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The Role of the Gut Microbiome in Exercise-Induced Inflammation and Recovery: A Narrative Review

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Abstract

Background

Exercise-induced inflammation is a complex physiological response influenced by both the intensity of physical activity and the gut microbiome. While moderate exercise enhances immune function and microbial diversity, excessive training can lead to gut dysbiosis, increased intestinal permeability, and chronic inflammation.

Objective

This review examines the interplay between the gut microbiome, exercise-induced inflammation, and recovery. It explores the mechanisms by which gut microbes influence immune regulation, metabolic adaptation, and muscle repair, while also identifying potential nutritional strategies to optimize gut health and enhance post-exercise recovery.

Results

Findings suggest that moderate exercise enhances microbial diversity and promotes an anti-inflammatory immune profile. Conversely, excessive training induces gut dysbiosis, increases intestinal permeability and elevates inflammatory cytokines. Nutritional interventions, particularly probiotic and prebiotic supplementation, polyphenol-rich foods, dietary fiber, and omega-3 fatty acids, have been shown to mitigate gut permeability, enhance SCFA production, and accelerate immune recovery.

Conclusion

The gut microbiome plays a critical role in regulating exercise-induced inflammation and recovery, influencing immune responses, metabolic efficiency, and muscle repair. Integrating microbiome-targeted nutritional strategies may optimize gut health, enhance recovery, and improve overall athletic performance. Future research should explore personalized microbiome-based interventions, considering individual variability in microbiota composition, training load, and dietary habits.
Keywords: gut microbiome, exercise-induced inflammation, short-chain fatty acids, dysbiosis, athletic recovery, sport performance

Introduction

Exercise-induced inflammation is a complex physiological response that results from both acute and chronic physical activity (Peake et al., 2017). While moderate exercise has anti-inflammatory benefits, intense and prolonged exercise can cause excessive oxidative stress, immune activation, and muscle damage (Scheffer & Latini, 2020). Recently, the gut microbiome has emerged as a key regulator of exercise-induced inflammation and recovery (Clauss et al., 2021). This review explores the interactions between the gut microbiota, exercise, inflammation, and recovery processes, shedding light on potential therapeutic interventions.

Methodology

Study Design

This review follows a systematic approach to synthesizing existing research on the relationship between the gut microbiome, exercise-induced inflammation, and recovery. A qualitative synthesis of peer-reviewed studies, systematic reviews, and meta-analyses published in the last two decades was conducted. The review focuses on the physiological and immunological mechanisms linking the gut microbiome to inflammation and recovery in athletes.

Search Strategy

A comprehensive literature search was performed using electronic databases, including PubMed, Scopus, Web of Science, and Google Scholar. The search was conducted to identify studies published between 2000 and 2025, with an emphasis on human-based research. The following search terms and Boolean operators were used to refine results: ("gut microbiome" OR "intestinal microbiota" OR "gut bacteria" OR "microbiome composition") AND ("exercise" OR "physical activity" OR "training" OR "endurance training" OR "resistance training") AND ("inflammation" OR "immune response" OR "oxidative stress" OR "cytokines" OR "immune modulation") AND ("recovery" OR "muscle repair" OR "post-exercise adaptation" OR "immune reconstitution") AND ("probiotics" OR "prebiotics" OR "short-chain fatty acids" OR "SCFAs" OR "dietary interventions") AND ("gut permeability" OR "intestinal barrier" OR "leaky gut") AND (human OR "athletes" OR "physically active individuals") NOT (animal OR mice OR rat).

Additional references were identified through backward citation tracking of key systematic reviews and meta-analyses.

Inclusion and Exclusion Criteria

Inclusion Criteria:

- Peer-reviewed studies investigating the effects of exercise on gut microbiome composition, inflammation, and recovery;
- Research involving human participants, particularly athletes or physically active individuals;
- Studies assessing microbial diversity, short-chain fatty acids (SCFAs), inflammatory markers (TNF-α, IL-6, IL-1β, CRP), and gut permeability;
- Studies utilizing validated microbiome analysis techniques, including 16S rRNA sequencing, metagenomics, and metabolomics;
- Nutritional intervention studies examining probiotics, prebiotics, polyphenols, dietary fiber, and omega-3 fatty acids in relation to gut microbiota and exercise recovery;
- Studies published in English between 2000 and 2025.

Exclusion Criteria:

- Studies conducted solely on animal models without human validation;
- Research focusing on sedentary populations or clinical conditions unrelated to exercise;
- Studies lacking microbiome sequencing or inflammatory marker assessments;
- Non-peer-reviewed literature, case studies, or conference abstracts without full methodological details;
- Articles that do not clearly define the relationship between the gut microbiome, exercise-induced inflammation, and recovery.

Data Extraction and Analysis

Key data were extracted from eligible studies, including:

- **Study characteristics**: Author(s), year, sample size, participant characteristics (age, sex, fitness level);
- **Methodology**: Study design (e.g., cross-sectional, longitudinal, randomized controlled trial), microbiome assessment methods (e.g., 16S rRNA sequencing, shotgun metagenomics), and inflammatory biomarker analysis;
- **Key findings**: Effects of exercise on gut microbiota composition, inflammation, recovery mechanisms, and nutritional strategies influencing gut health and immune response.

A qualitative synthesis was performed to identify trends, inconsistencies, and knowledge gaps across studies. Studies were categorized based on the type of exercise (endurance, resistance, high-intensity training), microbiome changes, inflammatory markers, and recovery outcomes. Methodological differences across studies were critically analyzed to assess reliability and validity.

Ethical Considerations

As this study is a literature review, it does not involve direct human or animal research and does not require ethical approval. However, all referenced studies were screened to ensure adherence to ethical research practices, as indicated by institutional review board (IRB) approvals in the original studies.

Limitations of Methodology

Several limitations should be considered in this review. The variability in microbiome assessment methods and differences in exercise protocols across studies may introduce inconsistencies. Individual differences in gut microbiota composition, dietary habits, genetic predisposition, and training status further contribute to variability in findings. Additionally, most research on gut microbiome and exercise has been conducted on male athletes, with limited data on female athletes, which may affect generalizability. Future research should aim for standardized protocols, larger sample sizes, and sex-specific analyses to enhance the applicability of findings.

The Gut Microbiome and Its Role in Systemic Inflammation

Dysbiosis and Systemic Inflammation

The gut microbiome is a complex and dynamic ecosystem composed of trillions of bacteria, fungi, and viruses that play a crucial role in immune regulation and overall systemic homeostasis (Adak & Khan, 2019). Emerging research highlights its significant role in inflammation, particularly in the context of dysbiosis—a disruption in microbial composition that can contribute to immune dysregulation (Vargas et al., 2025).

One of the primary mechanisms by which dysbiosis promotes systemic inflammation is by compromising intestinal permeability, thereby weakening the gut epithelial barrier—an essential defense system that prevents harmful microbial components from translocating into circulation (Chakaroun et al., 2020; Tariq et al., 2025). When this barrier becomes compromised, a condition commonly referred to as leaky gut develops, allowing microbial fragments such as lipopolysaccharides (LPS)—endotoxins derived from Gram-negative bacterial cell walls—to enter the bloodstream (Fukui, 2016). LPS activates immune receptors such as Toll-like receptor 4 (TLR4), leading to a persistent low-grade inflammatory response known as metabolic endotoxemia (Ghosh et al., 2020). This chronic immune activation is a major driver of inflammatory disorders, including metabolic syndrome, obesity, type 2 diabetes, cardiovascular diseases, and autoimmune conditions (Candelli et al., 2021; Massier et al., 2021).

The Role of Short-Chain Fatty Acids (SCFAs)

Another key mechanism through which gut microbiome exerts profound effects on immune homeostasis is through the production of short-chain fatty acids (SCFAs). These beneficial metabolites—butyrate, acetate, and propionate—are generated through bacterial fermentation of dietary fiber and are crucial for maintaining gut barrier integrity and immune regulation (Vargas et al., 2025). Butyrate, in particular, serves as a primary energy source for intestinal epithelial cells, reinforcing tight junction proteins and reducing gut permeability, thereby preventing endotoxin translocation into circulation (Chakaroun et al., 2020).

Moreover, SCFAs possess potent anti-inflammatory properties, as they promote the differentiation of regulatory T cells (Tregs)—key players in immune tolerance and inflammation control—while simultaneously suppressing the production of pro-inflammatory cytokines such as tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6), and interleukin-1β (IL-1β) (Massier et al., 2021; Mohammad & Thiemermann, 2021)

Dysbiosis-Induced Immune Dysregulation

In a state of dysbiosis, SCFA production declines, leading to gut barrier dysfunction, increased permeability, and systemic inflammation (Fukui, 2016). The altered microbial environment disrupts the balance of pro- and anti-inflammatory cytokines, skewing immune responses toward chronic inflammation. Gut microbes also modulate the function of key immune cells, such as macrophages and dendritic cells, which coordinate host defense mechanisms. Under healthy conditions, these immune cells are primed to maintain tolerance and suppress unnecessary inflammation (Candelli et al., 2021). However, in dysbiotic states, the shift toward a pro-inflammatory phenotype results in excessive cytokine signaling, further exacerbating chronic inflammatory diseases (Ghosh et al., 2020).

Exercise-Induced Inflammation and the Gut Microbiome

Exercise-induced inflammation is a complex physiological response that plays a dual role in both tissue repair and immune modulation. Physical exertion, especially intense or prolonged exercise, induces muscle microtrauma and cellular stress, activating the immune system and leading to a transient inflammatory response (Pedersen & Hoffman-Goetz, 2000). This process is mediated by the release of pro-inflammatory cytokines, including tumor necrosis factor-alpha (TNF-α), interleukin-1β (IL-1β), and interleukin-6 (IL-6), which mobilize immune cells such as neutrophils and macrophages to the site of tissue damage (Suzuki et al., 2020). Interestingly, IL-6 acts paradoxically—initially promoting inflammation but later exerting anti-inflammatory effects by stimulating the release of interleukin-10 (IL-10) and cortisol, which suppress excessive immune activation (Freidenreich & Volek, 2012; Scheffer & Latini, 2020). Exercise-induced inflammation also influences systemic immunity, altering the function of natural killer (NK) cells, T-cells, and monocytes, which enhances immune surveillance but can also lead to immune suppression if excessive training is performed without adequate recovery (Allen et al., 2015). Chronic moderate-intensity exercise is known to reduce basal inflammation, making it a key factor in preventing inflammatory diseases such as cardiovascular disease, diabetes, and neurodegenerative disorders (Madani et al., 2018). However, excessive training, particularly in endurance athletes, can induce immune suppression and increased infection risk, emphasizing the importance of periodized training and proper recovery strategies (Rossi et al., 2018; Shephard, 2011). The dynamic interplay between pro- and anti-inflammatory responses highlights the adaptive nature of exercise-induced inflammation, where the body fine-tunes immune function for optimal health and performance.

Additionally, exercise affects the gut-immune axis, as alterations in the gut microbiome have been linked to systemic inflammatory responses and post-exercise immune adaptation (Goh et al., 2014). While moderate physical activity is associated with increased microbial diversity and anti-inflammatory effects, excessive or prolonged exercise can induce gut dysbiosis and intestinal permeability, commonly known as "leaky gut" (Bennett et al., 2020). This process is mediated by key inflammatory markers such as tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6), interleukin-1β (IL-1β), and C-reactive protein (CRP) (Peake et al., 2017). Exercise influences key inflammatory markers, with TNF-α increasing after prolonged high-intensity activity, whereas moderate exercise lowers baseline TNF-α, reducing chronic inflammation risk (Fukui, 2016; Scheffer & Latini, 2020). IL-6 spikes acutely during exercise to mobilize energy but can contribute to chronic inflammation and immune suppression if persistently elevated (Candelli et al., 2021; Ghosh et al., 2020). IL-1β, linked to gut permeability, is commonly elevated in endurance athletes, increasing the risk of conditions like IBS and IBD (Massier et al., 2021). CRP, a systemic inflammation marker, is reduced by long-term moderate exercise but rises with excessive training, indicating systemic stress (Mohammad & Thiemermann, 2021).

Exercise-induced systemic inflammation is closely linked to gut microbiota composition. High-intensity endurance training has been shown to reduce levels of beneficial bacteria such as *Faecalibacterium prausnitzii* and *Akkermansia muciniphila*, which are known for their anti-inflammatory properties and role in gut barrier integrity (Peake et al., 2017). This dysbiosis contributes to increased gut permeability, allowing endotoxins such as lipopolysaccharide (LPS) to enter circulation, leading to metabolic endotoxemia—a condition where chronic low-grade inflammation is sustained by immune activation (Fukui, 2016).

On the other hand, moderate exercise enhances microbial diversity, increasing the production of short-chain fatty acids (SCFAs) such as butyrate, acetate, and propionate, which strengthen the gut barrier and suppress inflammatory responses (Scheffer & Latini, 2020). Studies suggest that physically active individuals exhibit a higher abundance of SCFA-producing bacteria, which contribute to the reduction of pro-inflammatory markers and improve immune regulation (Candelli et al., 2021).

The Gut Microbiome in Exercise Recovery

The gut microbiome plays a crucial role in exercise recovery, modulating inflammation, immune response, and metabolic processes essential for muscle repair and performance adaptation. The interaction between gut microbiota and post-exercise recovery is primarily mediated through short-chain fatty acids (SCFAs), gut barrier integrity, and immune signaling pathways (Carmichael et al., 2024; Mohr et al., 2020).

Exercise, especially prolonged or high-intensity training, induces transient immune dysfunction and systemic inflammation due to increased gut permeability and microbial translocation. This effect has been linked to the elevated release of inflammatory cytokines such as TNF-α, IL-6, and IL-1β, which may impair recovery when chronically elevated (Miranda-Comas et al., 2022). However, SCFA-producing bacteria, such as *Faecalibacterium prausnitzii* and *Akkermansia muciniphila*, contribute to immune modulation by reducing inflammation and promoting gut barrier integrity (Carmichael et al., 2024; Mohr et al., 2020).

SCFAs—butyrate, acetate, and propionate—are microbial metabolites that play a significant role in recovery. Butyrate enhances gut epithelial integrity, reducing intestinal permeability and the risk of endotoxin translocation, while propionate and acetate influence metabolic pathways associated with energy homeostasis and muscle repair (Carmichael et al., 2024; Mohr et al., 2020).

In addition to reducing inflammation, the gut microbiome supports energy metabolism critical for recovery. SCFAs enhance insulin sensitivity and glucose uptake, facilitating muscle glycogen replenishment post-exercise. Furthermore, the microbiota modulates amino acid metabolism, particularly branched-chain amino acids (BCAAs), which are vital for muscle protein synthesis and reducing fatigue. (Mohr et al., 2020)

Long-term exposure to exercise shapes the gut microbiome, favoring a more diverse and resilient microbial composition. Studies have shown that physically active individuals, particularly endurance athletes, exhibit higher levels of beneficial bacterial species, such as *Veillonella*, which metabolizes lactate into SCFAs, potentially improving exercise tolerance and recovery efficiency (Petersen et al., 2017). However, excessive training without sufficient recovery may lead to dysbiosis, compromising gut integrity and prolonging inflammation (Mohr et al., 2020).

Nutritional Strategies to Optimize Gut Microbiome and Recovery

Nutritional strategies play a fundamental role in optimizing gut microbiome health and enhancing exercise recovery. Prebiotics and probiotics, commonly found in fermented foods like yogurt, kefir, and kimchi, support gut barrier integrity and microbial diversity, which are crucial in immune regulation and mitigating exercise-induced gut permeability. Probiotic supplementation has been identified as a potential tool for optimizing recovery, particularly in endurance athletes prone to gut dysbiosis. Probiotics such as *Lactococcus lactis* and *Lactobacillus plantarum* have been shown to restore gut microbiota balance, strengthen mucosal immunity, and mitigate exercise-induced inflammation. Moreover, athletes who consume probiotics report faster post-exercise immune reconstitution, improved energy metabolism, and reduced muscle soreness (Miranda-Comas et al., 2022).

Polyphenol-rich foods, such as blueberries, green tea, and dark chocolate, have been shown to maintain gut microbiota balance and improve gut barrier function, which leads to a reduction in pro-inflammatory cytokines like TNF-α and IL-6. These compounds enhance short-chain fatty acid (SCFA) production, supporting immune recovery and reducing oxidative stress following strenuous exercise (Chen et al., 2024).

Dietary fiber from whole grains, fruits, and legumes is a key driver of SCFA production, particularly butyrate, which reinforces intestinal epithelial integrity and reduces systemic inflammation associated with intense physical activity. Athletes with high-fiber diets exhibit greater microbiome resilience, lower oxidative stress, and faster metabolic recovery (Clauss et al., 2021).

Omega-3 fatty acids, primarily from fish oil, play a crucial role in modulating gut microbiota composition and mitigating inflammation associated with exercise. Studies show that omega-3 supplementation increases beneficial bacteria such as Akkermansia muciniphila, which strengthens gut barrier function, reduces gut permeability, and enhances muscle recovery (Jäger et al., 2025).

Collectively, integrating prebiotics, probiotics, polyphenols, fiber, and omega-3s into an athlete's diet optimizes gut microbiome composition, strengthens immune defenses, reduces inflammation, and enhances metabolic efficiency. These dietary interventions are particularly beneficial for athletes aiming to maximize performance and accelerate post-exercise recovery (Akbari-Fakhrabadi et al., 2024).

Discussion

The growing body of research highlights the critical role of the gut microbiome in mediating exercise-induced inflammation and recovery. However, several questions remain regarding the precise mechanisms through which microbial communities interact with the immune and metabolic systems during and after exercise. Future studies should explore individualized responses to exercise and diet, considering factors such as genetic predisposition, training intensity, and dietary habits.

One of the key challenges in this field is distinguishing between beneficial exercise-induced inflammation necessary for adaptation and excessive inflammation that leads to chronic immune activation and impaired recovery. While current evidence suggests that SCFA-producing bacteria play a protective role, more research is needed to determine the most effective dietary and probiotic strategies for athletes across different sports and training regimens. Additionally, long-term studies are necessary to assess whether targeted microbiome interventions can sustain performance benefits and reduce the risk of inflammation-related disorders.

Another consideration is the potential influence of environmental and lifestyle factors, including stress, sleep, and antibiotic use, on gut microbiome composition and exercise recovery. Understanding the broader lifestyle context may provide more comprehensive strategies for optimizing gut health in athletes.

Overall, this review underscores the importance of gut microbiota in exercise physiology and highlights the need for further interdisciplinary research to translate these findings into practical applications for athletes and physically active individuals. By integrating microbiome-focused strategies with personalized training and nutrition programs, it may be possible to enhance exercise recovery, reduce inflammation, and improve overall health outcomes.

Conclusion

The interplay between exercise-induced inflammation, gut microbiome composition, and recovery is a complex yet crucial aspect of athletic performance and overall health. While moderate exercise enhances microbial diversity and anti-inflammatory responses, excessive training can lead to dysbiosis, increased gut permeability, and chronic inflammation. Gut-derived metabolites, particularly short-chain fatty acids (SCFAs), help regulate immune function, support gut barrier integrity, and promote recovery. Nutritional strategies, including probiotics, prebiotics, polyphenols, fiber, and omega-3 fatty acids, can optimize gut health, reduce inflammation, and enhance post-exercise recovery. Further research is needed to refine microbiome-based interventions for improving athletic performance and overall health.

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Conceptualization: SD, WK;

Methodology: SD, AB;

Software: n/a; check: SD, AB, WK;

Formal analysis: SD, AK, KSz;

Investigation: SD, AB, WK, AK, KSz;

Resources: SD, KSz, RT, MM;

Data curation: AB, WK, MM, AK, ABy;

Writing - rough preparation: SD, RT, KSz, Aby, WD;

Writing - review and editing: SD, AB, AK, MM, WD;

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