 0.21 32.22–32.93	<i>F</i> = 0.260	0.772
Propionate	2.40 ± 0.03 2.32–2.45	2.40 ± 0.03 2.37–2.45	2.40 ± 0.03 2.34–2.43	2.39 ± 0.03 2.32–2.44	<i>F</i> = 1.347	0.267
Butyrate	18.96 ± 0.02 18.93–19.00	18.96 ± 0.02 18.93–19.00	18.96 ± 0.02 18.94–19.00	18.96 ± 0.01 18.94–18.98	<i>F</i> = 1.500	0.231
GLP-1	12.25 ± 2.98 1.21–18.43	12.69 ± 2.51 7.80–18.43	12.02 ± 2.68 7.43–17.34	12.04 ± 3.71 1.21–16.61	<i>F</i> = 0.349	0.706
IBS-SSS	228.36 ± 34.22 175.00–290.00	228.50 ± 38.56 175.00–290.00	226.82 ± 31.38 180.00–280.00	229.77 ± 33.89 175.00–290.00	<i>F</i> = 0.040	0.961
IBS QOL	62.44 ± 7.76 50.00–80.00	62.09 ± 8.40 50.00–75.00	62.27 ± 8.96 50.00–80.00	62.95 ± 5.91 50.00–75.00	<i>F</i> = 0.074	0.929

BMI - body mass index, GLP-1 - glucagon-like peptide-1, HIIT - high-intensity interval training; IBS-QoL - irritable bowel syndrome quality of life questionnaire, IBS-SSS - irritable bowel syndrome severity scoring system, MICT - moderate-intensity interval training.

Continuous data are expressed as mean ± standard deviation (SD) and range, while categorical data are reported as frequencies and percentages (*n* [%]).

χ^2 : Chi-square test. *F*: One-way ANOVA test.

**p* < 0.05.

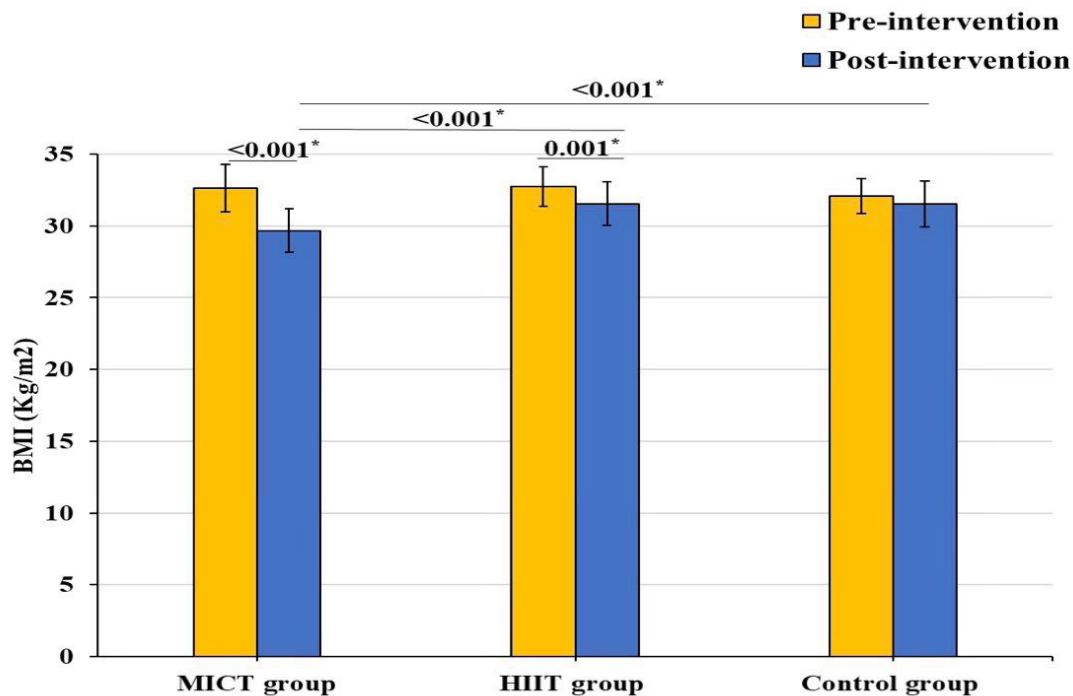


Figure 2. Changes in mean BMI before and after the intervention in the MICT, HIIT and control groups. Values are presented as mean ± SD. *p* < 0.001 indicates statistically significant differences within and between groups. BMI - body mass index, HIIT - high-intensity interval training, MICT - moderate-intensity interval training, SD - standard deviation

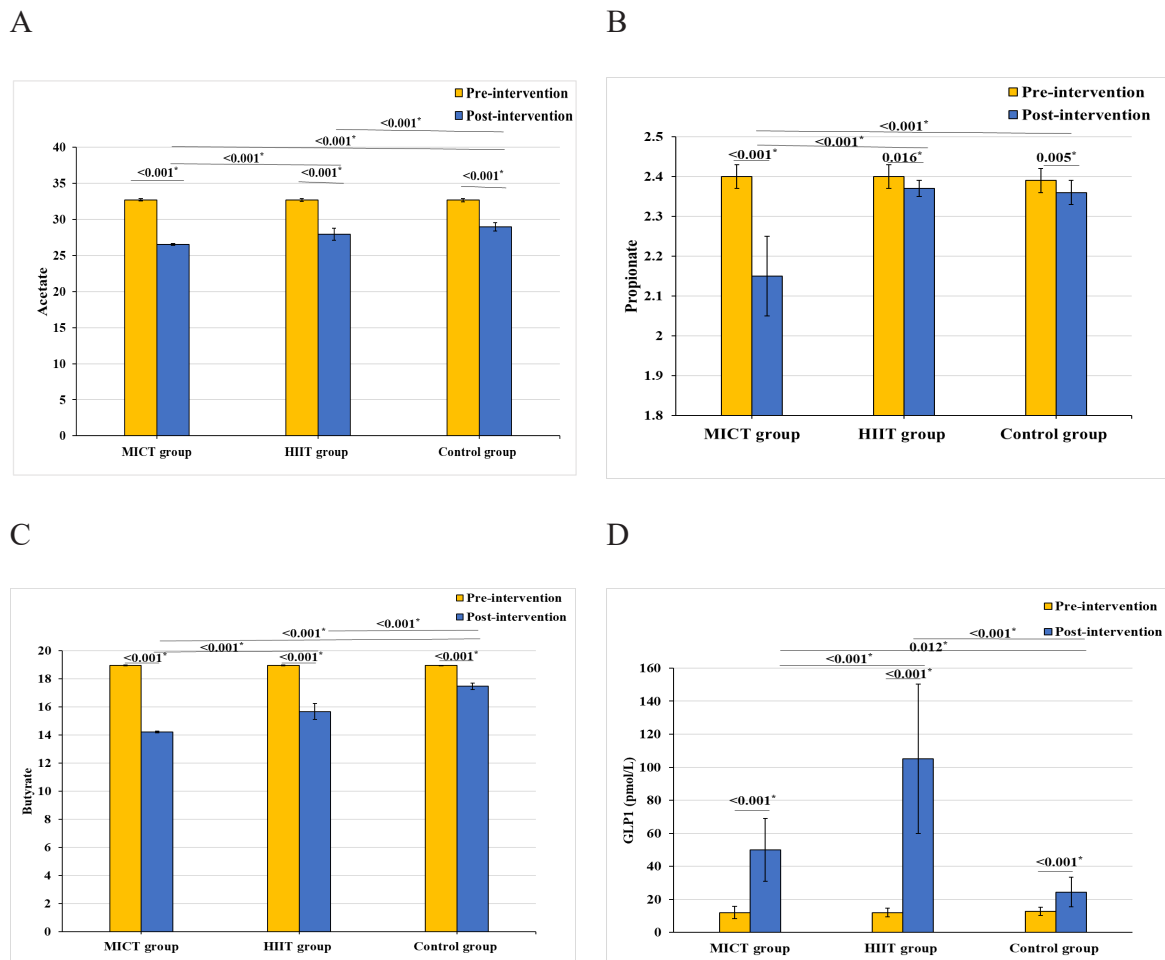
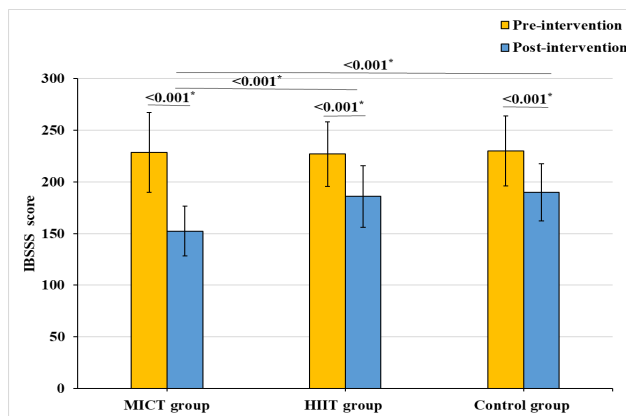


Figure 3. Changes in the mean levels of (A) acetate, (B) propionate, (C) butyrate and (D) GLP-1 before and after the intervention in the MICT, HIIT and control groups. Values are expressed as mean $\pm$ SD. $p < 0.05$ indicates statistically significant differences between pre-and post-intervention values within each group and across groups. GLP-1 - glucagon-like peptide-1, HIIT - high-intensity interval training, MICT - moderate-intensity interval training, SD - standard deviation

(MD = 38.02 pg/mL, 15.78%). Significant main effects of time ($F = 181.021, p < 0.001, \eta^2 = 0.742$), treatment ($F = 43.373, p < 0.001, \eta^2 = 0.281$) and time $\times$ treatment interaction ($F = 45.781, p < 0.001, \eta^2 = 0.592$) were observed (Figure 3D).

IBS symptom severity, assessed via IBS-SSS, significantly improved in all groups post-intervention. The MICT group displayed the greatest improvement (MD = -76.23, 33.36%), followed by HIIT (MD = -40.91, 18.04%) and control (MD = -39.77, 17.32%). Significant main effects of time ($F = 154.000, p < 0.001, \eta^2 = 0.710$), treatment ($F = 3.487, p = 0.037, \eta^2 = 0.100$) and time $\times$ treatment interaction ($F = 8.061, p = 0.001, \eta^2 = 0.204$) were identified (Figure 4A). A significant improvement in IBS-QoL scores from pre- to post-intervention was observed across all groups (Figure 4B). However, there were no significant between-group differences at either time point. Statistical analysis showcased a significant main effect of time ($F = 215.987, p < 0.001, \eta^2 = 0.774$) but no significant effects of group ($F = 0.666, p = 0.517, \eta^2 = 0.021$) or time $\times$ group interaction ($F = 1.554, p = 0.219, \eta^2 = 0.047$).

A



B

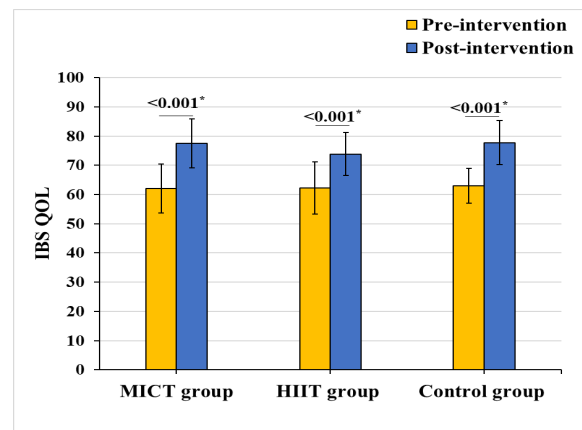


Figure 4. Changes in (A) IBS-SSS and (B) IBS-QOL scores before and after the intervention in the MICT, HIIT and control groups. Values are presented as mean ± SD. $p < 0.001$ for all within-group comparisons (pre- vs post-intervention). HIIT - high-intensity interval training, MICT - moderate-intensity interval training, IBS-QOL - IBS quality of life, IBS-SSS - IBS symptom severity score, SD - standard deviation

DISCUSSION

Alterations in GM composition and function have been implicated in the pathogenesis of various metabolic and inflammatory disorders, including obesity and IBS, primarily through mechanisms involving increased oxidative stress and cellular inflammation³⁴. Recently, PA has emerged as a key modifiable factor that not only promotes general health and reduces stress but also exerts protective effects on GI function, as highlighted by Bianco et al.³⁵. Several studies support the beneficial impact of aerobic exercise on gut microbial diversity. For instance, Dalton et al.³⁶, Varghese et al.¹² and Skrzydło-Radomska et al.³⁷ independently reported that regular aerobic exercise enhances commensal bacterial genera abundance, such as *Bifidobacterium* and *Lactobacillus*, which contribute to gut homeostasis by producing SCFAs and other anti-inflammatory metabolites. However, findings regarding high-intensity or prolonged exercise remain inconsistent. While Gevers et al.³⁸ observed that intense and sustained PA may lead to a microbial profile associated with increased inflammation, Motiani et al.³⁹ demonstrated that intense exercise could paradoxically reduce intestinal inflammation by modulating the GM, potentially improving glucose metabolism and metabolic health. These contrasting results suggest that the impact of exercise on GM composition is intensity-dependent and warrants further investigation to delineate its clinical implications.

Fani et al.⁴⁰ observed a mean reduction in IBS-SSS of 42.3 points after 6 weeks of treadmill exercise, whereas our MICT group showed a significantly greater improvement of 76.23 points over 12 weeks ($p < 0.001$), likely due to the extended intervention period and combined LFD. Similarly, Bianco et al.³⁵ investigated the effects of moderate-intensity aerobic exercise on physical capacity and IBS symptoms in a cohort of 40 patients who engaged in 180 minutes of exercise per week at 60%–75% of their maximum HR. Pre- and post-intervention assessments using the IBS-SSS demonstrated significant reductions in symptom severity and notable improvements in QoL, reinforcing the therapeutic potential of structured aerobic exercise in IBS management. However, Groenendijk et al.⁴¹ highlighted that not all forms of aerobic activity are equally well-tolerated among individuals with

IBS. Some patients reported discomfort associated with high-impact activities such as running and jumping, often avoiding or rescheduling these exercises during periods of mild symptom exacerbation. Vertical movements characteristic of running were perceived by some to provoke abdominal discomfort, particularly if defecation had not occurred beforehand. One participant noted a preference for stair walking over treadmill running due to reduced vertical impact, suggesting that individualised exercise prescriptions may be necessary to optimise adherence and symptom response in IBS populations.

Allen et al.⁴² demonstrated that aerobic exercise over 6 weeks modulated intestinal microbiota composition and SCFA profiles in individuals with obesity, with changes in SCFA levels correlating with improvements in cardiorespiratory fitness (VO_2max). These findings are supported by preclinical evidence showing that aerobic exercise increases faecal SCFA concentrations, as observed in rodent models⁴³, where exercise-induced hypoxia was shown to directly enhance SCFA production. However, the present study observed a significant decrease in faecal SCFA levels following both MICT and HIIT, which appears contradictory to previous reports. This observed reduction in faecal SCFA levels following both exercise interventions, particularly in the MICT group, may reflect improved colonic absorption rather than microbial depletion. In IBS, compromised epithelial integrity often leads to luminal accumulation of SCFAs due to impaired uptake⁴⁴. Exercise-induced enhancement of gut barrier function and mucosal perfusion may restore SCFA absorption, thereby reducing faecal excretion. Additionally, the LFD itself is a major driver of reduced SCFA output, as it restricts FODMAPs necessary for bacterial fermentation⁴⁵. The significant decrease in SCFAs in the control group, which underwent only the LFD, further supports the dominant role of diet in modulating SCFA levels. Thus, the decline in faecal SCFAs in our study may indicate a shift towards improved gut metabolic efficiency and host utilisation, rather than dysbiosis or microbial dysfunction. Farup et al.⁴⁶ reported higher faecal SCFA concentrations in IBS patients compared to healthy controls, attributing this finding to compromised gut barrier integrity, which may lead to increased luminal loss of SCFAs. Further, Duncan et al.⁴⁷ conducted a crossover trial in which 19 obese men followed a calorie-restricted diet for 4 weeks and found a significant reduction in total and individual SCFA concentrations with weight loss, suggesting that dietary and metabolic factors also influence SCFA dynamics. Similarly, Magzal et al.⁴⁸ reported higher faecal SCFA levels in sedentary individuals compared to physically active counterparts, reinforcing the notion that PA may reduce faecal SCFA excretion, potentially reflecting enhanced colonic absorption or microbial metabolism.

Dombrowski et al.⁴⁹ reported average fat mass reductions of 0.91 kg with MICT and 1.38 kg with HIIT after ~12 weeks. In our study, the MICT group achieved a greater BMI reduction ($\Delta = 2.96 \text{ kg/m}^2$, 9.07%) compared to HIIT ($\Delta = 1.18 \text{ kg/m}^2$, 3.61%), despite similar training frequency. This suggests that in the context of IBS and concurrent LFD, continuous aerobic exercise may be more effective for weight management than interval training. These findings align with the results of the present study, which also observed a significant decrease in BMI in both exercise groups compared to the control group. Notably, the greatest clinical improvements in IBS symptom severity and BMI were observed in the MICT group, which also exhibited the largest decline in faecal SCFAs. This inverse relationship suggests that the beneficial effects of exercise may be mediated through mechanisms beyond simple SCFA production, such as enhanced receptor sensitivity (e.g. GPR41/43), improved mitochondrial function in colonocytes or modulation of the gut-brain

axis⁵⁰. Therefore, faecal SCFA levels alone may not be a reliable proxy for gut health in the context of dietary and exercise interventions in IBS. Similarly, Wewege et al.⁵¹ reported that both short-term HIIT and MICT interventions led to comparable, modest improvements in body fat percentage and waist circumference among overweight and obese adults. Given that HIIT achieves similar outcomes to MICT with approximately 40% less weekly time investment, it may serve as a more time-efficient alternative for weight management in clinical populations.

Hu et al.⁵², in a meta-analysis of five studies, reported that both HIIT and MICT increased GLP-1 levels compared to control conditions, but found no significant difference between the two exercise modalities ($p = 0.12$). In contrast, our study demonstrated a significantly greater increase in serum GLP-1 in the HIIT group (MD = 93.12 pg/mL, 774.71%) compared to both the MICT group (MD = 38.02 pg/mL, 15.78%) and the control (MD = 11.80 pg/mL, 92.99%), with a statistically significant between-group difference ($F = 43.373$, $p < 0.001$). This discrepancy may be attributed to the longer intervention duration in our study (12 weeks vs acute or 4-week protocols in prior work), allowing for cumulative physiological adaptations. In contrast, Matos et al.⁵³ reported greater increases in total GLP-1 following MICT compared to HIIT protocols. However, the findings of the present study differ from both of these reports, as a significant increase in serum GLP-1 levels was observed after 12 weeks of HIIT, compared to both the MICT group and the control.

Strengths and limitations

This study has several strengths. First, it employed a randomised controlled design with supervised, standardised exercise protocols, enhancing internal validity. Second, outcome assessments included both subjective (IBS-SSS and IBS-QoL) and objective biomarkers (SCFAs, GLP-1 and BMI), providing a comprehensive evaluation of intervention effects. Third, dietary adherence was monitored through structured counselling and food diaries, improving the reliability of the LFD component. Finally, the use of validated tools and consistent intensity monitoring via HR contributes to the reproducibility of our findings.

Several limitations should be acknowledged. First, the 12-week intervention duration precludes assessment of long-term sustainability. Second, while SCFA levels were measured, we did not assess GM composition (e.g. via 16 S rRNA sequencing), limiting our ability to confirm dysbiosis or microbial remodelling. Third, all participants followed the LFD, which may have confounded the observed effects, as dietary changes independently influence SCFA production and symptom severity. Fourth, the absence of a non-diet, non-exercise placebo group prevents isolation of exercise-specific effects. Finally, maximal effort during stress testing, while guided by HR criteria, did not include direct VO_2 measurement, which may affect precision in intensity prescription.

CONCLUSIONS

While MICT appeared more effective in reducing BMI and IBS symptom severity, and HIIT showed greater increases in GLP-1, these findings should be interpreted with caution due to the absence of microbiota composition data and the confounding effect of the LFD across all groups. The observed changes may reflect synergistic rather than isolated exercise effects. Future studies should incorporate metagenomic sequencing to better characterise microbial remodelling.

FUNDING

This research did not receive any external funding.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

ACKNOWLEDGEMENTS

The authors would like to thank all participants for their commitment and cooperation throughout the study. Gratitude is also extended to the staff of Cairo University Hospitals and the Faculty of Physical Therapy for their support during data collection and intervention implementation.

REFERENCES

1. Hou K, Wu ZX, Chen XY, Wang JQ, Zhang D, Xiao C, et al. Microbiota in health and diseases. *Signal Transduct Target Ther*. 2022;7(1):135. doi: [10.1038/s41392-022-00974-4](https://doi.org/10.1038/s41392-022-00974-4).
2. Colella M, Charitos IA, Ballini A, Cafiero C, Topi S, Palmirotta R, et al. Microbiota revolution: how gut microbes regulate our lives. *World J Gastroenterol*. 2023;29(28):4368–83. doi: [10.3748/wjg.v29.i28.4368](https://doi.org/10.3748/wjg.v29.i28.4368).
3. Kim S, Seo SU, Kweon MN. Gut microbiota-derived metabolites tune host homeostasis fate. *Semin Immunopathol*. 2024;46(1):2. doi: [10.1007/s00281-024-01012-x](https://doi.org/10.1007/s00281-024-01012-x).
4. Zhang D, Jian YP, Zhang YN, Li Y, Gu LT, Sun HH, et al. Short-chain fatty acids in diseases. *Cell Commun Signal*. 2023;21(1):212. doi: [10.1186/s12964-023-01219-9](https://doi.org/10.1186/s12964-023-01219-9).
5. O’Riordan KJ, Collins MK, Moloney GM, Knox EG, Aburto MR, Fülling C, et al. Short chain fatty acids: microbial metabolites for gut-brain axis signalling. *Mol Cell Endocrinol*. 2022;546:111572. doi: [10.1016/j.mce.2022.111572](https://doi.org/10.1016/j.mce.2022.111572).
6. Portincasa P, Bonfrate L, Vacca M, De Angelis M, Farella I, Lanza E, et al. Gut Microbiota and short chain fatty acids: implications in glucose homeostasis. *Int J Mol Sci*. 2022;23(3). doi: [10.3390/ijms23031105](https://doi.org/10.3390/ijms23031105).
7. Hrnčir T. Gut microbiota dysbiosis: triggers, consequences, diagnostic and therapeutic options. *Microorganisms*. 2022;10(3). doi: [10.3390/microorganisms10030578](https://doi.org/10.3390/microorganisms10030578).
8. Wang L, Alammar N, Singh R, Nanavati J, Song Y, Chaudhary R, et al. Gut microbial dysbiosis in the irritable bowel syndrome: a systematic review and meta-analysis of case-control studies. *J Acad Nutr Diet*. 2020;120(4):565–86. doi: [10.1016/j.jand.2019.05.015](https://doi.org/10.1016/j.jand.2019.05.015).
9. Boulos M, Mousa RS, Jeries N, Simaan E, Alam K, Bulus B, et al. Hidden in the fat: unpacking the metabolic tango between metabolic dysfunction-associated steatotic liver disease and metabolic syndrome. *Int J Mol Sci*. 2025;26(7):3448. doi: [10.3390/ijms26073448](https://doi.org/10.3390/ijms26073448).
10. Acevedo-Román A, Pagán-Zayas N, Velázquez-Rivera LI, Torres-Ventura AC, Godoy-Vitorino F. Insights into gut dysbiosis: inflammatory diseases, obesity,

and restoration approaches. *Int J Mol Sci.* 2024;25(17):9715. doi: [10.3390/ijms25179715](https://doi.org/10.3390/ijms25179715).

11. Napolitano M, Fasulo E, Ungaro F, Massimino L, Sinagra E, Danese S, et al. Gut dysbiosis in irritable bowel syndrome: a narrative review on correlation with disease subtypes and novel therapeutic implications. *Microorganisms.* 2023;11(10). doi: [10.3390/microorganisms11102369](https://doi.org/10.3390/microorganisms11102369).
12. Varghese S, Rao S, Khattak A, Zamir F, Chaari A. Physical exercise and the gut microbiome: a bidirectional relationship influencing health and performance. *Nutrients.* 2024;16(21). doi: [10.3390/nu16213663](https://doi.org/10.3390/nu16213663).
13. Cataldi S, Bonavolontà V, Poli L, Clemente FM, De Candia M, Carvutto R, et al. The relationship between physical activity, physical exercise, and human gut microbiota in healthy and unhealthy subjects: a systematic review. *Biology.* 2022;11(3). doi: [10.3390/biology11030479](https://doi.org/10.3390/biology11030479).
14. Aragón-Vela J, Solis-Urra P, Ruiz-Ojeda FJ, Álvarez-Mercado AI, Olivares-Arancibia J, Plaza-Díaz J. Impact of exercise on gut microbiota in obesity. *Nutrients.* 2021;13(11). doi: [10.3390/nu13113999](https://doi.org/10.3390/nu13113999).
15. Bubnov R, Spivak M. Pathophysiology-based individualized use of probiotics and prebiotics for metabolic syndrome: implementing predictive, preventive, and personalized medical approach. *Advances in predictive, preventive and personalised medicine—microbiome in 3P medicine strategies.* Cham: Springer International Publishing; 2023. p. 133–96.
16. Gao C, Wei J, Lu C, Wang L, Dong D, Sun M. A new perspective in intestinal microecology: lifting the veil of exercise regulation of cardiometabolic diseases. *Gut Microbes.* 2024;16(1):2404141. doi: [10.1080/19490976.2024.2404141](https://doi.org/10.1080/19490976.2024.2404141).
17. Ribichini E, Scalese G, Cesarini A, Mocci C, Pallotta N, Severi C, et al. Exercise-induced gastrointestinal symptoms in endurance sports: a review of pathophysiology, symptoms, and nutritional management. *Dietetics.* 2023;2(3):289–307. doi: [10.3390/dietetics2030021](https://doi.org/10.3390/dietetics2030021).
18. Al-Beltagi M, Saeed NK, Bediwy AS, El-Sawaf Y, Elbatarny A, Elbeltagi R. Exploring the gut-exercise link: a systematic review of gastrointestinal disorders in physical activity. *World J Gastroenterol.* 2025;31(22):106835. doi: [10.3748/wjg.v31.i22.106835](https://doi.org/10.3748/wjg.v31.i22.106835).
19. Rojas-Valverde D, Bonilla DA, Gómez-Miranda LM, Calleja-Núñez JJ, Arias N, Martínez-Guardado I. Examining the interaction between exercise, gut microbiota, and neurodegeneration: future research directions. *Biomedicines.* 2023;11(8). doi: [10.3390/biomedicines11082267](https://doi.org/10.3390/biomedicines11082267).
20. Bycura D, Santos AC, Shiffer A, Kyman S, Winfree K, Sutcliffe J, et al. Impact of different exercise modalities on the human gut microbiome. *Sports (Basel).* 2021;9(2). doi: [10.3390/sports9020014](https://doi.org/10.3390/sports9020014).
21. Lavin KM, Coen PM, Baptista LC, Bell MB, Drummer D, Harper SA, et al. State of knowledge on molecular adaptations to exercise in humans: historical perspectives and future directions. *Compr Physiol.* 2022;12(2):3193–279. doi: [10.1002/cphy.c200033](https://doi.org/10.1002/cphy.c200033).
22. Suryani D, Subhan Alfaqih M, Gunadi JW, Sylviana N, Goenawan H, Megantara I, et al. Type, intensity, and duration of exercise as regulator of gut microbiome profile. *Curr Sports Med Rep.* 2022;21(3):84–91. doi: [10.1249/jsr.0000000000000940](https://doi.org/10.1249/jsr.0000000000000940).

23. Han Y, Quan H, Ji W, Tian Q, Liu X, Liu W. Moderate-intensity continuous training and high-intensity interval training alleviate glycolipid metabolism through modulation of gut microbiota and their metabolite SCFAs in diabetic rats. *Biochem Biophys Res Commun*. 2024;735:150831. doi: [10.1016/j.bbrc.2024.150831](https://doi.org/10.1016/j.bbrc.2024.150831).
24. Hailu GN, Gebremariam MM, Meles HA. The role of exercise in alleviating irritable bowel syndrome (IBS) symptoms: addressing diagnostic challenges and management shortcomings. *Egypt J Intern Med*. 2025;37(1):32. doi: [10.1186/s43162-025-00424-x](https://doi.org/10.1186/s43162-025-00424-x).
25. Morariu ID, Avasilcai L, Vieriu M, Lupu VV, Morariu BA, Lupu A, et al. Effects of a low-FODMAP diet on irritable bowel syndrome in both children and adults - a narrative review. *Nutrients*. 2023;15(10). doi: [10.3390/nu15102295](https://doi.org/10.3390/nu15102295).
26. Li C, Li J, Zhou Q, Wang C, Hu J, Liu C. Effects of physical exercise on the microbiota in irritable bowel syndrome. *Nutrients*. 2024;16(16). doi: [10.3390/nu16162657](https://doi.org/10.3390/nu16162657).
27. Jayasinghe M, Karunanayake V, Mohtashim A, Caldera D, Mendis P, Prathiraja O, et al. The role of diet in the management of irritable bowel syndrome: a comprehensive review. *Cureus*. 2024;16(2):e54244. doi: [10.7759/cureus.54244](https://doi.org/10.7759/cureus.54244).
28. Yin Y, Guo Q, Zhou X, Duan Y, Yang Y, Gong S, et al. Role of brain-gut-muscle axis in human health and energy homeostasis. *Front Nutr*. 2022;9:947033. doi: [10.3389/fnut.2022.947033](https://doi.org/10.3389/fnut.2022.947033).
29. Thomas-Dupont P, Velázquez-Soto H, Izaguirre-Hernández IY, Amieva-Balmori M, Triana-Romero A, Islas-Vázquez L, et al. Obesity contributes to inflammation in patients with IBS via complement component 3 and C-reactive protein. *Nutrients*. 2022;14(24). doi: [10.3390/nu14245227](https://doi.org/10.3390/nu14245227).
30. Zeid W, Ezzeldeen E, Khat tab M, Ahmed S, Abdo M. Effect of vitamin D3 (cholecalciferol) supplementation on gastrointestinal symptoms in patients with irritable bowel syndrome attending El-Mahsama family practice center, Ismailia, Egypt: a randomized clinical trial. *Al-Azhar Intern Med J*. 2020;1(7):37–42. doi: [10.21608/aimj.2020.32333.1254](https://doi.org/10.21608/aimj.2020.32333.1254).
31. Hou X, Chen S, Zhang Y, Sha W, Yu X, El sawah H, et al. Quality of life in patients with irritable bowel syndrome (IBS), assessed using the IBS-quality of life (IBS-QOL) measure after 4 and 8 weeks of treatment with mebeverine hydrochloride or pinaverium bromide: results of an international prospective observational cohort study in Poland, Egypt, Mexico and China. *Clin Drug Investig*. 2014;34(11):783–93. doi: [10.1007/s40261-014-0233-y](https://doi.org/10.1007/s40261-014-0233-y).
32. Mytinger M, Nelson RK, Zuhl M. Exercise prescription guidelines for cardiovascular disease patients in the absence of a baseline stress test. *J Cardiovasc Dev Dis*. 2020;7(2):15. doi: [10.3390/jcdd7020015](https://doi.org/10.3390/jcdd7020015).
33. Li Y, Zhao W, Yang Q. Effects of high-intensity interval training and moderate-intensity continuous training on mitochondrial dynamics in human skeletal muscle. *Front Physiol*. 2025;16:1554222. doi: [10.3389/fphys.2025.1554222](https://doi.org/10.3389/fphys.2025.1554222).
34. Mostafavi Abdolmaleky H, Zhou JR. Gut microbiota dysbiosis, oxidative stress, inflammation, and epigenetic alterations in metabolic diseases. *Antioxidants*. 2024;13(8):985. doi: [10.3390/antiox13080985](https://doi.org/10.3390/antiox13080985).
35. Bianco A, Russo F, Franco I, Riezzo G, Donghia R, Curci R, et al. Enhanced physical capacity and gastrointestinal symptom improvement in Southern

- Italian IBS patients following three months of moderate aerobic exercise. *J Clin Med*. 2023;12(21). doi: [10.3390/jcm12216786](https://doi.org/10.3390/jcm12216786).
36. Dalton A, Mermier C, Zuhl M. Exercise influence on the microbiome-gut-brain axis. *Gut Microbes*. 2019;10(5):555–68. doi: [10.1080/19490976.2018.1562268](https://doi.org/10.1080/19490976.2018.1562268).
 37. Skrzydło-Radomańska B, Prozorow-Król B, Cichoż-Lach H, Majsiak E, Bierła JB, Kosikowski W, et al. The Effectiveness of synbiotic preparation containing lactobacillus and bifidobacterium probiotic strains and short chain fructooligosaccharides in patients with diarrhea predominant irritable bowel syndrome - a randomized double-blind, placebo-controlled study. *Nutrients*. 2020;12(7). doi: [10.3390/nu12071999](https://doi.org/10.3390/nu12071999).
 38. Gevers D, Kugathasan S, Denson Lee A, Vázquez-Baeza Y, Van Treuren W, Ren B, et al. The treatment-naïve microbiome in new-onset Crohn's disease. *Cell Host Microbe*. 2014;15(3):382–92. doi: [10.1016/j.chom.2014.02.005](https://doi.org/10.1016/j.chom.2014.02.005).
 39. Motiani KK, Collado MC, Eskelinen JJ, Virtanen KA, Löyttyniemi E, Salminen S, et al. Exercise training modulates gut microbiota profile and improves endotoxemia. *Med Sci Sports Exerc*. 2020;52(1):94–104. doi: [10.1249/mss.0000000000002112](https://doi.org/10.1249/mss.0000000000002112).
 40. Fani M, Mostamand J, Fani M, Chitsaz N, Feizi A. The effect of aerobic exercises among women with mild and moderate irritable bowel syndrome: a pilot study. *J Bodyw Mov Ther*. 2019;23(1):161–5. doi: [10.1016/j.jbmt.2018.02.003](https://doi.org/10.1016/j.jbmt.2018.02.003).
 41. Groenendijk DW, Witterman BJ, Mulder BC. The experiences of female IBS patients concerning physical activity as treatment modality: a qualitative study. *Qual Health Res*. 2022;32(11):1690–700. doi: [10.1177/10497323221110109](https://doi.org/10.1177/10497323221110109).
 42. Allen JM, Mailing LJ, Niemiro GM, Moore R, Cook MD, White BA, et al. Exercise alters gut microbiota composition and function in lean and obese humans. *Med Sci Sports Exerc*. 2018;50(4):747–57. doi: [10.1249/mss.0000000000001495](https://doi.org/10.1249/mss.0000000000001495).
 43. Huang L, Li T, Zhou M, Deng M, Zhang L, Yi L, et al. Hypoxia improves endurance performance by enhancing short chain fatty acids production via gut microbiota remodeling. *Front Microbiol*. 2022;12:820691. doi: [10.3389/fmicb.2021.820691](https://doi.org/10.3389/fmicb.2021.820691).
 44. Chen S, Shen C, Zeng X, Sun L, Luo F, Wan R, et al. Energy metabolism and the intestinal barrier: implications for understanding and managing intestinal diseases. *Front Microbiol*. 2025;16:1515364. doi: [10.3389/fmicb.2025.1515364](https://doi.org/10.3389/fmicb.2025.1515364).
 45. Nikolaki MD, Kasti AN, Katsas K, Petsis K, Lambrinou S, Patsalidou V, et al. The low-FODMAP diet, IBS, and BCFAs: exploring the positive, negative, and less desirable aspects - a literature review. *Microorganisms*. 2023;11(10). doi: [10.3390/microorganisms11102387](https://doi.org/10.3390/microorganisms11102387).
 46. Farup PG, Rudi K, Hestad K. Faecal short-chain fatty acids - a diagnostic biomarker for irritable bowel syndrome? *BMC Gastroenterol*. 2016;16(1):51. doi: [10.1186/s12876-016-0446-z](https://doi.org/10.1186/s12876-016-0446-z).
 47. Duncan SH, Belenguer A, Holtrop G, Johnstone AM, Flint HJ, Lobley GE. Reduced dietary intake of carbohydrates by obese subjects results in decreased concentrations of butyrate and butyrate-producing bacteria in feces. *Appl Environ Microbiol*. 2007;73(4):1073–8. doi: [10.1128/aem.02340-06](https://doi.org/10.1128/aem.02340-06).
 48. Magzal F, Shochat T, Haimov I, Tamir S, Asraf K, Tuchner-Arieli M, et al. Increased physical activity improves gut microbiota composition and reduces

- short-chain fatty acid concentrations in older adults with insomnia. *Sci Rep*. 2022;12(1):2265. doi: [10.1038/s41598-022-05099-w](https://doi.org/10.1038/s41598-022-05099-w).
49. Dombrowski SU, Knittle K, Avenell A, Araújo-Soares V, Sniehotta FF. Long term maintenance of weight loss with non-surgical interventions in obese adults: systematic review and meta-analyses of randomised controlled trials. *BMJ*. 2014;348:g2646. doi: [10.1136/bmj.g2646](https://doi.org/10.1136/bmj.g2646).
 50. Sales KM, Reimer RA. Unlocking a novel determinant of athletic performance: The role of the gut microbiota, short-chain fatty acids, and “biotics” in exercise. *J Sport Health Sci*. 2023;12(1):36–44. doi: [10.1016/j.jshs.2022.09.002](https://doi.org/10.1016/j.jshs.2022.09.002).
 51. Wewege M, van den Berg R, Ward RE, Keech A. The effects of high-intensity interval training vs. moderate-intensity continuous training on body composition in overweight and obese adults: a systematic review and meta-analysis. *Obes Rev*. 2017;18(6):635–46. doi: [10.1111/obr.12532](https://doi.org/10.1111/obr.12532).
 52. Hu M, Kong Z, Shi Q, Nie J. Acute effect of high-intensity interval training versus moderate-intensity continuous training on appetite-regulating gut hormones in healthy adults: a systematic review and meta-analysis. *Heliyon*. 2023;9(2):e13129. doi: [10.1016/j.heliyon.2023.e13129](https://doi.org/10.1016/j.heliyon.2023.e13129).
 53. Matos VA, Souza DC, Santos VO, Medeiros ÍF, Browne RA, Nascimento PR, et al. Acute effects of high-intensity interval and moderate-intensity continuous exercise on GLP-1, appetite and energy intake in obese men: A crossover trial. *Nutrients*. 2018;10(7):889. doi: [10.3390/nu10070889](https://doi.org/10.3390/nu10070889).