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Educational Paper

Nutrition for optimising immune function and recovery from injury in sports

Nada Rotovnik Kozjek [a, b, *], Gašper Tonin [a], Michael Gleeson [c]

[a] Faculty of Medicine, University of Ljubljana, Vrazov trg 2, 1000, Ljubljana, Slovenia
[b] Slovenian Olympic Committee, Ljubljana, 1000, Slovenia
[c] School of Sport, Exercise and Health Sciences at Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK

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SUMMARY

The immune system, sports injuries, physical activity and clinical sports nutrition are closely linked. Inadequate nutrition and intense stress in athletes increase the risk of immune dysfunction, injury and disease, while injury reduces the positive effects of physical activity, creating a vicious cycle affecting health and performance. Nutritional support is key to reducing the risk of injury, speeding up recovery and shortening rehabilitation. The intake of energy, protein, carbohydrates, fats and micronutrients should be adapted to the needs following injury. Quality nutrition is preferred over the use of dietary supplements, which are limited to cases of identified deficiencies (e.g. vitamin D or iron deficiencies). Health professionals with knowledge of clinical nutrition have a key role to play in injury prevention, treatment and rehabilitation, and nutritional interventions are an indispensable part of a holistic approach to athletes' health.

Learning Objectives

- To present definitions of key physiological concepts of recovery and rehabilitation after sports injury.
- To learn stages of injury and rehabilitation.
- To understand the impact of nutritional interventions in sports injury prevention and their treatment and rehabilitation.
- To learn about the various lifestyle factors, including intensive exercise training, that can lower immunity in athletes.
- To understand nutritional strategies that may be effective in supporting immune function, lowering infection incidence, or reducing the severity or duration of illness symptoms.
- To understand the concept of immunometabolism in sports.
- To define the role of clinical nutrition in prevention and management of immune system dysfunction.

* Corresponding author. Faculty of Medicine, University of Ljubljana, Vrazov trg 2, 1000, Ljubljana, Slovenia.
E-mail addresses: NKozjek@onko-i.si (N.R. Kozjek), toningasper@gmail.com (G. Tonin), m.gleeson@lboro.ac.uk (M. Gleeson).

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Key Messages

- Strenuous prolonged exertion and heavy training are associated with an increased risk of injury and depressed immune functions in sports.
- Other lifestyle factors including poor sleep, psychological stress, and long-haul travel can also contribute to depressed immune function.
- Exercise induced immune changes mirror the individual response to physiological and metabolic stress.
- Injury and immunodepression can affect female and male athletes of all ages and competitive levels.
- Improper nutrition can elevate the risk for injury, delay recovery and rehabilitation after injury, and contribute to immune dysfunction.
- Dietary deficiencies of protein and specific micronutrients have long been associated with immune dysfunction.
- The extent of health and performance consequences due to injury and immune suppression are significantly influenced by individual moderating factors.
- Healthcare professionals with knowledge of clinical nutrition have an important role in prevention of injuries and immune system dysfunction, their treatment, and rehabilitation.

1. Introduction

Clinical nutrition measures have an important role in the prevention and treatment of injuries and immune system dysfunction in sports. High level athletes are very frequently exposed to high intensity or exhausting training programmes and other metabolic stressors that requires the knowledge of clinical sports nutrition. At the same time, regular exercise is also a key metabolic regulator in specific populations (children, elderly, patients with chronic diseases) which are at nutritional risk [1–4]. Therefore, any regular physical activity requires the application of appropriate, evidence-based sports nutrition to compensate its metabolic stress. Otherwise, without a proper nutritional strategy to cover metabolic requirements during exercise and for regeneration, factors connected with exercise (often in concert with other lifestyle stressors such as poor sleep and worry or anxiety) act as potential depressants of immune function, possibly leading to an increased likelihood of illness and injuries.

To understand this context, we have to define terms ‘physical activity’ and ‘exercise’ as they are often mistakenly used interchangeably. The term exercise is regarded as intentional physical activity, such as aerobic training, resistance training or high-intensity interval training [5]. The term physical activity describes exercise as well as usual occupational and/or domestic activity.

1.1. Relevance

Regular physical activity has been widely acknowledged for its numerous beneficial effects on health and its effects are observed across multiple organ systems (Fig. 1) [6–8]. The molecular mechanisms and mediators that underlie the beneficial effects of exercise on health, resilience and performance remain poorly understood. Nowadays, the broad spectrum of exercise-associated signaling molecules that are released in response to acute and/or chronic exercise, are defined as exerkines [7,8]. They exert their effects through endocrine, paracrine and/or autocrine pathways and represent the molecular background to improvements in cardiovascular, metabolic, immune and neurological health and functions. A multitude of organs, cells and tissues release these factors during exercise, including skeletal muscle (myokines), the heart (cardiokines), liver (hepatokines), white adipose tissue (adipokines), brown adipose tissue (baptokines) and neurons (neurokines).

On the other hand, the fear of sport related injury is considered to be one of major obstacles for sport participation despite known health benefits. Despite the desire to optimise metabolic and physiological training adaptations and body functions to achieve performance goals, it should be emphasised that staying healthy is extremely important long-term goal for athletes since it enables them sustain high training loads and compete at a high level [9]. The physiological stress of high intensity and/or prolonged exercise is associated with increased risk of injury and depressed immune cell function [10,11]. Therefore, it is not surprising that the field of exercise immunology was considered by early pioneers as a subset of stress immunology in line with other clinical situations with similar patterns of metabolic stressors (surgery, trauma, sepsis) [12,13]. This interpretation is very relevant from a clinical point of view and represents a practical background for a multimodal and multidisciplinary approach to moderating the stress response to physical activities. In this clinical strategy, clinical nutrition measures are one of the key moderating factors (Fig. 2).

The immune system, physical activity, and sports injury are closely intertwined on many different levels. Contemporary scientific perspectives consider skeletal muscle as an immunoregulatory organ that significantly affects lymphocyte and neutrophil trafficking as well as inflammatory processes. Considering this, the concept of “sports injury” should also include the dysfunction of the immune system [14]. On the other hand, the metabolic and immunological overload which leads to sports injuries and illnesses is very well recognised as the main cause of interruptions to training, being unable to compete or even cessation of being physically active [15]. Thus, the frequency, severity and duration of injuries and illnesses in athletes is inversely related to performance and sporting success. Therefore, the appropriate application of evidence-based clinical nutrition knowledge is one of the key moderating factors in metabolic and immune health. Additionally, as a part of exercise medicine, it plays a significant role in prevention, treatment and recovery from injuries as well as maintaining optimal immune function in relation to physical activity and other lifestyle stressors.

1.2. Injury in sports

The incidence, prevalence and type of sport injuries are different among gender and age groups [16]. Data showed that around 10 % of athletes competing at major multisport games lasting a week or more (e.g. Olympics) get injured [17,18]. The prevalence of injuries is surprisingly high in young athletes; for example, a 1-year injury rate of up to 91.2 % has been reported in elite adolescent athletes, especially women, which is worrying and may correlate with improper nutrition in this group of young athletes [19,20]. Furthermore, even though recreational sport activities are believed to be less psychologically or physically demanding relative to competitive sports, the reported injury rate is high. For instance, every year the US emergency hospital departments treat more than four million sports-related injuries [21]. As such, they are considered as one of the major causes of injury and morbidity in society, besides being an important contributor to an active and healthy lifestyle.

Injuries typically result in a cessation, or at least a reduction, in participation in sport and decreased physical activity. Study in Swedish athletes showed that around 50 % of injuries are severe

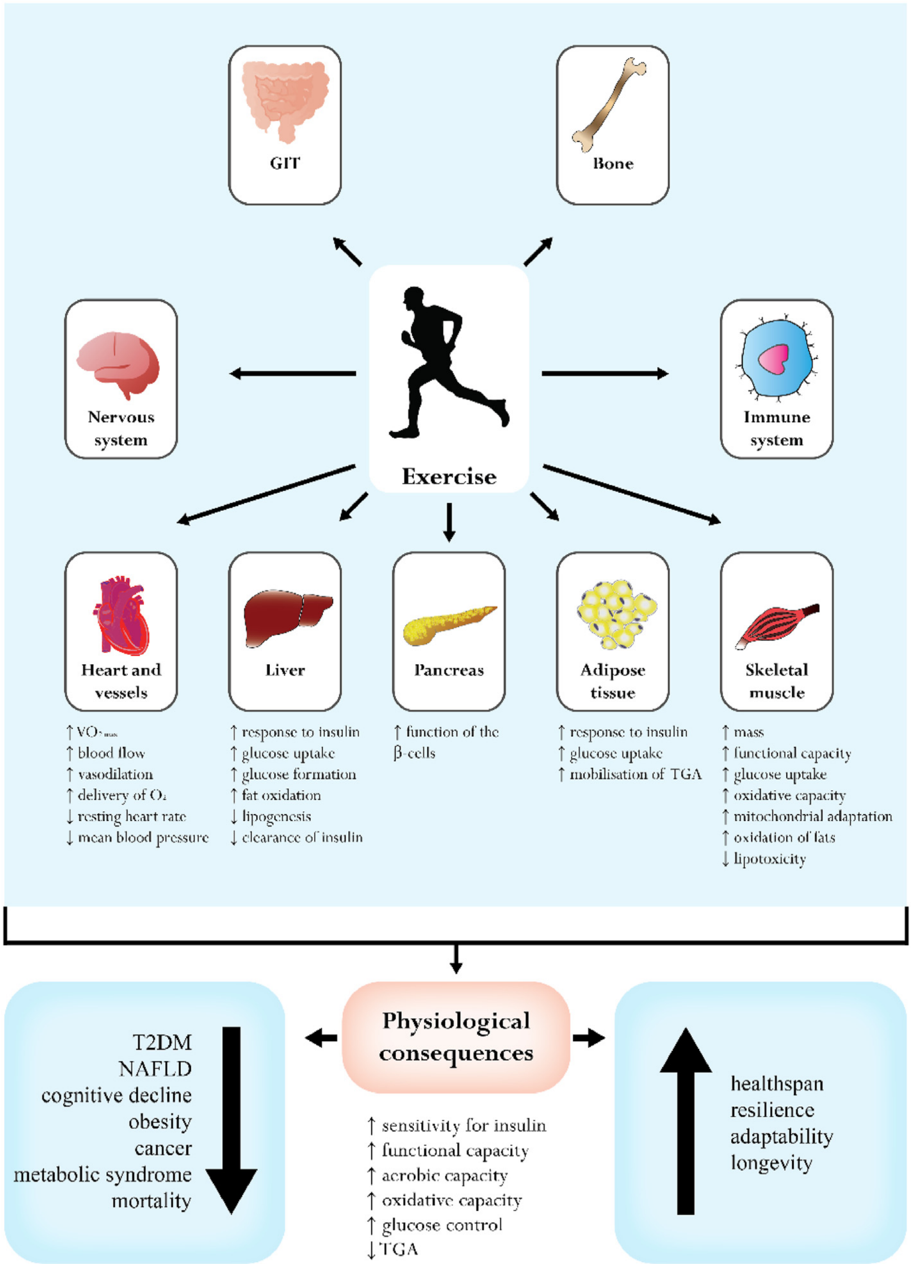

Fig. 1. Metabolic and health benefits of regular physical activity, adapted from [7].

and may result in immobilisation of a limb [22]. This is troublesome since significant strength loss and muscle atrophy develop just a few days after immobilisation [23–25]. The diminution of tendon functions and loss of training adaptations with immobilisation seem to appear earlier compared to reduction of muscle functions [26].

The majority of sports injuries lead to detraining (partial or complete loss of training-induced adaptations, in response to an insufficient training stimulus). Physiological and metabolic decline starts almost immediately after the injury and is worsened by immobilisation and the severity of the injury. The effects of detraining or deconditioning represent a complex spectrum of loss of training-induced adaptations including loss of metabolic adaptations, loss of muscle mass and strength, changes in connective tissues, musculotendon remodelling after immobilisation, and others. Effects may last weeks or months, depending on the severity of injury, time out of training, and numerous moderating factors. Short- and long-term detraining effects are described elsewhere and are beyond the scope of this module [27–30]. Nevertheless, it is important to know that detraining effects lead to substantial changes in body composition, metabolism, functional capacity, and performance as soon as within a month and are more pronounced with age [31,32]. Moreover, it is important to recognise that inactivity-induced loss of muscle mass and strength can occur in the whole body and especially in the immobilised extremities. Some consequences of muscle detraining are shown in Table 1.

Nutritional status of an athlete at the time of an injury and nutritional strategy during recovery represent key moderating factors in the timeline of the response to the detraining and recovery pathways, respectively.

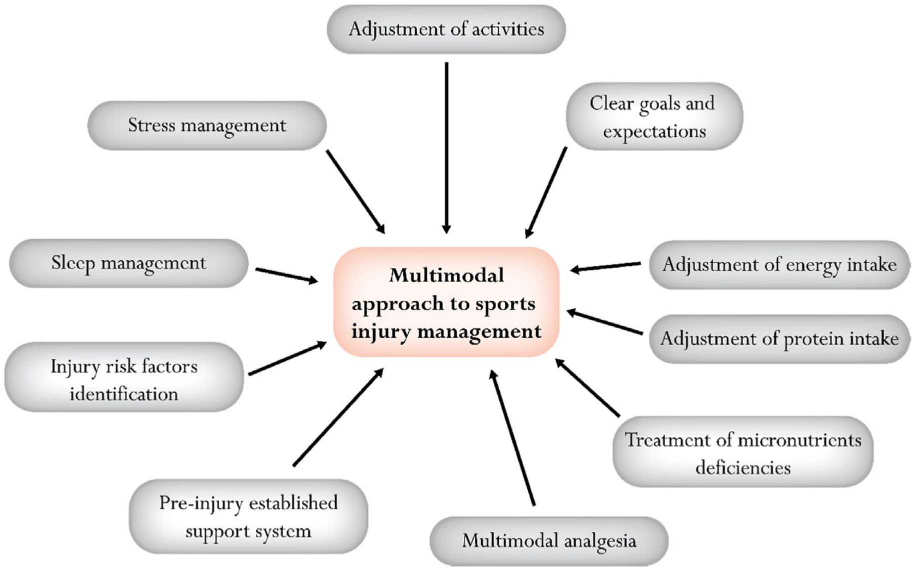

Fig. 2. Multimodal approach to sports injury management.

Table 1
Detraining effect on muscle mass and function. Adapted from [23–25,33–36].

- Loss of mass (atrophy) (150 g/day, ~1 kg/week)
- Loss of muscle mass during immobilisation or disuse ~0.5–0.6 %/day
- Loss of strength
- Loss of function
- Neuromuscular degeneration
- All the above worsen with immobilisation, disuse, inflammation, and/or energy and protein malnutrition
- Loss of type 2 fibres > type 1 fibres
- Reduced capillary density and oxidative enzyme activities
- Decline in MPS
- Decreased sensitivity of MPS to anabolic stimuli (amino acids and protein intake, insulin, exercise)
- Depression of mitochondrial metabolism, function, and biogenesis
- Decreased GLUT-4 content contributes to insulin resistance and lower uptake of amino acids

MPS - muscle protein synthesis; GLUT-4 - glucose transporter 4.

1.3. Immune system dysfunction

Immune system dysfunction may have long- and short-term effects on health and performance. A large body of evidence supports the theory that elite athletes undertaking prolonged heavy intensive exercise can exhibit immune changes, in association with physiological, metabolic, and psychological stressors, and pathogen/allergen exposure, that increase the risk of infection and/or airway inflammation (Fig. 3). Disorders in immune function may impact the ability of athletes to train and compete well when they result in increased infections and/or increased severity and duration of illness symptoms. Runners with systemic illness who elected to start the race despite being advised not to, had an 8 % chance of not finishing the race, compared with 1.6 % of runners in the control group (relative risk of 4.9) [9].

On the other hand, regular moderate exercise training has been considered to improve immune system function and is protective against common respiratory infections and systemic low-grade inflammation [37,38]. Moreover, during the COVID-19 pandemic, physically active people experienced far less severe negative health outcomes during COVID-19 infection than their sedentary counterparts and they also exhibited improved antibody response to vaccination against this highly contagious viral infection [39,40]. The evidence that elite athletes have more frequent infectious disease episodes than the general population is limited [41] but

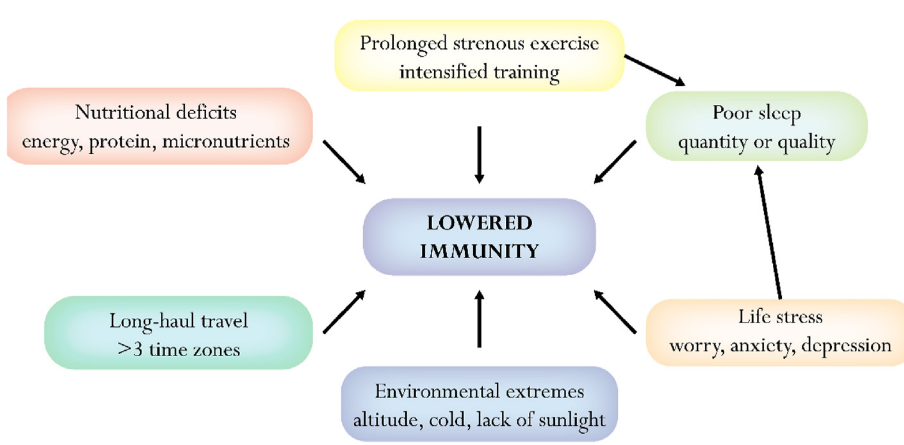

Fig. 3. Major causes of immune dysfunction in athletes.

higher rates of respiratory infection have been reported for athletes during periods of intensified training [42].

It seems that individual responses to different exercise loads vary widely, and that the changes in immune parameters reflect the magnitude of the stressors experienced by the athlete [43,44]. A "survivor" effect may exist for elite athletes whose immune system can be trained to adapt [45,46]. As many immune cell functions are modified by the physiological stress response to exercise, it could be speculated that exercise may impair cellular immune function due to a depletion of energy substrates (e.g. blood glucose and glutamine) and other metabolic perturbations that are augmented in the absence of appropriate nutrition (. Additionally, the contribution of elevated stress hormones to immuno-metabolic stress may further negatively affect immune cell malfunction. However, cell function can be regulated both positively and negatively by stress hormone exposure, so it may be an oversimplification to proclaim exercise as pan-immunosuppressive [47]. Athletes or anybody who is physically active, have individual physiological, metabolic, and psychological limitations and underlying genetic profile, which, in association with other stressors and environmental factors, will determine their risk profile for immune dysfunction (Fig. 4) [43]. There is some evidence that emotional intelligence and mental toughness can affect individual mood and psychological adaptability to exercise stress, which is also relevant from nutritional point of view [48–50].

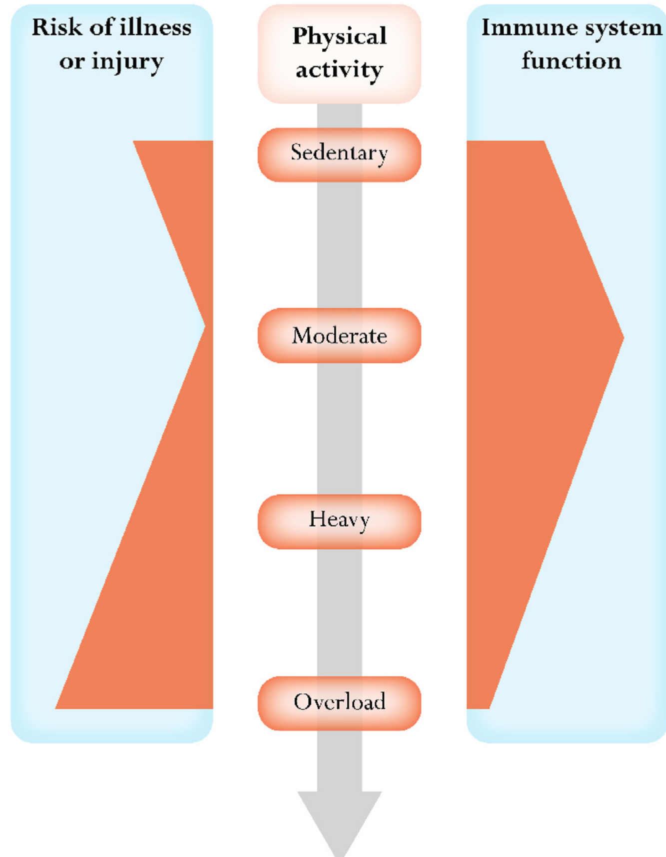

Fig. 4. Schematic presentation of the influence of exercise stress/workload on risk of illness/injury and immune system dysfunction.

2. Key terminology and concepts

2.1. Injury in sports

2.1.1. Terminology

A conceptual basis for terminology in **Sports injuries** is represented in Table 2 [15]. It serves as a foundation for the documentation of health problems, associated with participation in sports. The proposal is based on the notion of "impairment" as used by the World Health Organisation (WHO) in the functioning and disability classification: the International Classification of Functioning, Disability, and Health (ICF) [51].

2.1.2. The impact of nutritional status in injury prevention

Suboptimal nutritional status is a well-recognised risk factor for sport injury [52]. Moreover, Low Energy Availability (LEA; <30 kcal/kg FFM/day) and deficiencies in several nutrients (calcium, iron, vitamin D, carbohydrate, protein) may predispose the athlete for injury (see Module 1) [4,53,54].

2.1.3. Stages of injury

Injury causes complex physiological, metabolic and psychological disturbances (Fig. 5).

The *first stage of sport injury* corresponds to the **phase of wound healing with partial or full immobilisation and inactivity, which leads to muscle atrophy and decline in muscle mass and function.** It is a complex process involving three, overlapping phases: inflammation, proliferation and remodelling [55]. Both soft tissue and bone injuries result in inflammation to begin the healing process. Repair processes begin within only a few minutes after the injury and continue for days to weeks depending on the type and severity of the injury. Bone repair differs slightly from soft tissue repair [56].

The exact nature of the inflammatory process and its duration depend on the nature of the injury and its treatment (i.e. surgery) and moderating factors, such as nutritional status of an individual. Injury with or without surgery treatment may result in a significant stress response, which emphasises the importance and potential of proper nutritional support (Fig. 6) [57]. Regarding energy intake, it is important to understand that the inflammatory response demands energy for building new cells at the beginning of wound healing. The required energy is usually released from body energy stores and tissue protein. Beside proper energy intake, protein intake is another crucial point in the nutritional strategy after injury. A human body doesn't have reserves of excess protein as all the protein in the body serves a structural or functional role. If the person doesn't get the required amount of protein from the diet, then he breaks down useful tissue protein. Therefore, an appropriate nutritional strategy is crucial for the limitation of catabolic processes and the supply of energy and nutrients for synthetic processes.

The *second stage* of injury denotes **the return of mobility and readaptation to training** (active rehabilitation, "reathletisation"). The second stage is usually accompanied with the improvement in the psychological profile of an athlete.

2.2. Exercise immunology

Exercise immunology describes **the scientific field investigating the impact of physical exercise on the immune system** [6]. Every single bout of physical activity stimulates a recirculation of immune cells [14]. Regular exercise training promotes an anti-inflammatory state and improved antioxidant defences through multiple mechanisms that may play a critical role in countering immunosenescence and the development of chronic disease [58,59]. Nutritional influences on the immune system represent one of the key research and clinical areas of exercise immunology (Fig. 7). Recent technological advances allow a systems biology

Table 2
Categories of sports injuries through the concepts of sports impairment. Adapted from [15]. Definitions of sports impairment concepts represent the perspectives of health services, athletes, and sports institutions.

Categories	Definition
Clinical examination	
Sport injury	The loss of bodily function or structure due to sport activity that is the object of observations in clinical examinations
Overuse syndrome (sport disease)	Sports impairment caused by excessive bouts of physical exercise when observed by health service professionals during clinical examinations
Athlete perspective	
Sport trauma	An immediate sensation of pain, discomfort, or loss of functioning associated, by an athlete, with an isolated exposure to physical energy during sports training or competition having an intensity and quality making the sensation being interpreted by the athlete as discordant with normal body functioning
Sport illness	A progressively developing sensation of pain, discomfort or loss of functioning associated, by an athlete, with repeated bouts of physical load during sports training or competition without adequate recovery periods that reach an intensity and quality making the sensation being interpreted by the athlete as discordant with normal body functioning
Sports performance	
Sport incapacity/sickness	Represent the standpoints of society and its institutions on being unhealthy.

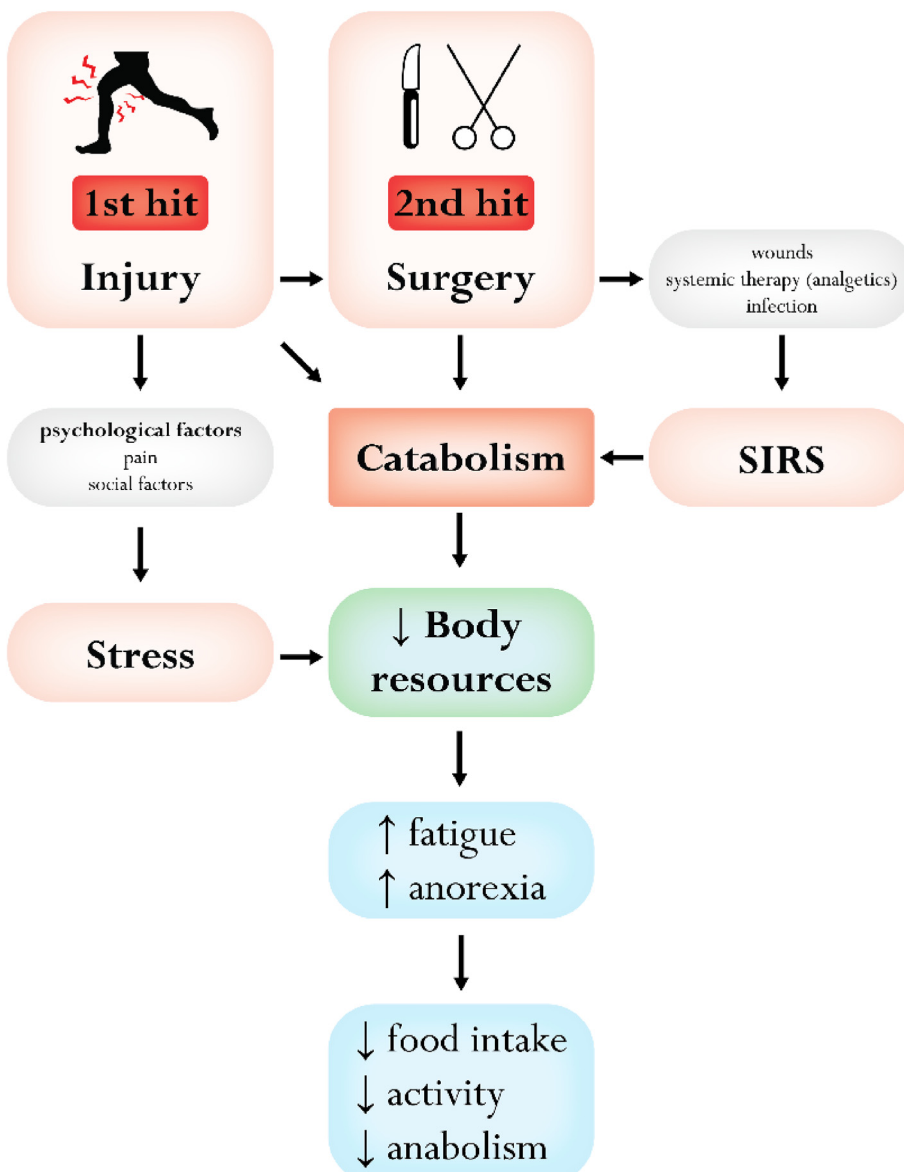

Fig. 5. Physiological, metabolic and psychological aspects of injury.

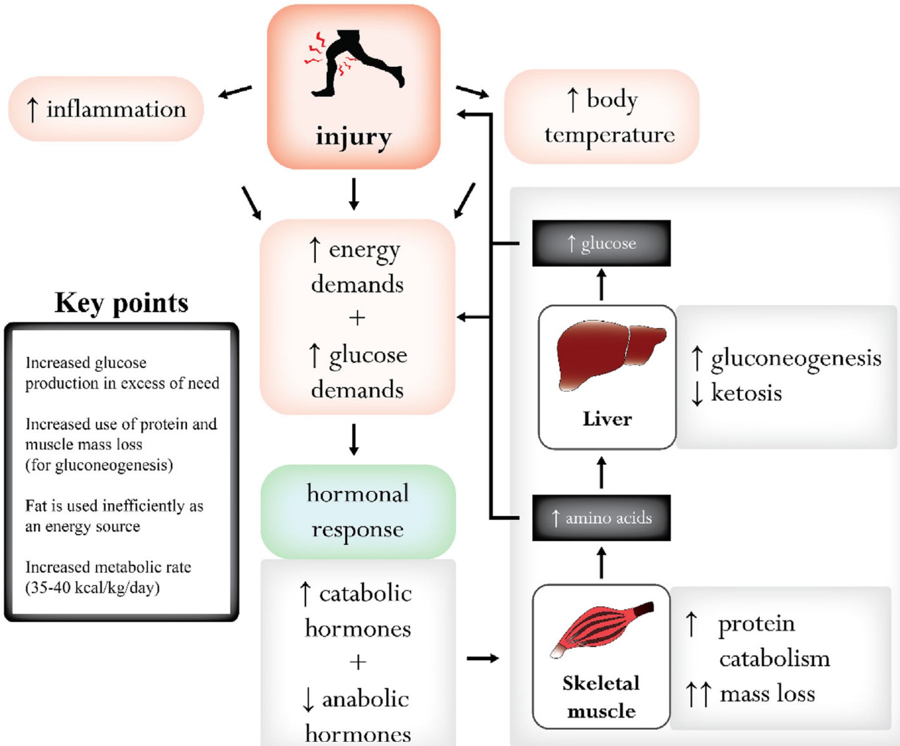

Fig. 6. Metabolic and physiological disturbances due to injury.

approach to exercise immunology (Fig. 6). New theoretical perspectives on how nutrition may influence athlete immune health are coming from the field of ecological immunology that includes the concepts of immune resistance (the ability to destroy microbes) and immune tolerance (the ability to dampen defence yet control infection at a non-damaging level) [60]. These concepts represent the background for research on tolerogenic (rather than immune-boosting) nutritional supplements which may lower the infection burden in athletes by reducing the severity and/or duration of infectious illness symptoms.

2.2.1. Immunometabolism

The term immunometabolism was proposed in 2011 to describe **the scientific field that merges immunology and metabolism** [61]. It highlights multilevel interactions between tissue metabolism and the immune system during physical activities. Exercise has important influences on both metabolism and immunity. Exercise causes fuel mobilisation and can reprogramme metabolism in immune cells by the actions of secreted myokines and other exerkines, as well as via modulation of intracellular energy sensors and immunometabolic regulators. Activated immune cells need faster energy production, so they upregulate their metabolic pathways to meet the increase energy demand. Exercise effects that cause metabolic reprogramming of immune cells help to provide energy support for immune functions during and after exercise. Inappropriate nutritional strategies for covering individual energy needs of exercise and recovery can lead to metabolic perturbations. With new technologies, used in metabolomics research, we are able to profile the metabolite shift representing the inflammatory response to exercise and compose a precise nutrition strategy for an individual [6,43].

2.2.2. Immunodepression

Immunodepression can be described as **a state of temporary or permanent immune response dysfunction, and often a suboptimal antibody response, resulting from insults to the immune**

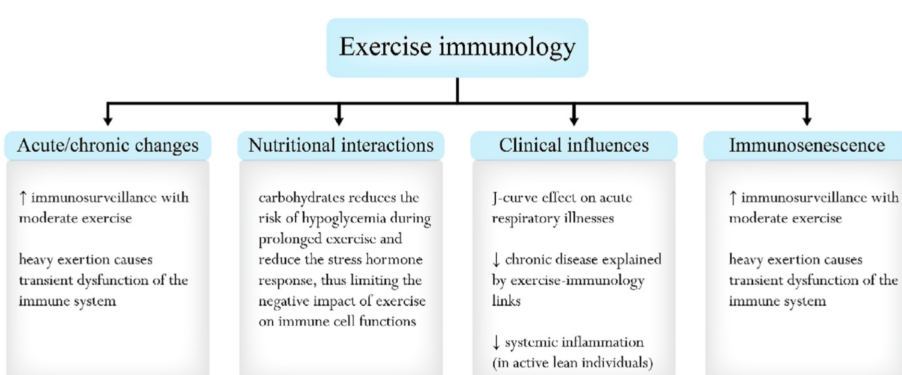

Fig. 7. Nutrition as one of key research areas in exercise immunology. Adapted from Nieman and Wentz (2019) [14].

system and leading to increased susceptibility to disease [63]. A classic view on factors contributing to immunodepression is represented in Fig. 8 [10].

2.2.3. Moderating factors

The immune system is a highly active organ system, distributed through whole body. Its functioning and response to injury and environmental factors, including pathogens, is highly dependent on energy and nutrient intakes [62,64,65]. Nutrition represents one of its most powerful moderating factors as illustrated in Fig. 8.

3. Nutrition in sports injuries

3.1. The role of nutritional assessment in injury prevention

Since poor nutritional status and nutrient deficiencies are recognised as important risk factors for sports injuries (see 1.1.2), the nutritional assessment of physically active individuals must be included as a part of regular preventive health examination. Regular monitoring of nutritional status, including body composition measurements and laboratory examinations, in elite and young athletes, as well as in chronic patients, is mandatory in order to minimise the risk of injury [52,66,67]. For instance, bone stress injuries are more frequent in sports with high training load, especially in young athletes. Consistent evaluations of energy availability by analysing nutritional strategy and body composition measurements may help in adjusting energy and nutrients intake according to health status and training load.

3.2. Nutrition recommendations

Nutritional interventions represent a part of multimodal approach in wound healing, reparation of damaged tissues and rehabilitation from injury. The physiological response to wound healing is complex and involves several energy demanding processes like inflammation, cell proliferation and remodelling (Fig. 9) [68]. Reduced activity and/or immobilisation of a limb result in loss an additional muscle mass, strength and function.

Wound healing is not always a progressive process; it can progress forward and backward through the phases depending on various moderating factors among which the contribution of nutritional status and nutritional care is still underrated. Moreover, the transition to the second stage of injury is not sharp and doesn't follow the same trajectory for different types of injuries. Rehabilitation to complete function after immobilisation is more standardised and usually takes longer than immobilisation [55,69]. Full recovery after some injuries is not possible or may take several years. Thus, nutritional support may be crucial to improve healing processes, recovery and rehabilitation after injury [55]. Clinical nutrition measures may lessen the length of time and reduce the negative aspects of reduced activity and immobilisation, as well as support the return to activity and training. In sports injuries that require immobilisation or even surgery the individually adjusted nutritional support must represent the integral part of trauma care [70]. Furthermore, even sportsmen with minor injuries will benefit from proper nutritional care.

Energy and nutrients requirements are basically similar during both stages of injury and are represented in Table 3. It is important

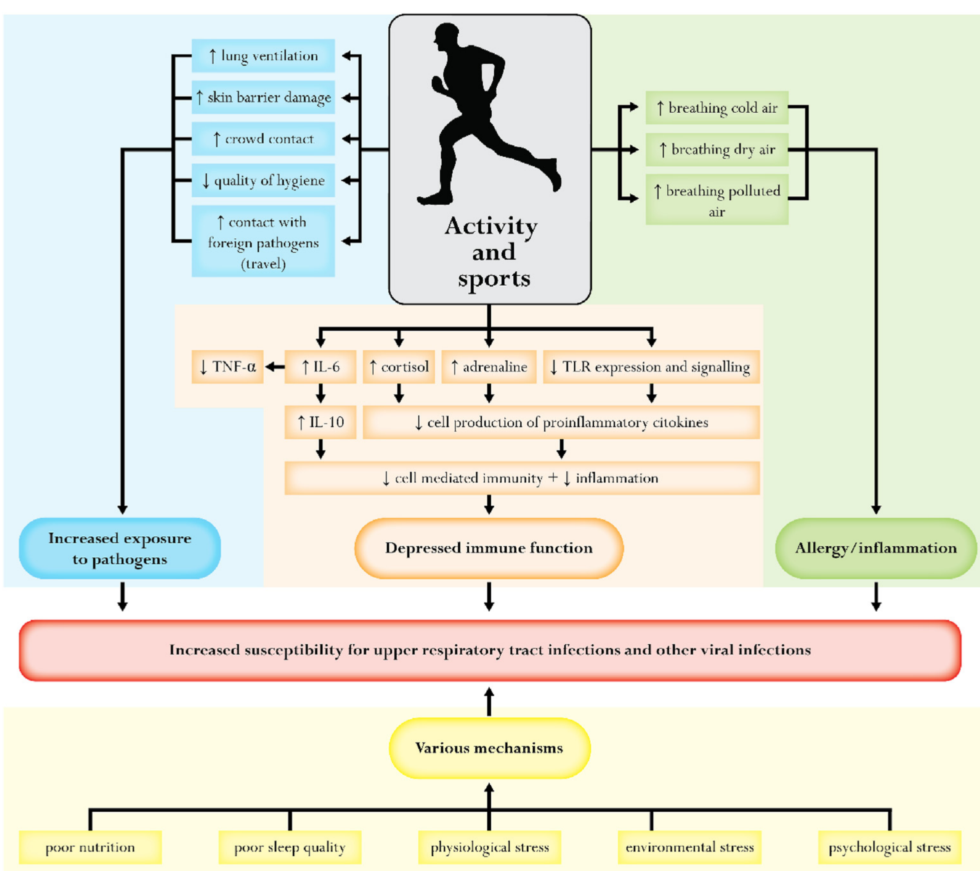

Fig. 8. Factors contributing to immunodepression. Adapted from [10].

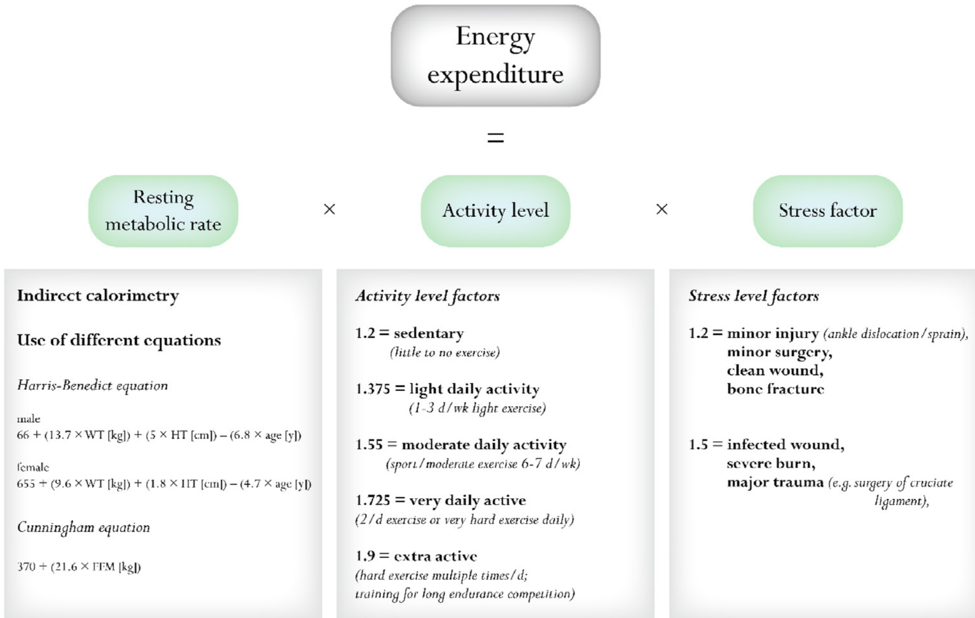

Fig. 9. Calculating energy expenditure. Adapted from [70].

to avoid LEA and ensure optimal protein and carbohydrate (CHO) intake [36,67,70]. In the rehabilitation stage, nutritional recommendations are similar to the nutritional strategy advice for gaining muscle mass [55,71].

Nutritional strategy is recommended to be based on high quality food (whole food), with meals evenly distributed during the day. Quality proteins sources are preferred and recent research showed that ingestion of a whole-food omnivorous meal containing beef results in greater postprandial muscle protein synthesis rates (+~47 %) in comparison with the ingestion of an isonitrogenous plant based meal in healthy, older adults [72]. As the same level of difference was not shown with protein isolate supplements, it

Table 3
Nutritional targets to cover physiological and metabolic demands after injury. Adapted from [11,36,70]. LEA – Low energy availability; BM – body mass; FFM – fat free mass; MPS – muscle protein synthesis; MPB – muscle protein breakdown; CHO – carbohydrate; EAA – essential amino acids; FA – fatty acids; EPA – eicosapentaenoic acid; DHA – docosahexaenoic acid; * see Fig. 9.

Nutritional target	Identification of metabolic needs	Comment
Energy	• Total daily energy requirement* = BMR × stress factor × activity level • Avoid chronic LEA (<30 kcal/kg FFM/day) • 45 kcal/kg FFM/day	Negative energy balance results in: • Slow wound healing • Increase muscle loss by decreasing MPS and facilitating MPB • Increase deconditioning • Prolong the time to return to play Adjust macronutrient composition of the diet to prevent body mass and fat gain *(2:1 = complex CHO: protein ratio)*. Avoid alcohol.
Protein	• Increased due to anabolic resistance • High protein diet 1.6–2.5 g/kg BM/day • 20–30 g of leucine rich protein per meal (providing 2.5–3.0 g leucine) or 10 g of EAA • 0.3–0.4 g/kg BM per meal • 0.4 g/kg BM pre-sleep	Inadequate protein intake: • Increased loss of muscle mass • Decreased tissue repair and healing Regular distribution of protein intake during the day (4–6 meals). Start protein consumption within 1 h of waking.
CHO	• 3–5 g/kg BM/day	Preferred energy source is a high CHO diet as it reduces protein breakdown more than a high fat diet. Complex CHO rich in micronutrients and fibre. Limit simple CHO.
Fat	• Moderate intake (~0.8–1.5 g/kg BM/day, depends on energy requirements) • Low omega-3 to omega-6 FA ratio in the diet	Omega-6 FA linoleic acid reduces the conversion of α-linolenic acid to EPA and DHA.
Micronutrients	• No need for specific supplementation in the absence in micronutrient deficiency Vitamin D: Supplementation required when serum level of 25-OH vitamin D < 75 nmol/l (suboptimal), <50 nmol/l (inadequate) or < 30 nmom/l (deficiency) • Therapy with oral vitamin D3 (2000–4000 IU/day) during the winter months to ensure serum level of 25-OH vitamin D > 75 nmol/l	Malnutrition is usually linked with low intake of vitamins, iron and zinc. Antioxidant supplementation may impair muscle regeneration. Vitamin D deficiency: • Increased injury risk • Delayed bone and muscle tissue healing • Increased infection risk

Table 4
Use of dietary supplements in injury prevention and treatment. Adapted from [36,55,70].

Dietary supplement	Recommendation	Comment
HMB	• ~3 g/day in period of extreme immobilisation • Same benefit with whey protein or leucine	Same benefit with whey protein or leucine No clear benefit
Creatine	• 20 g (4 × 5 g)/day in immobilisation (or 5 days) • 5 g/day in rehabilitation phase	No clear benefit
Omega-3 FA	• Use of high dosage of omega - 3 FA (3 g/day EPA, 2 g/day DHA) for short period to stimulate the resolution of inflammation	Prolonging intake for more than a few days may be counterproductive in the first stage of injury. Some evidence of benefit for the rehabilitation phase. No clear benefit
Prebiotics	• Positive effect on the gastrointestinal microbiota	Recommended to be consumed daily on an empty stomach.
Probiotics	• Less bacterial infections after surgery (*Lactobacillus acidophilus*, *Bifidobacterium longum*) • Improvement in protein absorption (*Bacillus coagulans*) • > 10^{10} colony-forming units of either strain; consumed in fermented food (e.g. yoghurt)	No clear benefit.
Collagen peptides and specific gelatin products	• Hydrolysed collagen 10 g/day • 15 g/day gelatin +500 mg/day vitamin C	No clear benefit.

seems that the protein anabolic properties of isolated proteins do not necessarily reflect the anabolic response to the ingestion of whole foods. The clinical use of dietary supplements as part of a nutritional strategy to prevent or treat injuries is limited and there are currently no clear evidence-based recommendations (Table 4) [36,55,70]. However, they may be helpful in situations where recommended energy or nutritional intakes cannot be reached due to low appetite, gastrointestinal upsets, poor availability of quality food or other issues.

4. Nutrition and immune function

As in sport injuries, inadequate or inappropriate nutrition can compound the negative influence of exercise on immunocompetence. LEA, low carbohydrate intake (LCA), dietary deficiencies of protein and specific micronutrients have long been associated with immune dysfunction [43,65,65,72–78]. Any kind of malnutrition can cause immune system dysfunction and diminish the efficacy of the immune system [62,79].

Therefore, any physically active person needs proper sports nutrition, not only for adaptation to exercise and regeneration, but also to protect and maintain functions of the immune system [60].

The first line of any nutritional strategy for a physically active population is a balanced daily intake of a variety of quality (whole) foods, which covers their energy, protein, micronutrient and fluid requirements. Additional energy and specific nutrient (carbohydrates, proteins) intakes should be carefully planned around training sessions and competitions, based on recommendations for sports and periodised nutrition (Table 5) [80,81].

There is limited evidence for use of dietary supplements in order to boost immunity or reduce infection risk (Table 5) [60,65,75,76,82]. It seems that as long as the diet meets the energy demands and provides sufficient nutrients to support the immune system, there is no need for consumption of any "immune boosting" supplements. One exception to this general rule may be vitamin D as humans get most of their daily needs from endogenous synthesis which requires UVB rays from sunlight which may be in short supply in some countries during the winter months. Studies confirm that in the winter months, many people (including athletes) can become deficient in vitamin D and that this can be corrected with daily vitamin D3 supplementation [83]. Therefore, clinical nutrition measures, including the use of supplements, should be part of preventive as well as curative medical health assessment in athletes. Any use of supplements must be under medical supervision by a physician. Furthermore, medical personnel and athletes must be familiar with anti-doping regulations regarding nutritional supplements [84]. Third party testing is recommended to verify the content of nutritional supplements [85].

With age, due to immunosenescence, the positive effect of exercise on health may be more pronounced. On the other hand, the systemic inflammatory response increases with age and the healthy line between positive and negative effects of exercise becomes narrower. Therefore, the importance of the concept of precise nutrition to protect health benefits, including benefits for immune function, are even more pronounced in the elderly. Individualised nutritional strategies and evidence-based use of sports supplements are becoming increasingly important with ageing in order to obtain the optimum benefit of physical exercise for immune health. Additionally, because of lack of evidence, unsupported use of immune system modulating supplements should be avoided.

An often overlooked but important point is that becoming infected increases energy and nutrient needs above normal resting requirements [88]. This is because the immune system needs more fuels (glucose and glutamine) when it is activated. It also needs more amino acids (from dietary protein) as building blocks for the increased production of antibodies and other antimicrobial proteins. Additional quantities of some nutrients such as zinc are desirable for their antiviral actions. Some nutrients also support immune tolerance to protect the body against excessive tissue damage caused by replication of a virus, the cytolytic action of natural killer cells, free radicals produced by activated neutrophils, and the actions of other immune cells. Nutrients that help to achieve tolerance include those with antioxidant actions (e.g. vitamins A, C, and E; zinc and selenium as cofactors of antioxidant enzymes) and anti-inflammatory nutrients (e.g. omega-3 fatty acids and plant polyphenols). This concept is summarized in Fig. 10.

5. Summary and conclusion

The immune system, injury in sports, physical activity, and clinical sports nutrition are closely intertwined. Improper nutrition along with extensive stress in athletes leads to dysfunction of the immune system and greater risk of injury and illness in sport. Moreover, a dysfunctional immune system and metabolic overload might even accentuate this effect. Since injury often leads to severe reduction of physical activity, this diminishes its positive effect on metabolic and immunological function, leading to creation of a vicious circle that impacts athletes' health and performance.

Table 5
Nutritional factors and practical recommendations to protect the immune system. Adapted from [65,76,81,86–89].

Nutritional factor	Practical recommendations
LEA • Rapid weight loss • Prolonged LEA (<30 kcal/kg FFM/day) with moderate insufficiency of micronutrients (e.g. iron, zinc) • Weight cycling CHO intake: • Low daily intake • During exercise	• Estimation of energy expenditure • EA > 45 kcal/kg FFM/day • Monitor energy intake. • Monitor micronutrient intake to reach population referenced standards. • Monitor nutritional status and markers of immune function in athletes during training session with LEA or low CHO intake • Limit fibre intake in athletes with very high energy requirements • When weight loss is mandatory, try early season intervention to reach target body mass • Rapid loss of body mass should be avoided • Daily CHO intake must be individualised and periodised to the amount and intensity of training and to the specific training period. • Intake of 30–60 g CHO per hour of during sustained intensive exercise • > 60 g CHO per hour in specific situations (longer duration of training session/competition, high intensity) • 1.0–1.2 g CHO/kg BMwithin 2 h after exercise, absolute quantity should be adjusted to the duration and the intensity of training session/competition and the duration of the recovery period before the next exercise.
Protein/AA intake • Low daily protein intake • Low quality protein intake • Inappropriate timing of protein intake	• Recommended daily protein intake: 1.2–1.7 g/kg BM/day. • Protein intake should be individualised; mainly depends on the nature of athlete training, age and training status of athlete and his/her metabolic characteristics. • Regular intake ~20–30 g of protein at ~3 h intervals throughout the day is recommended for maximising net protein balance. • The evidence for further supplementation of protein intake (>2 g/kg BM/day) or single (glutamine) or multiple amino acids (BCAA) to improve immune function is not clear. • Check protein quality in regular food to avoid AA imbalances.
Vitamin D	• Regular seasonal (summer, winter) check of serum level of 25-OH vitamin D should be part of routine medical examination for athletes. • Treatment of deficiency of vitamin D (serum 25-OH vitamin D < 30 nmol/L) with 2000–4000 IU/day vitamin D3 is recommended. It seems that in otherwise healthy people 4000 IU/day for 8 weeks will attain adequate vitamin D status for most who are deficient. • Supplementation of vitamin D3 in winter months in athletes with suboptimal levels of vitamin D (serum 25-OH vitamin D < 75 nmol/L) with 1000–2000 IU/day and athletes with dark skin tone or training indoors. • Excessive intake of vitamin D should be avoided in the absence of deficiency.
Antioxidants	• Variety of fresh fruits and vegetables together with other quality food sources are recommended to be consumed during the day to provide sufficient intake of antioxidants. • Additional supplementation with antioxidant vitamins is not recommended. It is well recognised that exercise generated free radicals and other oxidants are central to the control of gene expression, cell signalling pathway regulation, and physiological modulation of skeletal muscle functions. Excessive vitamin C + vitamin E intake has been shown to impair training adaptation. • Moderate additional intake of vitamin C in dosage 0.25–1.0 g/day may reduce the incidence, duration and severity of the common cold in athletes. It may be useful in some athletes when they are exposed to extreme unaccustomed acute physical stress. • Supplementation of omega-3 fatty acids (DHA and EPA at a dose of 250 mg/day) may benefit immune tolerance. DHA and EPA present at the site of inflammation are converted into compounds called resolvins, protectins, and maresins, which promote the resolution of inflammation and support healing, including healing in the respiratory tract.
Zinc (Zn), magnesium (Mg) and iron (Fe)	• The benefit of routine supplementation in absence of deficiency has no evidence. • Short term Zn supplementation (75 mg/day within 24 h of onset of illness symptoms) may reduce severity and duration of common cold and may have benefit in periods of high psychological/physiological stress in athletes with history of recurrent URI. Bioavailability of Zn is impaired by simultaneous intake of food rich in phytates (whole-grain breads, cereals, and legumes), and by Fe supplementation. • In absence of deficiency, magnesium supplementation has no proven benefit. • Treatment of iron deficiency with high-dose iron supplements must be done under medical supervision.
Glutamine	• Despite reduced availability of plasma glutamine after prolonged exercise there is no clear benefit of oral glutamine supplementation on respiration infection incidence.
Dehydration	• Maintaining fluid balance is important to ensure optimal performance and health. • Daily monitoring of body mass may help to maintain fluid balance in training in the heat or at altitude. • During training in temperature extremes or at altitude monitoring of either urine osmolality or specific gravity can be useful to support the application of a hydration strategy. • The mouth should be kept moist to maintain the saliva flow as the first line of immune defence.
Probiotics and fermented foods	• A balanced diet with whole foods helps to maintain a healthy gut microbiota and prevent dysbiosis. • Probiotics and prebiotics may be consumed as supplements, enriched or fermented food, or beverages (yoghurts, kefir, kombucha, etc.). • No strain-specific consensus for probiotics exists but positive results have been reported for Lactobacillus and Bifidobacterium species consumed in doses of 10^{10} CFU per day. • Use of multi-strain probiotic (species Lactobacillus and Bifidobacterium with the viable number of cells per species greater than 10^9 CFU per day) should be considered 14 days prior to travel or training camp.
Bovine colostrum	• May be effective in preventing the incidence of respiratory illness episodes and number of symptom days in adults engaged in exercise training. • Not on the banned list of substances but not recommended for athletes according to WADA since 2020 based on concerns of elevated serum IGF-1 levels, although such high levels have only been associated with higher doses than the efficacious dose for illness reduction which is 20 g/day.
Herbal supplements	• **Plant polyphenols** Plant polyphenols extracts (quercetin, resveratrol) showed small effects in increasing antioxidant capacity. Good food sources of polyphenols, including flavonoids, are tea, coffee, fruits, (nonalcoholic) beer and wine. Quercetin dosage 0.5 – 1g may reduce symptoms of respiratory illness in athletes. However, it was not shown to be effective as an alternative to NSAID (i.e. ibuprofen) in the treatment of inflammation or postexercise pain/soreness. • **Echinacea** Some limited evidence for therapeutic immunomodulation in athletes. • **Ginseng** No clear benefit for immunomodulation in athletes.

LEA – low energy availability; EA - energy availability; CHO – carbohydrate; FFM – fat free mass; AA – amino acids.

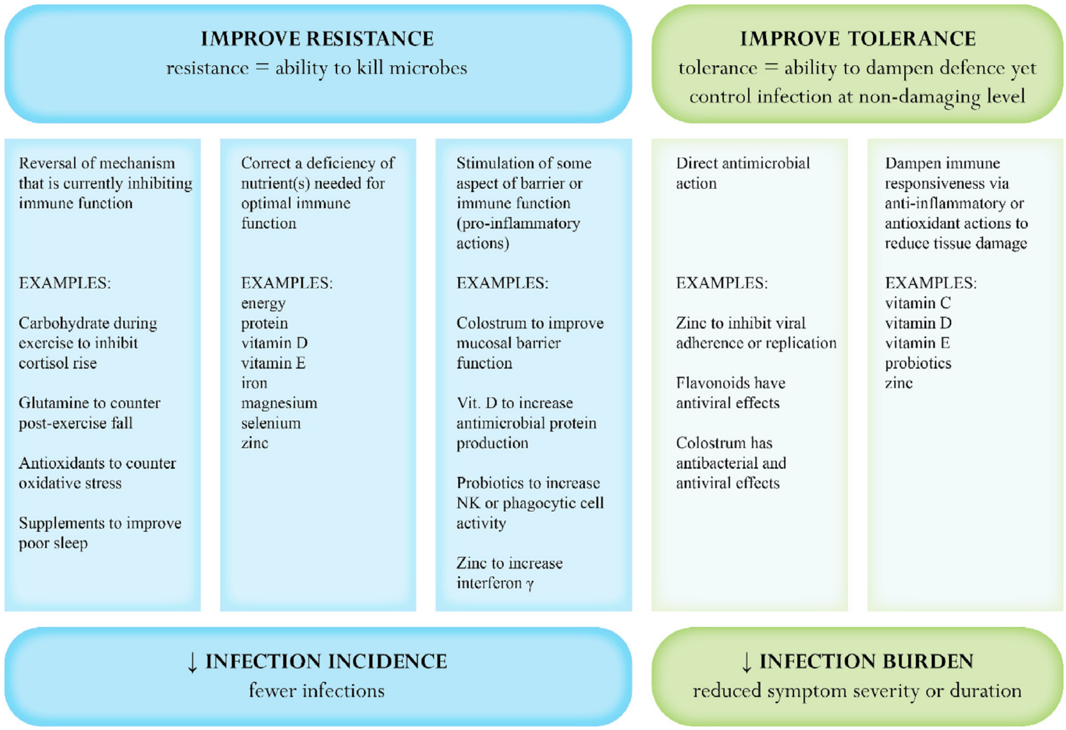

Fig. 10. Nutritional supplements may improve host resistance to infection (boost immunity) or improve tolerance of microbes to reduce infection burden.

Despite its severity being dependent on an individual athlete's genetic and other moderating factors, this downward spiral will only be amplified without proper clinical nutrition support.

It is important to know basic terminology regarding injury in sports and differentiate between its different categories. It can affect athletes of all ages and competitive levels. Regular monitoring of nutritional status, including body composition measurements and laboratory examinations, in elite and young athletes, as well as in chronic patients, is mandatory to minimise the risk of injury. The physiological response to injury healing is complex and involves several energy-demanding processes like inflammation, cell proliferation, and remodelling. These taxing processes together with reduced activity and/or immobilisation of a limb result in loss of muscle mass, strength, and function.

Poor nutritional support can therefore elevate the risk of injury, delay recovery and prolong rehabilitation after injury. Intake of energy, protein, CHO, fat and micronutrients must be adjusted to satisfy different demands after injury. It is preferable that the chosen nutritional strategy is based on high quality food (i.e. whole foods rather than processed foods which have a lower essential nutrient density). The clinical use of dietary supplements for recovery from injury is limited since there are no clear evidence-based recommendations. Similarly, there is no need for micronutrient supplements if there is no identified deficiency. Nevertheless, dietary deficiencies of protein and specific micronutrients have long been associated with immune dysfunction and it is well established that immune cells play an important role in the repair of tissue damage. A range of nutrients have multiple roles in supporting immune function and optimal intakes may be desirable but some (e.g. vitamin D, selenium and zinc) cannot easily be achieved through diet alone. In cases where micronutrient supplementation is actioned due to an identified or suspected deficiency, it is advisable for the physician to monitor micronutrient status level if possible (e.g. for vitamin D or iron supplementation).

Healthcare professionals with a good knowledge of clinical nutrition have an important role in the prevention of injuries and immune system dysfunction, as well as their treatment and rehabilitation. Nutritional interventions represent an important part of a multimodal approach regarding this issue.

Authors contributions

NRK, MG Conceptualization; NRK, GT, MG Formal analysis; NRK, GT, MG Project administration; NRK, MG Supervision; GT Visualization; NRK, GT, MG Writing- original draft; NRK, GT, MG Writing-review & editing.

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Declaration of competing interest

Authors have no conflicts of interest.

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