Chapter 5

Exercise and Immunology

Muhammet Raşit İnaç[1]

Abstract

This abstract provides a concise overview of the profound and multifaceted interactions between exercise and the human immune system, highlighting their significant implications for overall health and well-being. Regular physical activity is consistently demonstrated to exert a powerful immunomodulatory effect, leading to enhanced immune surveillance and improved host defense mechanisms. Moderate, consistent exercise is associated with beneficial adaptations, including increased natural killer cell activity, optimized cytokine profiles that balance pro- and anti-inflammatory responses, and improved efficiency in immune cell trafficking. These adaptations contribute to a more robust immune response against pathogens, reducing the incidence and severity of common infections.

Furthermore, the beneficial effects extend to the management of chronic conditions. Exercise has been shown to mitigate chronic low-grade inflammation, a common underlying factor in many non-communicable diseases, including cardiovascular disease, type 2 diabetes, and certain cancers. While acute, high-intensity exercise can transiently suppress certain immune functions, leading to a temporary "open window" of increased susceptibility, the long-term benefits of consistent, moderate physical activity far outweigh these transient effects. Understanding these intricate interactions provides a strong scientific basis for prescribing exercise as a powerful tool in preventive medicine and as an adjunct therapy in the management of immune-related health challenges.

1. Introduction

Human health is one of the fundamental determinants of quality of life, and the immune system plays a vital role in maintaining this quality (Calder et al., 2017). The immune system is a complex defense network that protects

1 Erzurum Technical University, Faculty of Sports Sciences, Department of Coaching Education, https://orcid.org/0009-0008-5547-3805, muhammet.inac@erzurum.edu.tr

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the body against external threats such as bacteria, viruses, and parasites. At the same time, it enhances our resistance to diseases by regulating internal imbalances within the body. Elements such as our daily habits, dietary patterns, sleep quality, and stress levels directly influence the effectiveness of the immune system (Besedovsky et al., 2012). In recent years, the role of exercise in modulating the immune system has attracted growing attention from both the scientific community and individuals interested in healthy living. The positive effects of exercise on overall health have long been recognized; it strengthens the cardiovascular system, supports muscle mass, and enhances mental well-being (Gleeson et al., 2011). However, the specific contributions of exercise to the immune system represent an area that warrants in-depth investigation, particularly in guiding individuals toward adopting a more informed and health-conscious lifestyle.

Exercise is not merely a physical endeavor, but a multifaceted mechanism that interacts with the body's biological processes on multiple levels (Hawley et al., 2014). A regular and balanced exercise routine enhances blood circulation, thereby promoting more efficient movement of immune cells throughout the body (Meeusen et al., 2013). Regular exercise helps young people channel their energy in a constructive way, reduce emotional stress, and manage aggressive impulses more healthily (Nmalı et al., 2024). Moreover, by regulating stress hormones, it can reduce the risk of chronic inflammation, thereby preventing the immune system from becoming overburdened (Pedersen & Saltin, 2015). However, alongside these positive effects, excessive or inappropriate forms of exercise may suppress the immune system, increasing vulnerability to infections. This paradox highlights that the effects of exercise on the immune system depend not only on individual differences but also on the type and nature of the exercise performed (Peake et al., 2017). Therefore, properly adjusting the dose and frequency of exercise is critically important for supporting the healthy functioning of the immune system.

The immune system is one of the most sophisticated systems in the human body, functioning through the coordinated interaction of numerous cells, tissues, and organs (Iwasaki & Medzhitov, 2015). Exercise can influence this system through various mechanisms—for instance, by enhancing lymphocyte activity, regulating cytokine production, or reducing oxidative stress (Nieman, 1994). However, in order to fully understand how these effects occur, it is essential to first grasp the fundamental dynamics of the immune system. In this introduction, we will first briefly explore the main components and functioning of the immune system, followed by a more detailed examination of its relationship with exercise. This approach will

allow us to assess the role of exercise on immunity from both a theoretical and practical perspective.

2. Fundamental Mechanisms Between the Immune System and Exercise

The immune system is a complex network that plays a fundamental role in the body's defense against diseases. It consists of two main components: innate immunity and adaptive immunity. While innate immunity provides a rapid and non-specific defense, adaptive immunity develops long-lasting protection against specific pathogens (Ca, 2001). Key components of the immune system include lymphocytes (T cells and B cells), macrophages, dendritic cells, and signaling molecules such as cytokines. These cells and molecules work together to detect pathogens, combat infections, and support tissue repair, thereby maintaining the body's homeostasis (Abbas et al., 2014). Having established an understanding of the fundamental components of the immune system, we can now explore how exercise interacts with this intricate network.

The General Effects of Exercise on the Immune System

Exercise is a physiological stressor that influences the immune system on both acute and chronic levels. Regular, moderate-intensity exercise enhances the circulation of immune cells, thereby strengthening the body's ability to defend against pathogens (Nieman & Wentz, 2019). For instance, the increased blood flow during exercise facilitates the transport of lymphocytes and natural killer (NK) cells to peripheral tissues (Simpson et al., 2020). This allows immune cells to reach sites of infection more rapidly. Additionally, myokines—proteins released from muscles during exercise—exert anti-inflammatory effects, contributing to the reduction of chronic inflammation (Pedersen & Febbraio, 2012).

However, the effects of exercise on the immune system vary depending on factors such as intensity, duration, and individual characteristics. While moderate-intensity exercise generally supports immune function, prolonged and high-intensity exercise may temporarily suppress certain immune responses (Walsh et al., 2011). This phenomenon is often explained by the "open window" hypothesis, which is frequently observed in elite athletes. According to this hypothesis, the immune system becomes temporarily more vulnerable to infections for several hours following intense exercise (Nieman, 1994). However, in individuals who engage in regular exercise, this suppressive effect is minimal, and the immune system is strengthened over the long term.

The Effects of Exercise on Cellular and Molecular Mechanisms

1. To fully understand the effects of exercise on the immune system, it is essential to examine the underlying cellular and molecular mechanisms. Exercise influences immune function through various pathways that regulate the number and activity of immune cells:
2. **Lymphocyte Circulation and Activation**: During exercise, the sympathetic nervous system and stress hormones—such as catecholamines—are activated. This activation accelerates the mobilization of lymphocytes from the bone marrow and lymphoid organs into the bloodstream (Krüger et al., 2008). Notably, natural killer (NK) cells and CD8+ T cells show a marked increase in circulation during exercise. These cells provide a rapid line of defense against viral infections (Campbell & Turner, 2018).
3. **Cytokine Profile and Inflammation**: Exercise influences the balance between pro-inflammatory cytokines (e.g., IL-6, TNF-α) and anti-inflammatory cytokines (e.g., IL-10). Moderate-intensity exercise increases the release of muscle-derived cytokines such as IL-6, which contributes to the establishment of an anti-inflammatory environment and plays a role in the prevention of chronic diseases (Petersen & Pedersen, 2005). However, excessive exercise may lead to the overproduction of pro-inflammatory cytokines, which can suppress immune function.
4. **Oxidative Stress and Antioxidant Defense:** Exercise can increase the production of reactive oxygen species (ROS). However, moderate-intensity exercise enhances the activity of antioxidant enzymes—such as superoxide dismutase—thereby helping to balance oxidative stress (Simioni et al., 2018). However, excessive exercise may overwhelm the body's antioxidant capacity, leading to cellular damage and negatively affecting immune function.
5. **Hormonal Regulation**: Hormones released during exercise—such as cortisol and epinephrine—affect the behavior of immune cells. While moderate exercise helps regulate cortisol levels, excessive exercise may enhance cortisol's immunosuppressive effects on immune cells. (Hackney & Lane, 2015).

Long-Term Adaptations of the Immune System to Exercise

Regular exercise induces long-term adaptations within the immune system. For instance, individuals who engage in aerobic training exhibit increased natural killer (NK) cell activity and enhanced T cell diversity (Simpson et al.,

2015). Moreover, regular exercise may slow down immunosenescence—the age-related decline in immune function. In older adults, consistent physical activity improves T cell function and enhances vaccine responsiveness (Duggal et al., 2018). This demonstrates that exercise supports immune health not only in younger individuals but also within the older population.

However, the effects of exercise on the immune system are influenced by individual differences. Genetic factors, age, sex, nutritional status, and existing health conditions all play a role in shaping the immunological impact of physical activity. For instance, in individuals with inadequate nutrition, the immune-supportive effects of exercise may be limited (Gleeson, 2007).

The Contradictory Effects of Exercise on the Immune System

While exercise can enhance immune function, it may also exert suppressive effects when performed excessively. For example, prolonged endurance activities such as marathon running can temporarily reduce the functionality of immune cells and increase the risk of upper respiratory tract infections (Nieman & Wentz, 2019). In contrast, engaging in moderate-intensity exercise several times a week reduces the risk of infection and strengthens the immune system. This is consistent with the findings of Uğraş et al. (2024), who indicate that excessive physical training can surpass physiological thresholds and may adversely affect overall health if not appropriately regulated.

We have observed how exercise can influence the immune system. However, not all forms of exercise produce the same effects. The duration, intensity, and frequency of physical activity play a critical role in shaping immune responses. Therefore, it is essential to examine in detail how different types of exercise impact immune function.

3. Types of Exercise and Their Differential Effects on the Immune System

We have seen how exercise can influence the immune system; however, not all forms of exercise exert the same effects. The duration, intensity, and frequency of physical activity play a pivotal role in shaping immune responses. Different types of exercise produce distinct effects on various mechanisms, including immune cell circulation, cytokine production, and inflammatory responses. (Walsh et al., 2011). Aerobic exercises, resistance training, high-intensity interval training (HIIT), and even low-intensity activities such as yoga modulate the immune system through different pathways. In this section, we will explore in detail how various types of exercise influence

immune function and discuss the implications of these effects for individual health.

The Effects of Aerobic Exercise on the Immune System

Aerobic exercises—such as running, cycling, and swimming—typically involve moderate-intensity, long-duration activities. This form of exercise is among the most extensively studied in relation to immune support. Regular aerobic training enhances the circulation of lymphocytes and natural killer (NK) cells, thereby promoting a rapid immune response against pathogens (Nieman & Wentz, 2019). For example, engaging in moderate-intensity aerobic exercise for 30 to 60 minutes, 3 to 5 times per week, may reduce the incidence of upper respiratory tract infections (URTIs) (Barrett et al., 2018). This effect is associated with exercise-induced increases in the production of anti-inflammatory cytokines—such as IL-10—and a consequent reduction in chronic inflammation.

However, the effects of aerobic exercise on the immune system vary depending on its intensity and duration. For instance, prolonged and high-intensity aerobic activities—such as marathon running—may temporarily suppress immune function. This phenomenon is associated with post-exercise elevations in cortisol and pro-inflammatory cytokines, and it supports the "open window" hypothesis (Nieman, 2000). Therefore, to fully benefit from the positive effects of aerobic exercise on the immune system, it is important for individuals to maintain a balanced approach in planning the intensity and duration of their workouts.

The Effects of Resistance Training on the Immune System

Resistance training—such as weightlifting and bodyweight exercises—is designed to enhance muscular strength and mass (Gençoğlu & Çabuk, 2024). The effects of this form of exercise on the immune system involve mechanisms that differ from those of aerobic activity. Acutely, resistance training may increase the release of pro-inflammatory cytokines (e.g., IL-6); however, with regular practice, this response tends to shift toward a more anti-inflammatory profile (Calle & Fernandez, 2010). Moreover, resistance training may help slow immunosenescence—the age-related decline in immune function—by improving T cell functionality in older adults (Duggal et al., 2018).

The immunological effects of resistance training depend on the volume (i.e., number of sets and repetitions) and intensity of the exercise. While moderate-intensity resistance workouts support immune function, excessively intense or high-volume training may lead to immunosuppression (Hackney

& Lane, 2015). For example, studies conducted on elite weightlifters have shown that excessive resistance training can temporarily reduce natural killer (NK) cell activity (Egan & Sharples, 2023). Therefore, to optimize the beneficial effects of resistance training on the immune system, rest intervals and training volume should be carefully planned and managed.

High-Intensity Interval Training (HIIT) and Immunity

High-Intensity Interval Training (HIIT) is a form of exercise that combines short bursts of high-intensity activity with periods of low-intensity rest or recovery. HIIT has gained popularity due to its time efficiency and metabolic benefits; however, its effects on the immune system are complex. Acute HIIT sessions stimulate the immune system by increasing the circulation of lymphocytes and natural killer (NK) cells (Soltani et al., 2023). However, repeated high-intensity sessions—especially when combined with inadequate recovery—may lead to immunosuppression. (Bae, 2015).

The effects of HIIT on the immune system depend on an individual's fitness level and the specific exercise protocol used. In individuals with moderate fitness levels, performing HIIT two to three times per week may support immune function and reduce the risk of upper respiratory tract infections (URTIs) (Campbell & Turner, 2018). However, in elite athletes or in cases where excessive HIIT protocols are performed with insufficient recovery, elevated cortisol levels may negatively impact immune function. Therefore, to optimize the immunological benefits of HIIT, exercise frequency and recovery periods must be carefully balanced.

Low-Intensity Exercise and Immunity

Low-intensity exercises such as yoga, tai chi, and walking place less stress on the immune system and are generally associated with anti-inflammatory effects. These activities help support balanced immune function by reducing stress hormones, such as cortisol (Falkenberg et al., 2018). In particular, yoga and meditation-based exercises may enhance anti-inflammatory responses and reduce chronic inflammation through vagus nerve stimulation (Buric et al., 2017). Additionally, low-intensity exercises represent a safe and effective option for supporting immune function in older adults and individuals with chronic health conditions.

The immunomodulatory effects of low-intensity exercise become more pronounced with consistent practice. For example, engaging in 30- to 60-minute yoga sessions several times per week may boost natural killer (NK) cell activity and help alleviate stress-related immunosuppression (Lin & Cheifetz, 2018). Such exercises are especially appropriate for individuals

who are new to physical activity or for populations in whom high-intensity exercise may be contraindicated.

The Importance of Exercise Dose and Frequency

The effects of exercise on the immune system depend not only on the type of exercise but also on its dose—namely intensity, duration, and frequency. While moderate and regular physical activity enhances immune function, excessive exercise may lead to immunosuppression. The "J-curve" model is often used to describe this relationship. According to this model, sedentary individuals have a higher risk of infection; those who engage in moderate exercise experience reduced risk; but in elite athletes or individuals who exercise excessively, the risk increases once again (Chen et al., 2024). Therefore, tailoring exercise programs to individual needs and fitness levels is critically important for optimizing immune health. Understanding how exercise influences the immune system is also critically important for disease prevention. Therefore, it is essential to examine the relationship between physical activity and various health conditions (Alaeddinoğlu & Kishalı, 2020).

4. Exercise, Immunity, and Disease

We have seen that exercise can both enhance and suppress immune function. But what are the long-term consequences of these effects? What role does physical activity play in protecting against infectious diseases and managing chronic conditions? In addition to defending the body against infections, the immune system plays a critical role in the regulation and control of chronic diseases such as cancer, diabetes, cardiovascular disease, and autoimmune disorders (Calder et al., 2017). Exercise stands out as both a preventive and therapeutic tool by modulating inflammatory processes associated with these conditions and by optimizing immune function. In this section, we will explore in detail the relationship between exercise and both infectious and chronic diseases, and assess the role of the immune system within this context.

Exercise and Infectious Diseases

The protective effects of exercise against infectious diseases are well documented, particularly in the context of upper respiratory tract infections (URTIs). Moderate-intensity, regular physical activity enhances the circulation of immune cells—such as natural killer (NK) cells and T lymphocytes—thereby enabling a more rapid response to pathogens (Nieman & Wentz, 2019). For instance, individuals who engage in 30–60 minutes of aerobic exercise 3 to 5 times per week may experience a 40–50%

reduction in URTI incidence compared to sedentary individuals (Barrett et al., 2018). This effect is linked to increased production of anti-inflammatory cytokines and the regulation of stress hormones induced by exercise.

However, excessive exercise may increase the risk of infectious diseases. Prolonged and high-intensity physical activity—particularly when coupled with insufficient recovery—can temporarily suppress the immune system and heighten susceptibility to infections (Nieman, 2000). For instance, marathon runners have been shown to exhibit an increased risk of upper respiratory tract infections (URTIs) in the days following a race. This phenomenon is attributed to post-exercise elevations in cortisol levels and a transient reduction in NK cell activity (Walsh et al., 2011). Therefore, to benefit from the protective effects of exercise against infections, it is essential to carefully manage exercise dosage and recovery periods.

The relationship between exercise and viral infections—such as influenza and COVID-19—has been the focus of extensive research in recent years. Regular physical activity may enhance immune responses to viral infections by improving vaccine efficacy (Simpson et al., 2015). For example, in older adults, consistent exercise has been shown to increase antibody production in response to influenza vaccination and reduce infection risk (Duggal et al., 2018). In the context of the COVID-19 pandemic, emerging evidence suggests that regular exercise may lessen disease severity and reduce the risk of hospitalization (Sallis et al., 2021). These effects are largely attributed to exercise-induced improvements in immune function and modulation of inflammatory responses.

Exercise and Chronic Diseases

Exercise plays a regulatory role in the prevention and management of chronic diseases through its impact on the immune system. Most chronic conditions—such as type 2 diabetes, cardiovascular disease, and cancer—are associated with low-grade chronic inflammation. Physical activity helps to control this inflammation by increasing the production of anti-inflammatory cytokines (e.g., IL-10) and reducing levels of pro-inflammatory cytokines (e.g., TNF-α) (Pedersen & Febbraio, 2012; Çiftçi et al. 2023). In the sections below, we will explore in detail how exercise interacts with several common chronic diseases.

Exercise and Type 2 Diabetes

Type 2 diabetes is characterized by insulin resistance and chronic inflammation. Regular exercise improves insulin sensitivity and reduces inflammatory responses, primarily through the release of myokines from

skeletal muscle (Petersen & Pedersen, 2005). For example, individuals with diabetes who engage in 150 minutes of moderate-intensity aerobic exercise or resistance training per week show improvements in the inflammatory profile of the immune system and reductions in HbA1c levels (Colberg et al., 2010). Moreover, exercise enhances the capacity of immune cells to cope with metabolic stress, thereby reducing diabetes-related complications.

Exercise and Cardiovascular Diseases

Cardiovascular diseases are closely linked to atherosclerosis and chronic inflammation. Exercise improves endothelial function and reduces inflammatory markers, such as C-reactive protein (Joyner & Green, 2009). Performing aerobic exercise several times per week suppresses pro-inflammatory immune responses, thereby lowering the risk of heart disease. Moreover, regular physical activity helps maintain vascular health by reducing immune cell infiltration into atherosclerotic plaques (Gleeson et al., 2011).

Exercise and Cancer

The role of exercise in cancer prevention and treatment is closely linked to its regulatory effects on the immune system. Regular physical activity enhances natural killer (NK) cell activity, thereby strengthening immune surveillance against tumor cells (Bigley et al., 2014). Additionally, exercise can reduce cancer risk by lowering systemic inflammation. For instance, in cancers such as colorectal and breast cancer, consistent physical activity has been shown to decrease disease risk by 20–30% (Moore et al., 2016). Among patients undergoing cancer treatment, exercise has been found to improve immune function and mitigate treatment-related side effects (Courneya et al., 2015).

Exercise, Immunity, and Autoimmune Diseases

In autoimmune diseases—such as rheumatoid arthritis and multiple sclerosis—the immune system mistakenly attacks the body's own tissues. Exercise can help alleviate symptoms in these conditions by modulating inflammatory responses. For example, in patients with rheumatoid arthritis, moderate-intensity exercise has been shown to reduce joint inflammation and enhance immune tolerance (Cooney et al., 2011). However, exercise programs for individuals with autoimmune diseases must be carefully tailored to the severity of the condition and the individual's status, as excessive exercise may exacerbate symptoms.

Individual Factors Influencing the Relationship Between Exercise and Disease

The relationship between exercise and disease is influenced by individual factors such as age, sex, genetic background, and overall health status. For instance, in older adults, physical activity can help slow immunosenescence, thereby enhancing protection against both infectious and chronic diseases (Duggal et al., 2018). In women, hormonal fluctuations may alter the immunological effects of exercise; for example, estrogen levels have been shown to modulate immune responses (Gleeson, 2007). Additionally, conditions such as obesity or malnutrition can limit the beneficial effects of exercise on immune function. Strengthening the immune system is essential in the prevention and management of disease. However, exercise alone is not sufficient—nutrition also plays a key role. Therefore, we now turn to another important component of the exercise–immunity relationship: nutrition.

5. The Relationship Between Exercise and Nutrition: Implications for Immune Function

Exercise alone is not sufficient to strengthen the immune system. Proper nutritional strategies are also essential for optimizing immune function. Nutrition provides the energy and micronutrients necessary for the production, activation, and function of immune cells (Walsh, 2019). Exercise increases metabolic demands, thereby altering nutritional requirements, and the interaction between these two factors directly influences immune efficiency. Inadequate or imbalanced nutrition can limit the beneficial effects of exercise on immunity and, when combined with excessive training, may even contribute to immunosuppression (Gleeson, 2007). In this section, we will explore the synergistic effects of exercise and nutrition on immune function and discuss recommended nutritional strategies to support immune health.

The Role of Nutrition in Immune System Function

The immune system is a dynamic network that requires both macronutrients (carbohydrates, proteins, and fats) and micronutrients (vitamins and minerals) to function properly. Proteins are essential for antibody production and the renewal of immune cells, while carbohydrates provide the necessary energy for immune cell activity during exercise (Calder, 2020). Micronutrients such as vitamins A, C, D, and E, along with zinc and selenium, support immune cell function and help reduce oxidative stress (Calder, 2013). Inadequate nutrition can impair the production

and activation of immune cells, thereby increasing the risk of infection. For example, zinc deficiency may weaken T cell function, whereas a lack of vitamin D can increase susceptibility to viral infections (Gombart et al., 2020).

Exercise increases nutritional requirements because physical activity elevates energy expenditure, oxidative stress, and the need for tissue repair. In individuals who engage in regular exercise, adequate and balanced nutrition supports the immune system's adaptation to physical stress and mitigates the negative effects of excessive training on immune function (Walsh et al., 2011). Therefore, the relationship between exercise and nutrition requires an interdisciplinary approach to effectively optimize immune health.

The Synergy Between Exercise and Nutrition

Exercise and nutrition exert complementary effects on the immune system. For instance, cytokines such as interleukin-6 (IL-6), released from skeletal muscle during exercise, contribute to the creation of an anti-inflammatory environment, while nutrition provides the dietary components that support this response (Pedersen & Febbraio, 2012). In the following section, we will examine the synergistic effects of exercise and nutrition on immunity in the context of major nutrient groups.

The Role of Carbohydrates in Exercise-Induced Immune Modulation

Carbohydrates serve as the primary energy source for immune cells during exercise. Prolonged or high-intensity physical activity can deplete glycogen stores, thereby limiting immune cell function. For instance, carbohydrate deficiency has been shown to reduce lymphocyte proliferation and natural killer (NK) cell activity (Nieman, 2000). Consuming carbohydrates before and after exercise helps replenish glycogen stores and prevents exercise-induced immunosuppression. Studies have demonstrated that ingesting 30–60 grams of carbohydrates per hour during exercise can lower cortisol levels and help maintain immune function (Burke et al., 2013). Therefore, for individuals with high energy demands—such as endurance athletes—a carbohydrate-rich diet plays a vital role in supporting immune health.

The Role of Proteins in Immune Function and Post-Exercise Recovery

Proteins play a critical role in the production and repair of immune cells. Physical exercise induces muscle damage and increases the need for immune cell renewal; thus, adequate protein intake supports immune function (Li et al., 2007). For example, the amino acid glutamine serves as a key fuel source for lymphocytes and macrophages, and post-exercise declines in glutamine

levels have been associated with immunosuppression (Cruzat et al., 2018). In physically active individuals, consuming 1.2 to 2.0 grams of protein per kilogram of body weight per day supports the regeneration of immune cells and the production of antibodies. High-bioavailability protein sources, such as whey protein, have been shown to be particularly effective in enhancing post-exercise immune function (Krissansen, 2007).

The Role of Dietary Fats in Immune Function

Fats—particularly omega-3 fatty acids such as EPA and DHA—play a regulatory role in modulating the immune system's inflammatory responses. Omega-3 fatty acids help control chronic inflammation by reducing the production of pro-inflammatory cytokines (Calder, 2013). Among physically active individuals, omega-3 supplementation or the consumption of fish oil has been shown to attenuate post-exercise inflammatory responses and support immune cell function (Gutiérrez et al., 2019). However, excessive fat intake—especially trans fats—can negatively impact immune health. Therefore, individuals engaging in regular exercise should prioritize healthy fat sources such as avocados, nuts, and olive oil (Sales-Campos et al., 2013).

The Role of Micronutrients in Immune Function

Micronutrients play a critical role in regulating the immune system. For example:

• Vitamin C: Reduces oxidative stress through its antioxidant properties and supports lymphocyte proliferation. Post-exercise vitamin C supplementation may reduce the risk of upper respiratory tract infections (URTIs) (Hemilä & Chalker, 2013).

• Vitamin D: Regulates the activation of immune cells and enhances protection against infections. Vitamin D deficiency increases the risk of immunosuppression in physically active individuals (Gombart et al., 2020).

• Zinc: Supports T cell function and plays a role in antiviral defense. Zinc supplementation after exercise may improve immune function (Prasad, 2008).

• Probiotics: Support the immune system by modulating the gut microbiota. Probiotic supplementation in exercising individuals may reduce the frequency of URTIs (Cox et al., 2010).

Adequate intake of these micronutrients in physically active individuals supports immune adaptation to exercise and reduces the risk of infection.

Negative Effects of Exercise and Nutrition on Immune Function

Inadequate or imbalanced nutrition can limit the positive effects of exercise on immune function. For instance, calorie restriction or low-carbohydrate diets may deplete glycogen stores in physically active individuals, leading to immunosuppression (Gleeson, 2007). Additionally, insufficient protein intake combined with excessive training can impair immune cell regeneration and increase susceptibility to infections. Particularly in elite athletes, nutritional deficiencies during intense training periods may weaken the immune system and result in performance decrements (Walsh, 2019).

Nutritional Strategies to Support Immune Health

To support immune health, individuals engaging in physical exercise are recommended to adopt the following nutritional strategies:

1. **Adequate Energy Intake:** A carbohydrate-rich diet should be prioritized to replenish glycogen stores after exercise. Examples of good carbohydrate sources include whole grains, fruits, and vegetables.
2. **High-Quality Protein:** Consuming 20–30 grams of high-bioavailability protein post-exercise (e.g., eggs, dairy products, chicken) supports the repair of immune cells.
3. **Healthy Fats:** Foods rich in omega-3 fatty acids (such as salmon and flaxseeds) should be incorporated into the diet.
4. **Micronutrient Support:** Foods high in vitamins C and D and zinc (e.g., citrus fruits, fatty fish, nuts) should be consumed regularly. Supplements can be used under medical supervision if necessary.
5. **Gut Health:** Probiotic-containing foods (such as yogurt and kefir) or supplements support gut microbiota, thereby enhancing immune function.
6. **Hydration:** Adequate fluid intake during exercise supports immune cell circulation and reduces the risk of infection (Baker & Jeukendrup, 2014).

So far, we have examined the effects of exercise on the immune system, its relationship with disease, and the importance of nutrition. But how can we integrate all this information? In the conclusion section, we will synthesize the findings and offer practical recommendations.

6. Conclusions and Emerging Research Perspectives

The relationship between exercise and the immune system requires an interdisciplinary approach. Considering factors such as nutrition, training load, and individual differences, it is possible to develop scientifically supported strategies for healthier individuals. It is well established that exercise supports the immune system by enhancing immune cell circulation, regulating inflammatory responses, and strengthening protection against infections (Nieman & Wentz, 2019). Moreover, the dose, type, and frequency of exercise have been shown to play a critical role in determining its effects on immunity. While moderate and regular exercise optimizes immune function, excessive training can lead to immunosuppression (Walsh et al., 2011).

Nutrition emerges as a fundamental component that complements the effects of exercise on the immune system. Adequate intake of carbohydrates, proteins, and micronutrients supports the positive impacts of exercise on immunity, whereas nutritional deficiencies may limit these benefits (Calder et al., 2017). Furthermore, the relationship between exercise and both infectious and chronic diseases highlights the regulatory role of the immune system and underscores the importance of healthy lifestyles in disease prevention. Notably, regular physical activity has been shown to provide protective effects across a broad spectrum of conditions, ranging from upper respiratory tract infections to cancer (Moore et al., 2016).

Practical Recommendations

Taking into account the effects of exercise and nutrition on immune function, here are some practical recommendations that individuals and healthcare professionals can implement:

1. **Balanced Exercise Programs:** Engaging in 150–300 minutes of moderate-intensity aerobic exercise per week, or performing resistance training 2–3 times weekly, is ideal for supporting immune function. Exercise programs should be tailored to an individual's age, fitness level, and health status.
2. **Adequate Nutrition:** Individuals engaging in physical exercise should follow a diet rich in carbohydrates, proteins, and omega-3 fatty acids. Sufficient intake of micronutrients such as vitamins C and D, as well as zinc, strengthens immune function.
3. **Recovery and Rest:** Adequate rest and recovery periods should be planned to prevent immunosuppression caused by excessive exercise. Particularly in elite athletes, attention should be given to nutrition and sleep quality during intensive training phases.

4. **Consideration of Individual Differences:** Age, sex, genetic factors, and existing health conditions influence the effects of exercise on immunity. Therefore, exercise and nutrition plans should be tailored to meet individual needs.
5. **Attention to Gut Health**: Probiotic-containing foods or supplements can enhance immune function by supporting the gut microbiota.

Future Perspectives

Throughout this section, we have thoroughly examined the effects of exercise on the immune system. However, many topics remain to be explored. Future research should focus more deeply on the role of genetic factors and individual adaptations in the exercise-immunology relationship. For example, understanding how genetic variations influence exercise-induced immune responses could be a crucial step toward developing personalized exercise and nutrition programs (Timmons et al., 2010). Additionally, the role of the gut microbiota in mediating the interaction between exercise and immunity has garnered increasing attention in recent years. Microbiota-based interventions—such as probiotics or prebiotics—offer a promising new avenue for supporting immune health (Bassaganya-Riera et al., 2021).

Technological advancements are also transforming exercise-immunology research. Wearable devices and biosensors may enable real-time monitoring of immune markers during exercise. This could allow for the optimization of exercise dosage based on individual immune responses (Simpson et al., 2020). Furthermore, increased investigation into the effects of exercise on immunity in older populations and individuals with chronic diseases will contribute to the development of targeted interventions for these groups.

Finally, the relationship between exercise and immunity can play a significant role in the development of public health policies. The immune-enhancing effects of exercise may serve as a cost-effective strategy for the prevention of infectious and chronic diseases. In the future, integrating exercise- and nutrition-based interventions into public health initiatives could contribute to building healthier and more resilient populations.

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