Elite sports and the gut microbiome

The potential of the gut microbiome in an elite athlete

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Abstract

Elite athletes undergo rigorous training and adhere to specialized diets aimed at optimizing performance, often prioritizing carbohydrate loading, high protein intake, and certain performance enhancing supplementation. However, intense exercise can lead to gastrointestinal issues and alterations in gut permeability, leading to risks to an athlete's health. Strategies to prevent gastrointestinal issues include dietary interventions such as dark chocolate consumption and Konjac glucomannan supplementation.
Despite this, research suggests that exercise positively impacts the gut microbiome, with certain bacterial species correlating with improved athletic performance. This thesis explores the relationship between elite sports performance and the gut microbiome, investigating how dietary habits, exercise regimes, and microbial composition intersect to influence athlete health and performance. Furthermore, the potential of probiotics, postbiotics, and butyrate-producing bacteria to enhance athletic performance by modulating the gut microbiome is discussed.

KEYWORDS:

microbiome composition, aerobic fitness, sports performance, athletes, butyrate, dietary interventions, intestinal-permeability, gastrointestinal issues

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1. Introduction/background

Elite sports and gut health

Elite athletes follow a strict training and diet plan to optimize their performance and eventually their race/match results. It is known that diet and exercise have an influence on the gut microbiome, so it might be helpful to investigate the gut microbiome in relation to elite sports. The extraordinary lifestyle may not be optimal for gut microbiome health, which in turn may lead to other health risks and possibly even performance drops. Even minor health issues may reduce the performance levels of elite athletes and it may deprive them of victories, as race decision margins can be very narrow in elite level sports.

What is the relation between exercise and gut microbiome health in an elite athlete and could certain gut microbiome compositions optimize an athlete's performance? And do the performance gains of certain nutrition strategies of endurance athletes always outweigh the toll that it takes on gut health?

Gut microbiome

Our human body hosts a lot of microorganisms that live inside our body, but also reside on the surface of our body. The complex community of micro-organisms known as the gut microbiota resides in the digestive tracts of both humans and other animals, including insects (Gomaa, 2020).
The quantity and composition of the human microbiota differs along the digestive tract; the stomach and the small intestine host a relatively low amount of microbial species, whereas the colon contains a microbial ecosystem where every gram of intestinal substance contains up to 10^{12} microbial cells. The organisms that live in the gut may belong to all three branches of the tree of life: *Archaea, Eukarya and Bacteria* (Milani, 2017). Most of the microorganisms are bacteria and almost all (99%) that reside in the gut are anaerobes, but in the cecum, a higher number of aerobic microbes can be found. Most of the gut microbes play a crucial role in maintaining a normal (gut) physiology and health. The gut microbiome affects health primarily by playing a relevant role in the development of immunity and in the regulation of specific fundamental metabolic pathways (Bibbò, 2016). A disturbance in this composition of the gut microbiome, a dysbiosis, can lead to several diseases, such as inflammatory bowel diseases (IBD), cardiovascular disease, allergies, autoimmune diseases, diabetes and obesity (Gomaa, 2020)(Bibbò, 2016).

Gut microbiome compositions differ between individuals due to genetic factors, environmental factors and the diet.(Bibbò, 2016). The role of diet on gut microbiota has seen an increased interest by the scientific community in the last years, but the role of (elite) sports on the gut microbiota is less well understood. In this thesis the role of sports on the gut microbiota is further investigated, but the role of the gut microbiota on the athletic performance of an individual will also be looked into. Gut microbiota might play a bigger role in the performance of an athlete than we currently understand. In the world of (elite) sports the role of the diet and the athletic performance is very well documented, but the gut microbiota might be an overlooked component in the relationship between diet and sports performances.

It is also known that the gut microbiota composition can improve human health, but less is known about the possible positive effects of the microbial composition on athletic performances.

Extreme amount of exercise

This thesis focuses on sports in which cardiovascular endurance and muscle strength play a significant role.

Endurance exercise is mostly performed at a submaximal intensity, with the goal of raising the anaerobic threshold (= the start of anaerobic metabolism and lactate production, when exercising at a high intensity). This eventually leads to a better athlete's performance, because below the anaerobic threshold, so aerobically, ATP is produced in a more efficient way. This shift in anaerobic threshold occurs through complex alterations in muscle metabolism, with increased mitochondrial density and oxidative enzymes (= the machinery necessary for energy production), shifts in muscle fiber types and an increase in capillarization of muscle fibers (Morici, 2016).

For aerobic exercise, the respiratory and cardiovascular systems must be perfectly synchronized in order to give the muscles the energy they need to work. An increase in cardiac output is necessary for the cardiovascular system to supply the participating skeletal muscles with more arterial blood (and oxygen) and to constantly remove metabolic waste (such carbon dioxide or lactate) generated by the muscles that are contracted (Morici, 2016).

These sports, characterized by an increased respiration and heart rate when performed, are beneficial for an individual's health. Occasionally performing endurance sports can strengthen the heart, lungs, and circulatory system. Additionally, they can postpone or even prevent a number of illnesses that are prevalent in the elderly, including diabetes, cardiovascular diseases and cancer (NIA, 2021).

However, performing endurance sports too frequently or at a very high intensity and volume, can lead to health risks. One case of this was investigated by Morici et al.. They found that intense aerobic exercise induces mild epithelial injury and inflammation in the airways (Morici, 2016). In non-elite/recreational athletes this does not seem to negatively impact the airway cells or bronchial reactivity, but in elite athletes this seems to cause problems. The elite athletes showed a higher susceptibility to development of asthma, which is possibly related to exposures to allergens or poor conditioning of inspired air. This phenomenon is called 'sports asthma' and is an example of a case where elite sports form a possible health risk.

The increase in cardiac output that is seen during exercise may also cause potential health risks. The increase in blood flow can have major consequences for the digestive system, including ischemia in the gut, because of the blood flow redistribution (Clauss, 2021). This redistribution of blood can lead to both upper- and lower gastrointestinal disorders. Gastro-intestinal problems that occur during and after an ultra-endurance exercise are related to gut ischaemia-associated leakage of lipopolysaccharide into the circulation (Jeukendrup, 2000). This in combination with muscle tissue damage, leads to an increased

cytokine response, which causes various body responses and these gastro-intestinal problems.These disorders and potential health risks highlight the importance of a normal functioning of the digestive tract and its microbiota on athletic performance in endurance sports.

Extraordinary diet of elite athletes

In sports where athletes are required to make muscle repetitions for a prolonged time, such as running, cycling, swimming and rowing, a certain dietary habits are needed for optimal performance. An elite athlete's lifestyle differs from one of an average person. In an optimal situation, all lifestyle choices of an athlete are directed to optimizing one's performance. Nutrition plays a key role in the life of an athlete and is an important factor in fueling the athlete's body during exercise, but also plays a big role in recovery and growth of for example muscle tissue.

Carbohydrate loading and low fiber diets
One example of an extraordinary dietary habit of elite endurance athletes is carbohydrate loading. To prepare for race efforts, athletes 'load' carbohydrates to store muscle glycogen. The amount of carbohydrates that needs to be eaten, depends on the length of the race effort, but according to a study performed by Burke et. al, race runners should eat 7-10 gr of carbohydrates per kg of body mass in 24 hours before <90 minute races (Burke, 2019). For longer races, the amount of carbohydrates per kg of body mass that need to be consumed, can go up to 13 gr. This high-carbohydrate diet often lacks fiber and can be seen as a low-fiber diet. This helps to prevent gut problems before and during the race and also leads to a small reduction in body mass. Losing body mass by having a low-fiber diet prior to a race/match can be particularly helpful in sports where body weight plays an important role, for example in sports with weight divisions, such as boxing and rowing (Reale, 2017).

High protein intake
Elite athletes not only consume more carbohydrates than an average human, they also require a higher protein intake than the Recommended Daily Allowance (RDA) of 0,8g/kg/day in order to improve performance and training adaptation (Vitale, 2019). A sufficient protein intake and timing of intake is crucial to any athlete; both endurance exercise and resistance exercise regimes should include a high protein diet. The American College of Sports Medicine (ACSM) recommends an intake of 1,2-2,0/kg/day for elite athletes. Depending on individual demands, endurance athletes should consume in the lower range and strength and power athletes should consume in the upper range. An additional benefit may be provided to the athlete when protein is consumed during intense exercise. 24 hours after exercise, muscle protein synthesis (MPS) is stimulated. Because of the increased protein absorption during this time, this is the best time to maximize protein consumption. This is necessary to preserve muscular mass, as a catabolic state and subsequent muscle breakdown can be induced after endurance or resistance exercise (Jäger, 2017).

Performance enhancing supplements

In addition to an optimized intake of macronutrients, elite athletes may also use supplements to further increase their performance. Many studies have shown that sodium bicarbonate supplementation improves athletic performance in various combat sports and high-intensity cycling, swimming, running and rowing (Grgic, 2021). Sodium carbonate is an ergogenic acid with an extracellular buffering capacity. There is evidence that sports that are more reliant on glycolysis as fuel source and thus have a higher accumulation of H^+, may have more benefit from sodium carbonate supplementation than exercise that are either too short or too long for marked acidosis (Maughan, 2018). β-alanine has a similar functions as sodium bicarbonate; both supplements buffer H^+, and is therefore an interesting supplement for elite rowers, where race efforts usually are 6-8 min. β-alanine increases carnosine concentration in muscle to maintain muscle pH, which delays exercise induced fatigue (Kim, 2020).

2. The relation between exercise and the microbiome

In endurance exercise, both short periods of workout and longer training periods have effects on the gut microbiota and health of an individual (Clauss, 2021). Acute workouts of moderate exercise (<70% of VO2 max) and intense exercise (>70% of VO2 max) both have positive effects on the gut microbiome. Intense exercise significantly causes more disturbance of the body homeostasis than moderate exercise does; inflammation levels rise after intense exercise in elite athletes, but these changes are temporary and are outweighed by the potential benefits of high exercise load. The health benefits may be explained through the decreased intestinal permeability that is induced by moderate exercise. A lower intestinal permeability can prevent pathogens or other antigens from crossing the intestinal barrier, which in turn leads to lower inflammation levels (Clauss, 2021).

A study performed in 2016 by Estaki et al. showed that cardiorespiratory fitness in subjects was positively correlated with the production of fecal butyrate, which is a short-chain fatty acid (SCFA) that is associated with an increase in gut health (Estaki, 2016). The increase in butyrate production is likely caused by an increase in butyrate-producing taxa (*Clostridiales, Roseburia, Lachnospiraceae, and Erysipelotrichaceae*). These 4 taxa had higher abundances in fecal samples of physically fit subjects. The cardiorespiratory fitness of the subject (VO2 peak) was measured by using a continuous incremental ramp exercise test on a cycle ergometer. The VO2 peak was also correlated with a higher microbial diversity. This study motivates the use of exercise as a therapy for diseases which are caused by a dysbiosis in gut microbiota.

A Japanese study performed in 2023 by Akazawa also provides evidence that sports influence the gut microbiome (Akazawa, 2023). They did research on training phase periodization in Japanese elite athletes from a selection of different sport disciplines and found that a decrease in the genus *Bacteroides* was correlated with an increase in VO2 max. They also showed that an increase in *Fusicatenibacter* was associated with a higher anaerobic power in these athletes. They also found that a decrease in the *Bacteroides* genus seems to attenuate ammonia elevation during exercise and seemed to positively change the maximal aerobic exercise test. In contrast, they found no correlation between

submaximal aerobic capacity and microbial changes. This study shows that an athlete's condition may be influenced by the gut microbiota to a certain extent.

A study from 2024 by Humińska-Lisowska et al. also saw a correlation between certain bacterial species and physical exercise (Humińska-Lisowska, 2024). This study discovered a negative correlation between *Bacteroides* species and VO2 max, which is in line with the findings published by Akazawa et. al in 2023. In addition to this they found that the bacterial species *Bifidobacterium longum* and *Bifidobacterium adolescentis* are strongly associated with VO2 max in strength and endurance athletes. These bacterial species are SCFAs producers with probiotic properties. A positive correlation between *Prevotella* and VO2 max was also found. Higher *Prevotella* to *Bacteroides* ratios are known to be associated with an improved glycogen storage and glucose metabolism (Kovatcheva-Datchary, 2015). Interestingly they did find that physical fitness was positively correlated with microbial diversity, but did not find any significant differences between the control, strength and endurance athletes. This was probably because all three groups were similarly physically active and were not influenced by the stressors of intense exercise that is seen in elite athletes.An enrichment of dietary fiber degrading bacteria was seen in the endurance group, which implies that the microbiome may adapt to performance-specific circumstances.

3. The microbiome of an elite athlete

In a Polish study from 2023 by Kulecka et al. the gut microbiome of e-sports players (= professional gamers) were compared to physically active healthy students and professional athletes (Kulecka, 2023). They did not find any differences in bacterial diversity, *Bacteroides/Firmicutes* ratio, composition of enterotype clusters, metagenome functional content, or SCFA concentrations between e-sports players and healthy students. However, these parameters were different in professional athletes.
Species belonging to the genera *Parabacteroides* and *Bacteroides* had a lower abundance in professional athletes in comparison to the two other groups. In addition to that a lower *Bacteroides/Firmicutes* ratio was found.. These two findings are in line with the research performed by others (Akazawa, 2023)(Humińska-Lisowska, 2024). The species *Roseburia hominis,* which is also known as butyrate producer (Machiels, 2014), was also abundant in professional athletes. A decrease in abundance of this bacterial species is associated with ulcerative colitis.
Overall, this study by Kulecka et al. showed that these professional Polish athletes have higher abundances in beneficial bacteria and lower abundances in harmful bacteria, compared to esports players and students.

The potential negative effects of intense exercise on the gut microbiome

Sports and regular exercise have a positive effect on the gut microbiome composition and gut health in general. Even in elite athletes the composition of bacteria still seems to be healthy. The amount of exercise itself does not seem very harmful to the gut microbiome composition. However, as earlier described, excessive and intense exercise can cause an increase in gut permeability. This increase in gut permeability can open the opportunity for bacterial translocation from the colon, which is related to a higher risk of gastrointestinal problems (Elzbieta Wegierska, 2022)(O'Brien, 2022).

An increase in intestinal permeability after intense exercise was also seen in a study from 2017 (Karl, 2017). This intestinal permeability changed in soldiers during the increase of physiological stress of military training, independently of the soldiers' diet. In contrast to the afore-mentioned studies, here the bacterial composition did change. Soldiers saw a decrease in the abundance of *Bacteroides,* which is related to a higher VO2 max and was also seen in earlier discussed studies (Akazawa, 2023)(Kulecka, 2023)(Humińska-Lisowska, 2024).

Effect of nutrition strategies of elite athletes on the gut microbiome

The effect of high-carbohydrate and high-protein diets in elite, highly trained endurance runners was investigated by Furber et. al. in 2022 (Furber, 2022). They found that a high-carbohydrate diet improved the time-trial performance by +6.5%. This increase in performance was associated with an increase of *Ruminococcus* and *Collinsella* bacterial species. *Ruminococcus* species are associated with an increase in resistance starch intake and are well-known for being able to degrade resistance starch (Abell, 2008).
An isocaloric high-protein intake however, reduced the running performance in these athletes. This reduced performance was correlated with an increase in both free and inducible *Sk1virus* and *Leuconostoc* bacterial populations. This highlights that not only bacterial species analysis are important, but changes in gut viral communities can also give an insight in gut stress during dietary interventions (Furber, 2022)

Possible strategies to prevent gastro-intestinal issues

The negative effect of intense exercise on intestinal permeability in combination with an existing barrier dysfunction can lead to an increased risk in numerous diseases, such as inflammatory bowel disease (IBD), irritable bowel syndrome (IBS), alcoholic liver disease, nonalcoholic steatohepatitis (NASH), liver cirrhosis, acute pancreatitis, primary biliary cholangitis (PBC), type 1 and type 2 diabetes, chronic kidney disease, chronic heart failure (CHF) and depression (Fukui, 2017). These diseases will all be detrimental to an athlete's health and most importantly, their performance. Hence, intestinal permeability plays an interesting role in the direct career and in preventing diseases later in elite athletes.

In a recent study by Nocella et. al the effect of cacao polyphenols on the gut permeability in elite football athletes and amateur footballers was investigated (Nocella, 2023). They compared measures of biomarkers of intestinal permeability in footballers after a 30 day diet intervention, which consisted of at least 40g dark chocolate (85% cacao) per day, versus a control group that did not have this dietary intervention. They found that elite footballers indeed had an increased intestinal permeability compared to amateur footballers, but more interestingly the dark chocolate intake decreased the intestinal permeability. The control group saw no change in intestinal permeability. Therefore, including dark chocolate in the diet of an athlete seems like an easy strategy to prevent gastro-intestinal issues.

Another recent study from 2023 by Mao et. al. also showed the potential of diet on exercise-induced gastro-intestinal issues (Mao, 2023). They showed that Konjac glucomannan (KGM), a plant polysaccharide, counteracted the negative effects of excessive

strength or endurance exercise in mice. The mice that were administered the highest doses of KGM also maintained their microbial composition after intense exercise, whereas the control groups had a significant microbial shift.

4. Altering the gut microbiome to enhance performance

The relation between the gut microbiome and athletic exercise is not one-directional. Certain bacterial species might enhance athletic performance, so enriching the human gut with these species will be very helpful in that case. An accessible way of altering the human gut microbiome is the use of probiotics. Different recent studies have shown the performance-enhancing potential of certain probiotics.

Probiotics
One example is a study done by Przewłócka et. al. in 2023, where the influence of a combination of probiotics and vitamin D3 supplementation on aerobic performance in Mixed Martial Arts (MMA) athletes was tested (Przewłócka, 2023). MMA athletes were either supplemented with only vitamin D3 or with vitamin D3 + a probiotic mixture composed of lyophilized strains of bacteria: (*Bifidobacterium lactis W51, Levilactobacillus brevis W63, Lactobacillus acidophilus W22, Bifidobacterium bifidum W23,* and *Lactococcus lactis W58*). The group that received the probiotic mixture + vitamin D3 supplementation had a significantly extended time to exhaustion after a 4-week supplementation. However, all other aerobic performance parameters did not differ significantly; the maximal oxygen uptake and lactate threshold did not change. The intestinal permeability did improve after probiotic supplementation, which means that this still remains an interesting strategy for increasing exercise performance in athletes.

Another performance-enhancing strategy involving probiotic supplementation was investigated by Zhu et. al. in 2023 (Zhu, 2023). This study did not focus on aerobic or strength performance, but focused on the psychological wellbeing of athletes, which is also a very important factor in an elite athlete's performance (Beckmann, 2015).
In this study the effect of probiotic yogurt (containing *Bifidobacterium animalis ssp. lactis BB-12)* on psychological fatigue in female Taekwondo athletes. The psychological fatigue was measured using the Athlete Burnout Questionnaire (ABQ) developed in 2001 (Raedeke and Smith, 2001).
The researchers found that the group that had an 8-week dietary supplementation of probiotic yogurt scored significantly better on the ABQ tests compared to the control group. They also found that *Escherichia coli* was significantly reduced in the group that received probiotics. *E. coli* may be associated with mental fatigue, as this bacterial species has also been known to be associated with post-stroke cognitive impairment (Huang, 2021).

Postbiotics
Another interesting strategy to improve athletic performance may be postbiotics. Postbiotics are substances of microorganisms that are, contrary to probiotics, not alive anymore (Vinderola, 2022). Postbiotics must be derived from well-defined microorganisms or a combination of microorganisms for which genomic sequences are known.

The potential application of postbiotics to improve athletic performance was investigated by Cheng. et al. (Cheng, 2023). This study investigated the effects of heat-killed *Lactiplantibacillus plantarum* TWK10 (TWK10-HK) on exercise endurance performance, muscle weight and strength, fatigue, and body composition. After a 6-week administration of TWK10-HK the exercise endurance time and muscle weight was significantly improved compared to the control group that did the same exercise.

Butyrate-producing bacteria
As described earlier in this paper, an increase in aerobic performance in athletes is correlated to an increase in abundance of butyrate-producing bacteria, such as *Clostridiales, Roseburia, Lachnospiraceae, and Erysipelotrichaceae* (Estaki, 2016). SCFAs, such as butyrate, could be beneficial to enhance the athlete's immunity, as well as act to improve exercise recovery via anti-inflammatory activity (Bongiovanni, 2021). SCFAs could also provide the host (elite athlete) with additional energy substrates for optimal performance. Administering a probiotic supplementation containing butyrate-producing bacteria therefore might enhance athletic performances. However, these are still in development.

5. Discussion

Overall, moderate exercise and intense exercise both have a significant effect on the human gut microbiome. This effect is generally positive, increasing gut microbiome diversity and health-associated bacteria. While moderate exercise appears to decrease intestinal permeability and inflammation, intense exercise increases intestinal permeability and inflammation, which can have a negative effect on an athlete's health (figure 1). The chronic diseases that are associated with this increase in intestinal permeability will probably develop later in an athlete's life, so this doesn't have a direct negative effect on an athlete's performance. The short-term gains of intense exercise seem to outweigh the negative effect on gut health, but it remains important to acknowledge the long-term risks these exercise regimens may have.
The link between specific bacterial taxa to athletic performance parameters such as VO2 max and anaerobic power is clearly present. For instance, an increased abundance of butyrate-producing bacteria like *Clostridiales* and *Roseburia* has been associated with improved performance, while certain taxa like *Bacteroides* show a negative correlation with aerobic capacity. This knowledge can be used for further research and future targeted interventions, such as probiotic supplementation containing beneficial bacterial strains, to optimize gut microbiome composition and enhance athletic performance. However it remains partly unclear if either the bacterial composition improves athletic performance, or if the improved athletic performance and associated diet and training load alters the bacterial composition. This most probably is a bidirectional relationship, because there is evidence of probiotics improving aerobic performance, while there is also evidence that exercise load and certain diets (e.g. high-carbohydrate diets seen in endurance athletes) alter the bacterial composition.
It is important to realize that the human gut microbiome plays a minor role in an athlete's performance. Therefore, an athlete's diet should still primarily focus on appropriately fueling an athlete's body, while also focussing on recovery and possible muscle growth. In addition to this, an athlete can include foods in their diet to maintain a healthy gut permeability or

improve the microbial composition. Studies exploring the effects of cacao polyphenols and Konjac glucomannan have demonstrated promising results in maintaining a healthy gut permeability. Other studies, discussed in this paper, exploring the improved performance of an athlete after taking probiotics also seem to acknowledge that implementing certain probiotics in an athlete's diet can be helpful. However, some probiotics that may improve aerobic fitness, only positively influence one performance parameter, while other aerobic performance parameters remain unchanged. On the other hand, also minor improvements in performance are still interesting, as race decision margins can be very narrow in elite level sports.

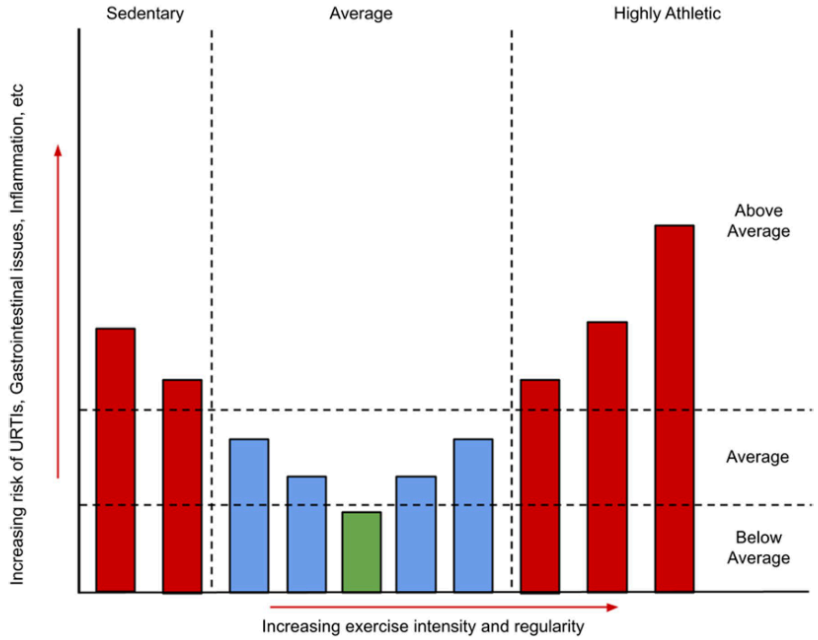

Figure 1. *This table shows the effect of an increased exercise intensity and regularity on the risk of inflammation and gastrointestinal- and upper respiratory tract issues. This indicates that a sedentary lifestyle, as well as a highly athletic lifestyle both have an increase in health risks. Figure retrieved from (O'Brien, 2022)*

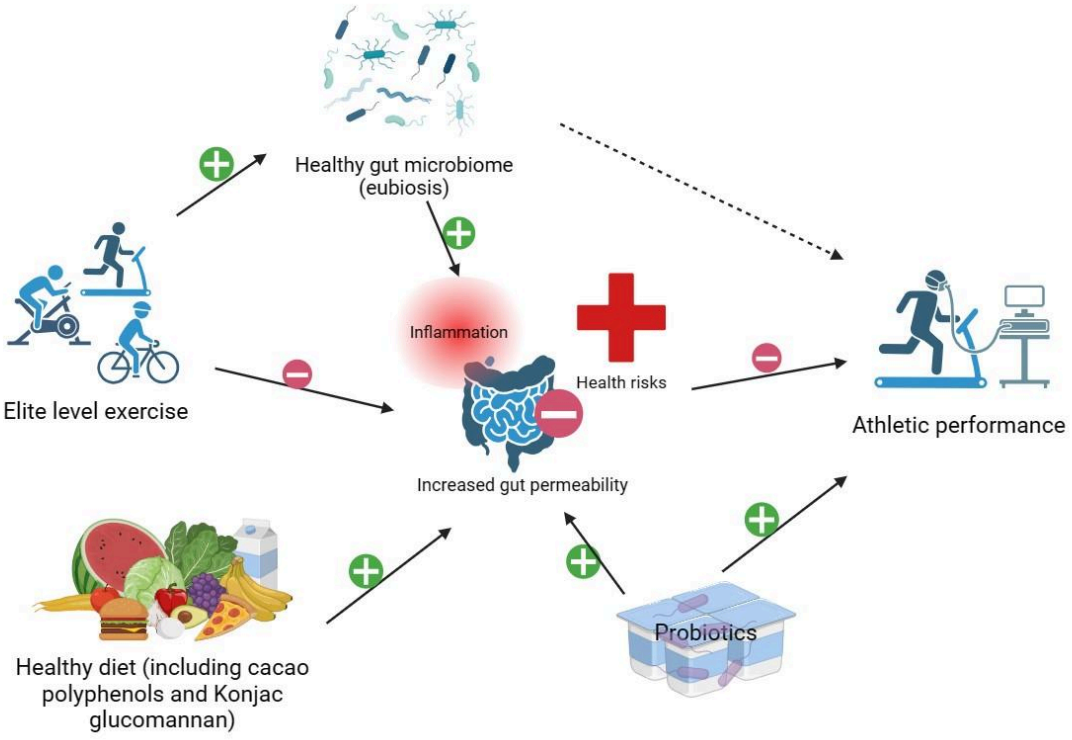

Figure 2. A global overview of the relation between elite sports and the gut microbiome.

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