Chapter

The Interaction between Dietary Components, Gut Microbiome, and Endurance Performance

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Abstract

Research so far indicates that gut microbiome and diet interactions influence obesity, diabetes, host immunity, and brain function. The ability of athletes to perform to optimum for a more extended time, as well as the ability to resist, withstand, recover from, and have immunity to fatigue, injury depends on the genetic factor, age, sex, training history, psychological factors, mode, intensity and frequency of training and their interactions with the external dietary components. However, recent evidence indicates that the gut microbiome may also potentially influence the development of endurance in response to the type and composition of the external diet, including several food supplements. Thus, the gut microbiome has become another target in the athlete's pursuit of optimal performance. This chapter discusses the effect of exercise on the gut microbiome, the interplay between dietary components and supplements on the gut microbiome, and its impact on endurance performance.

Keywords: Diet, Gut, Endurance

1. Introduction

Endurance exercises can be defined as prolonged exercises like running, cycling, cross-county skiing, aerobics and swimming, often involving resistance [1]. Endurance exercises require systemic and muscle-based physiological and biochemical responses to complete the endurance activity [2]. The athletes expose their bodies beyond their physiological circumstances, which affect the homeostasis, overwhelming normal tissue function [3]. Prolonged physical exercise will force body to defend against the events that will result in the synthesis of proteins, releasing of hormone, changes in body fluid as well as metabolic balance [4]. In order to adapt toward the endurance exercise, an individual should improve his mechanical, neuromuscular, metabolic and contractile functions in muscle, rebalance of electrolytes and decrease in glycogen storage [5]. Furthermore, endurance exercise will cause muscle damage, alterations in intestinal permeability, systematic inflammation, immune response and oxidative stress in the athletes [6]. Excessive exercise will effect the blood flow, resulting in loss of fluids and electrolytes. The body will start synthesizing glucocorticoids and adrenaline hormones to re-establish homeostasis [7].

Human gut microbiota act as an endocrine organ and plays a significant role in energy harvesting, nutrient uptake, vitamin synthesis, modulation of inflammatory, host immune response etc. Several intrinsic and extrinsic factor effect the gut microbiota, which will lead to dysbiosis. Some factors include diet, lifestyle, environment, antibiotic use, age and birth delivery route. Recent findings reported that exercise induced changes in gut microbiota, through mechanisms not well-understood results modifications in metabolism, physiology, immunity and behavior in host [8]. Dysbiosis depends on the intensity, types and timing of excessive exercise [9]. Human gut microbiota also influences muscle mass and aging of the body. Studies reported the reduction of microflora in gut microbiota having anti-inflammatory and proanabolic effects [10]. To adapt to the excessive physical load and increased energy consumptions, individuals performing excessive exercise e.g. athletes, should balance gut microbiota composition, which can only be done by adopting good dietary habits and using sports nutritional supplements. Gut microbiota plays significant role in the wellbeing, health and sports performance in athletes [11]. This chapter, discusses the effect of exercise on the gut microbiome, the interplay between dietary components and supplements on the gut microbiome, and its impact on endurance performance.

2. Gut Microbiota

Gut microbiota refers to specific microbial population in the gut that includes the bacterial and viral origin and is considered as non-pathogenic [12]. Gut microbiota coordinately works with the immune system of the host, to protect from pathogen colonization and invasion. Gut microbiota act as a good source of essential nutrients and vitamins, also help in the extraction of nutrients, including vitamins and SCFA from food. In the end, host depends on its intestinal microbiota, and intestinal microbiota contribute to the host's health [13]. The interplay between gut microbiota and host physiology influences the metabolic phenotype, stress response of the host. Further, the equilibrium between the microbial diversity is is essential maintain the host homeostasis including energy metabolism, oxidative stress, hydration status, immunity response, systematic inflammatory response and brain-gut axis [14]. The dysbiosis in the gut microbiota may contribute to the onset of chronic conditions including inflammatory and irritable bowel diseases, gastrointestinal symptoms linked to exercise, colorectal cancer, obesity, diabetes, metabolic syndrome, allergy, depression, anxiety [15]. The factors that influence host intestinal microbiota are genetic, lifestyle including physical activities, diet and environmental factor [9]. Physical activity is linked to specific markers of intestinal health [16–18]. Some of the evidence suggests that exercise positively influence the gut microbial community, which is beneficial to the host [19].

2.1 Effect of diet on gut microbiota

The human diet is very complex, where foods are not consumed separately, and nutrients are act synergistically. Hence, the dietary patterns are considered the key element of human health. Dietary habits includes the diet variety, nutrient adequacy, intake of healthy food, and considerable amount of less healthy foods [15, 20]. Changes in dietary habits leads to change in the GM. GM since diet has a significant role in determining the composition of GM [21, 22]. Alternative or mismanagement in dietary patterns may harm the population of healthy microorganisms in GM. Researchers have identified that prevailing dietary patterns in US, European and Asian populations, may have a risk of diabetes and obesity [23, 24]. *Bifidobacteria*, *Clostridium* and *Bacteroidetes* decreases due to low carbohydrate diet as carbohydrate is the source of energy for these microbes [25, 26] studies have found that intake of dietary fiber in the diet increases the short chain fatty acid (SCFA) producing bacteria in the GM. The western diet rich in animal protein and fat showed a significant reduction in gut microbiota diversity due to the low amount of dietary fibers [27]. The mediterranean diet includes intake of various polyphenol rich fruits, herbs and vegetables which lower down the risk of metabolic diseases especially diabetes and obesity [28]. Intake of a high protein diet leads to increased *Bacteroidetes*, *Lactobacillus*, *Bifidobacteria* which will benefit the host for metabolism, immune system and nervous system [29]. Keto diet will lead to Dysmicrobism because microbiota need carbohydrates as a source of energy [30]. Intake of high-fat diet will result in impairments in colonic epithelial integrity and barrier function due to the decrease in *Bacteroidetes* and *Firmicutes* [31].

2.2 Effect of endurance performance on gut microbiota

The effect of excessive exercise on human gut microbiota compositions depends on several factors like body fat, age, diet, timing, training status of the particular subjects. Effect of exercise start early in life. Physical activities promote increases in *Bacteroidetes* and decreases in the *Firmicutes* phylum in the gut of young than in adults, also increases in lean body mass through the adaptation of host metabolism [32, 33]. Several have reported that microbial population altered by exercise favour the development of the brain [9]. Several pieces of evidence reveal the present of diverse microflora in an athlete, with an abundance of *Bacteroidetes, Akkermansia, Veillonellaceae, Prevotella,* and *Methanobevibacter* [32]. A higher amount of *Prevotella* and *Methanobrevibacter smithii* were found in professional as compared to amateur cyclists. This microflora is known to involve in carbohydrate and energy metabolism in the human body [34, 35]. Overweight adults, following a fiber and whole-grain-rich diet for six weeks, the presence of *Prevotella* abundance predictive of weight loss, suggesting that enterotype should be considered in personalized nutritional strategies to counteract obesity [36, 37]. One of the studies shows the difference of microflora between active and sedentary Women. Active women have a higher amount of health-promoting bacterial species, including *Akkermansia muciniphila, Roseburia hominis, Faecalibacterium prausnitzii* and *Coprococcus* genus [38, 39]. *Akkermansia muciniphila* is a mucin degrading bacteria that protects the intestinal lumen, and its levels are, negatively associated with metabolic disorder in pateints with inflammatory bowel diseases [40, 41]. In addition, exercise has shown positive impact on the gut mucus layer, which is an essential substrate for the mucosa-associated bacteria e.g. *Akkermansia muciniphila. Roseburia hominis* and *Faecalibacterium prausnitzii* were known to produce butyrate, showing a positive impact on intestinal function and metabolism of lipid, thereby having anti-inflammatory properties [42]. Other studies have also reported the abundance of *Coprococcus* genus in active women [32]. One of the study conducted between lean and obese adults performing endurance exercise under proper dietary control reveal the abundance of butyrate producing taxa in lean adults as compared to the obese adults [43]. Similar studies reported by Galle, (2019), showed the abundant of *Faecalibacterium* sp. in lean adults compared to obese adults [44]. This study confirmed the influence of BMI in gut microbiota. Thereby normalizing the BMI, age and diet can have a beneficial effect on individuals, by increasing butyrate producing taxa.

Recently, it was reported that *Veillonella* is a performance enhancing microbe known to utilize lactate and produce propionate [45]. Similar studies reported that lactate can be converted into propionate by the *Veillonella* [46]. Thus the production of SCFA by gut microbiota will promote health benefits toward the host during exercise, thereby contributing to exercise-induced adaptation. The SCFA produce by the microbiota fermentation will later act as an energy source for the liver and muscle cells, thereby improving endurance performance. Moreover, it is needed to balance the gut microbiota composition over time.

3. Dysbiosis of gut microbiota during endurance performance

The dysbiosis in the GM is linked to various pathophysiological conditions such as intestinal disorders (inflammatory bowel disease, coeliac disease, irritable bowel disease) and extra-intestinal disorders (allergy, metabolic syndrome, asthma, cardiovascular disease, obesity, oxidative stress) [47]. The beneficial bacteria play an essential role in controlling the fermentation and absorption of dietary nutrients such as SCFAs [48]. The dysbiosis in the microbiota influences the development of disease which involved the pivotal mutualistic relationship between colonic microbiota, their metabolic product and the host immune system. Recent evidence has implicated the influence of excessive exercise on GM dysbiosis [49]. Studies in mice found that excessive exercise negatively impacts immunity, substance and energy metabolism, and gut microbial diversity [50].

Generally, it is believed that exercise is beneficial for the gut, but athletes with regular training and exercise have been reported to experience gastrointestinal disorders termed exercise-induced gastrointestinal syndrome. The frequency of developing the syndrome depends on numerous factors like sport type, the intensity of exercise, gender and syndrome often observed: loose stool, diarrhea, abdominal pain, intestinal bleeding in the lower digestive tract [51, 52]. There are two pathways suggested as causative for this disorder: Circulatory- gastrointestinal pathway and neuroendocrine-gastrointestinal pathway. In Circulatory-gastrointestinal pathway, high intensity exercise cause gut ischemia–reperfusion, which is a factor associated with site specific oxidative stress intestinal injury and in Neuroendocrine-gastrointestinal pathway, both physical and psychological stresses alter the gut motility and transit through enteric nervous activity which causes gut malabsorption of nutrients [53–55]. Studies found that intense endurance running (triathletes) lead to malabsorption of carbohydrates [27]. Evidence suggests that female endurance runners had a higher abundance of inflammation related bacteria and a higher concentration of succinate in the intestinal lumen due to dysbiosis, thus affecting the endurance performance [56].

3.1 Energy metabolism

During endurance exercise, energy availability is the essential limiting factor, and restoring the cellular energy homoeostasis is a must. There is a complex relationship between gut microbiota and host's energy metabolism. Gut microbiota increases the ability to harvest the energythe energy from digested food, thereby producing metabolites and microbial products (SCFA, secondary bile acids, and lipopolysaccharides). These microbial products will later modulate appetite, energy uptake and storage, gut motility and energy expenditure [57]. Healthy gut microbiota can exert positive effects in athletes. One of the studies reported that physical exercise and associated dietary adaptation are linked with changes in the gut microbial diversity [58]. Supplementation of probiotic bacteria *Lactobacillus plantarum* TWK10 improves energy metabolism. It transports the host fatty acid to the organ via bloodstream, further metabolized in the mitochondria to generate energy [59].

3.2 Immune response

During endurance exercise, immune response activation plays an important role. Some evidence suggests that, prolonged periods of intense exercise suppress the immune response, including monocyte, granulocyte, leukocyte count, and serum immunoglobulin levels among individuals [60]. Intense exercise training increased the number of pro-inflammatory cytokines, also anti-inflammatory modulator, intestinal lymphocytes. These will lead to the fluctuation of gut microbiota diversity and in their secreted metabolites, increase hyperthermia, gastrointestinal permeability, destruction of gut mucous membrane thickness and weakens the activity of antioxidant enzymes [61]. Studies found that strenuous exercise suppresses the lymphocytes proliferation, levels of secretory IgA in saliva and modulates the synthesis of inflammatory cytokines [62]. Studies suggest that monitoring the gut microbiota diversity and modulating it by the supplementation of probiotics and prebiotics will be more cost effective compared to the utilization of drugs [63].

3.3 Oxidative stress

During endurance exercise, oxygen consumption increases which will cause disturbance in intracellular pro-oxidant-antioxidant homeostasis [64]. Modulations of oxidative and nitrative stress can control tissue damage, bacterial translocation and intestinal permeability. Enzymatic and nonenzymatic antioxidant protect excessive oxidative damage, and therefore, consumption of antioxidant would be a beneficial to control the oxidative damage [65]. The relationship between gut microbiota and controlling GI redox is still not clear. Some data found that *Lactobacillus* and *Bifidobacterium* levels are negatively correlated with oxidative stress, while the *Escherichia coli* population is positively correlated with oxidative stress [66]. Study in mice, found that higher levels of *Bacteroidetes* protect against intestinal infection by supressing pro-inflammatory and pro-oxidant responses [67].

3.4 Dehydration status

During endurance exercise, an increased in fluid loss from sweating will lead to dehydration [68]. One of the main functions of mucosal epithelial cells is transportation of electrolyte. For proper functioning and protection of intestinal barrier, proper water transport and mucosal hydration are necessary [69]. During excessive exercise, studies found that healthy gut microbiota can maintain proper hydration and will prevent inflammatory response. Evidence suggest that activation of Cl- secretion alters the colonic inner mucus layer which lead to the increased in abundance of *Firmicutes* phylum and *Alistipes* genera [70]. In order to obtain a good hydration state and protect intestinal barrier in athletes, it became necessary to understand the role gut microbiota on water transport, diet and mucus intestinal layer.

4. Diet modulation of gut microbiota in athletes

Dietary changes are the most significant factor in altering gut microbiota both in infancy and in adulthood. Recently, it has been found that probiotics, polyphenols, prebiotics and antibiotics can modulate the gut microbiota community [71]. Many evidence have been reported, how probiotics, prebiotics alter the gut microbiota population which will benefit individuals suffering from metabolic disorder, gut permeability, inflammation, immune system and energy metabolism [14, 72].

Probiotics are food supplements that contained a live microorganism (Lactic acid bacteria), which confer a health benefits a health benefit for the host [73]. Many probiotics products are available in the markets like fermented milk and yogurt, etc. [74]. Consuming probiotics has a positive effect gut microbiota's population which will influences the immune function as well as intestinal epithelium cell proliferation, function and protection in the athletes. Various double-blind clinical trials, cross-over pilot studies show that supplementation of probiotic bacteria can modulate the gut microbiota and have a beneficial effect on the individual with regular exercise training (listed in **Table 1**).

The effect of probiotic bacteria in athletes has been reported and assists athletes with respiratory and gastrointestinal disorders during the specific training periods. However, the effects of prebiotics are not being studied in athletes. Many researchers reported the specific type of dietary components can do a measurable change in gut microbiota composition thereby increasing the levels of *Lactobacilli* and *Bifidobacteria* and many butyrate producing bacteria. The increase in *Lactobacilli* and *Bifidobacteria* can influence the immune functions, intestinal epithelium cell proliferation and protect individuals from oxidative stress induced due to the exercise [82]. Some of the studies reported that supplementation of polyphenol increased health promoting microbiota *Lactobacillus, Bifidobacterium,* and decreased pathogenic species *Clostridium* [83]. Roopchand [84] reported that polyphenols obtained from grape promote the growth of the gut bacterium *Akkermansia muciniphila* resulting in lower intestinal and systemic inflammation and improved metabolic system. These reported data can be a promised toward the various functional foods can regulate gut microbiome community, their structure and function

Exercise	Experimental design	Supplementation of Probiotic bacteria	Effect on GM	Remarks	References
Endurance trained men (triathletes, runners, cyclists)	Randomized, double-blinded, placebo controlled trial	*Bifidobacterium bifidum* W23, *Bifidobacterium lactis* W51, *Enterococcus faecium* W54, *Lactobacillus acidophilus* W22, *Lactobacillus brevis* W63, and *Lactococcus lactis* W58	—	Beneficially affected TNF-α and exercise induced protein oxidation	[75]
Athletes	Random trial	*L. rhamnosus* IMC 501® and *L. paracasei* IMC 502®	—	Increase antioxidant levels and neutralize the effects of reactive oxygen species.	[76]
Endurance Athletes	Randomized, double blind crossover study	*Lactobacillus Salivarius* (UCC118)	—	Attenuates exercise-induced intestinal hyperpermeability	[77]
Endurance Exercise (Swimming)	Random study	*Lactobacillus salivarius*	—	Improve muscle strength and endurance performance, increased hepatic and muscular glycogen storage, and decreased lactate, blood urea nitrogen (BUN), ammonia, and creatine kinase (CK) levels after exercise	[78]

Exercise	Experimental design	Supplementation of Probiotic bacteria	Effect on GM	Remarks	References
Treadmill exercise	Double-blind placebo-controlled clinical study.	*L. plantarum* TWK10	—	Physiological adaptation and health benefits for amateur runners	[59]
Treadmill exercise	Double-blind, placebo-controlled, crossover trial	*Lactobacillus fermentum* VRI-003	—	Enhance the mucosal immune system of elite athletes	[79]
Triathlon-high-intensity exercise	Double-blind experimental design	*Lactobacillus plantarum* PS128	**Decreases:** *Anaerotruncus*, *Caproiciproducens*, *Coprobacillus*, *Desulfovibrio*, *Dielma*, *Family_ XIII*, *Holdemania*, and *Oxalobacter*) **Increases:** *Akkermansia*, *Bifidobacterium*, *Butyricimonas*, and *Lactobacillus*	Ameliorate inflammation and oxidative stress, with improved exercise performance	[80]
Endurance exercise	Cross-over pilot study	SymbioLactComp® (*Lactobacillus paracasei*, *Lactobacillus acidophilus*, *Lactococcus lactis* and *Bifidobacterium animalis* subsp. *lactis*)	**Increase:** *Akkermansia muciniphila*, *Faecalibacterium prausnitzii*, *Bifidobacterium* spp.	Prevent intestinal or immune disorders	[81]

Table 1.
Effect of probiotics in trained individuals.

which will directly or indirectly contribute toward the health and performance of athletes. Also, protein diet supplementation, increased *Akkermansia muciniphila,* thereby influence host immunity and host metabolism in athletes [51].

5. Conclusion

Endurance exercise requires a considerable amount of energy, and when this energy cannot maintain a stable supply, it will lead to fatigue and reduce exercise performance. Endurance exercise has a profound impact on oxidative stress, intestinal permeability, muscle damage, systemic inflammation and immune response, dehydration. Gut microbiota promotes digestion and absorption of food to produce energy in host, thereby playing a great role on athlete's energy consumption and exercise performance. There is a close interaction between exercise, microbiota and diet (**Figure 1**), the details warrant comprehensive investigations. Exercise, the proportion, timing and composition of the diet modulates the gut microbiota diversity. Better understanding, the impact of diet on gut microbiota and how gut microbiota respond to exercise, a nutritional strategy can be developed to modulate the gut microbiota diversity which can lead to enhanced the athlete's overall performance and health.

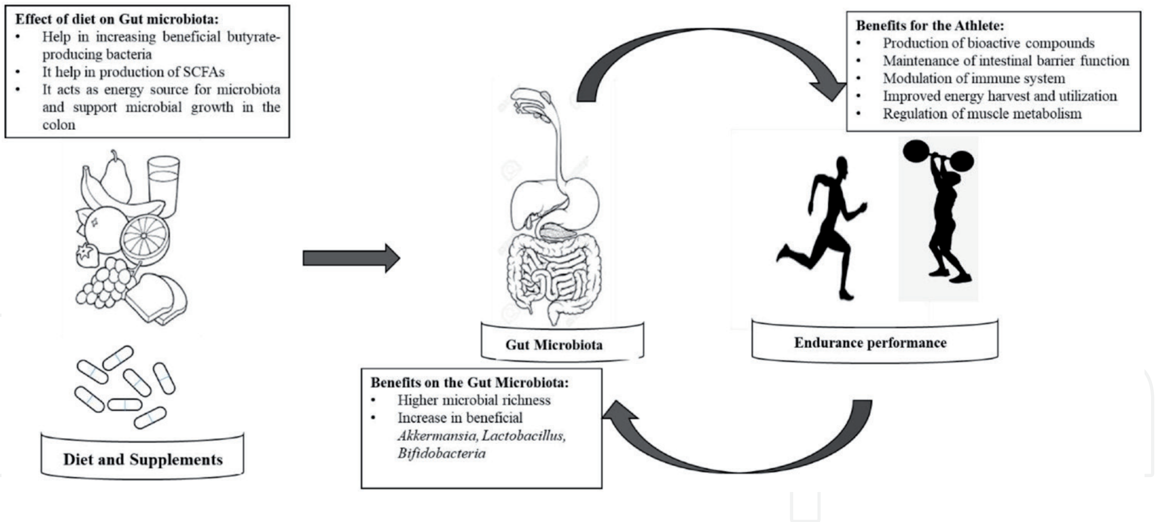

Figure 1.
Interaction between dietary components, gut microbiome, and endurance performance.

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Declaration of interests

We declare no competing interests.

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