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IRON DEFICIENCY AND 'SPORTS ANAEMIA' IN YOUNG FEMALE ATHLETES

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ABSTRACT

Iron deficiency, including non-anaemic iron deficiency (NAID), is a common problem among young, menstruating female athletes, requiring precise differentiation from 'athlete's anaemia', which is a physiological adaptive haemodilution. The aim of this narrative review was to summaries the mechanisms, prevalence, diagnostic principles, and clinical and performance-related consequences of these disorders. Epidemiological data indicate that hypoferritinaemia (ferritin ≤30 ng/mL) affects up to 47% of young female athletes, and 23.1% develop overt anaemia according to WHO criteria. The Pathomechanism of the negative iron balance is multifactorial and includes losses through sweat, gastrointestinal micro bleeding, mechanical haemolysis, and exercise-induced increases in interleukin-6 and hepcidin, which temporarily block intestinal iron absorption and recycling. It has also been shown that aerobic training is associated with a poorer haematological profile than anaerobic training. The consequences of NAID extend beyond reduced physical performance and fatigue, also including a decrease in bone mineral density and an increased risk of stress injuries to the lower limbs. In laboratory diagnostics, haemoglobin alone has been shown to have low sensitivity, which justifies routine measurement of ferritin (with the sports threshold raised to <30–35 ng/mL), sTfR and TSAT.

In summary, optimal therapeutic management should be holistic, encompassing the provision of adequate energy intake, monitoring of vitamin levels (D, B12, folic acid) and targeted, 6–8-week course of oral supplementation in confirmed cases, whilst strictly avoiding the routine administration of high doses and intravenous infusions without clear laboratory indications.

KEYWORDS

Iron Deficiency, Anaemia in Athletes, Endurance Exercise, Non-Anaemic Iron Deficiency (NAID), Dilutional Pseudoanaemia, Ferritin, Hepcidin, Exercise-Induced Haemolysis

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1. Introduction

Haemoglobin (Hb), the number of red blood cells (RBCs) and iron stores are crucial for transporting oxygen, maintaining blood buffering capacity and improving exercise performance. In endurance sports, blood adaptations occur, such as an increase in RBC mass and haemoglobin (Hb) levels, and an expansion of plasma volume. These adaptations allow for increased oxygen delivery to the muscles while simultaneously lowering haematocrit, a condition sometimes referred to as 'athletic anaemia' (Damian et al., 2021). Although this adaptive haemodilution is physiologically beneficial, it may nevertheless mask actual deficiencies and significantly hinder the unambiguous interpretation of routine haematological parameters.

Iron deficiency is a common phenomenon in sport, particularly affecting young, menstruating female athletes. Among sporting populations, the prevalence of iron deficiency is often reported to be significantly higher than among non-athletic peers (Roy et al., 2022). Additionally, young female athletes are at risk of a negative iron balance. This is due to increased demand, losses through sweat, menstrual bleeding, microdamage to the gastrointestinal tract and exercise-induced haemolysis (Damian et al., 2021; Osman et al., 2024). A chronic deficiency of this micronutrient, even in the absence of overt anaemia, impairs mitochondrial function and ATP synthesis, which directly results in athletes feeling tired more quickly and taking longer to recover after exercise.

This review summarises the mechanisms, prevalence, diagnostic principles and consequences of iron deficiency and anaemia in young female athletes, particularly in relation to endurance versus anaerobic exercise. Preliminary data suggest that aerobic training may be associated with a less favourable haematological profile and iron status than anaerobic training, despite comparable ferritin levels (Osman et al., 2024). Understanding these discrepancies is key to optimising screening strategies and developing personalised dietary and supplementation guidelines tailored to the specific training demands of a given sport.

2. Methodology

This paper provides a narrative review of the literature on iron deficiency in young female athletes. The aim was to summarise the mechanisms, prevalence, diagnostic principles, and consequences of iron deficiency and anaemia in this population, with a particular focus on the differences between endurance and anaerobic exercise, and the impact of these conditions on exercise capacity and health.

The review included studies from PubMed and the Cochrane Library which described the following: the mechanisms of anaemia in athletes; the prevalence of iron deficiency and anaemia in young female athletes in cross-sectional, cohort, and clinical studies; the effect of exercise type on blood count and iron status; diagnostic principles in sports medicine, including identifying iron deficiency without anaemia; clinical and performance consequences; and prevention and treatment strategies.

Results from cross-sectional and cohort studies involving large groups of athletes were analysed, including a retrospective study of 629 German elite athletes and Japanese cohorts of female student-athletes. Interventional and observational studies assessing the impact of training and supplementation on haematological parameters and hepcidin regulation were also analysed, as well as numerous narrative and systematic reviews concerning iron in sport, with a particular focus on women and adolescents.

As this is a narrative review of the literature, a formal search protocol or quantitative meta-analysis was not employed. Instead, there was integration of results in a descriptive way, involving a critical comparison of data from different types of studies and their application to the specific characteristics of young female athletes.

3. Epidemiology and prevalence of iron deficiency in female athletes

Epidemiological data suggest that iron deficiency, frequently occurring without overt anaemia, is one of the most prevalent health issues among young female athletes. This applies to both elite sport and intensive activity in school and university sports clubs (Levy et al., 2023; Nabeyama et al., 2023; Roy et al., 2022; Williams et al., 2009; Yamamoto et al., 2022). Systematic and narrative reviews consistently show that iron deficiency, frequently without anaemia, is prevalent among adolescent and young adult female athletes. The prevalence of this condition among athletes exceeds that reported for their peers in the general population. This emphasises the importance of routine screening and early intervention for this group (Nabeyama et al., 2020). A retrospective study of 629 German elite athletes was conducted. Iron deficiency was found in 35.9% of female athletes. The proportion among men was significantly lower (10.9%). Notably, the analyses revealed no statistically significant differences between individual sports disciplines, suggesting that gender, age and related factors are stronger risk determinants than the specific discipline (Roy et al., 2022). It has been confirmed through Japanese studies on female students involved in sport that a large proportion of female athletes have depleted iron stores even before the development of anaemia. In one such study, 47% of female university students had hypoferritinaemia (ferritin ≤30 ng/mL) despite having normal haemoglobin levels. This phenomenon was observed across various sports, including kendo, badminton, baseball, and handball (Nabeyama et al., 2023). Another study was carried out at an anaemia clinic, with young people aged 13–22 who were members of sports clubs participating. This study revealed that 23.1% of patients met the World Health Organization (WHO) criteria for diagnosing anaemia. The study revealed that hypoferritinaemia and high creatine kinase levels were independent risk factors, suggesting a combination of iron deficiency and a high training load (Yamamoto et al., 2022). It is worth noting that regular, non-competitive sporting activity does not increase the risk of anaemia or iron deficiency in women of childbearing age. However, physical exertion has been demonstrated to affect serum iron concentrations, given that it has been shown to reduce transferrin iron saturation and increase levels of the soluble transferrin receptor (sTfR). However, the prevalence of anaemia among amateur athletes is significant, with almost one-fifth affected. Additionally, a substantial proportion, approximately one-third, are iron-deficient, which can hinder their physical performance (Di Santolo et al., 2008).

4. Mechanisms of 'athlete's anaemia' and iron deficiency

The term 'athlete's anaemia' refers to two distinct conditions: adaptive haemodilution and absolute iron-deficiency anaemia. The development of the latter is triggered by a chronic negative balance of this micronutrient. Continuous physical activity has a simultaneous impact on plasma volume, haemolysis, blood loss and the regulation of the IL-6-hepcidin-ferroportin axis.

Researchers observe reduced haematocrit and haemoglobin levels alongside an increased total red blood cell mass in trained athletes, particularly those involved in endurance sports. This corresponds to 'pseudo anaemia', which is associated with plasma volume expansion rather than a decrease in red blood cell mass.

(Damian et al., 2021). Such haemodilution is part of a beneficial circulatory adaptation and does not meet the criteria for clinical anaemia (Damian et al., 2021; Mairbäurl, 2013).

True anaemia in athletes, however, develops as a result of increased, multi-directional iron loss during physical exertion. The results of a narrative review indicate the significant importance of iron loss through sweat, haematuria, gastrointestinal micro bleeding, and exercise-induced inflammation as the main causes of a negative iron balance (Solberg & Reikvam, 2023). In contrast, other authors identify mechanical damage to erythrocytes as a significant cause of haemolysis. This occurs as a result of the breakdown of blood cells during their passage through the capillaries of contracting muscles and due to repeated mechanical pressure on the soles of the feet, e.g. in runners, or the palms of the hands, e.g. in weightlifters (Mairbäurl, 2013).

The IL-6-hepcidin-ferroportin cytokine-hormone axis also plays a significant role in the pathogenesis of iron deficiency in athletes. Data from a systematic review indicate that exercise-induced inflammation leads to a transient increase in IL-6 and hepcidin concentrations. This phenomenon results in a period during which intestinal absorption and iron recycling are reduced, and the body's iron stores exhibit reduced bioavailability for erythropoiesis (Solberg & Reikvam, 2023). The body's response to training loads also depends on the duration and intensity of the exercise, which is closely linked to the regulation of hepcidin levels. In young female dancers, 2 months of continuous training was associated with a reduction in hepcidin and a concurrent decrease in RBC, Hb and Hct, as well as an increase in erythropoietin (Kobayashi et al., 2024). This was interpreted as the result of increased haemolysis and erythropoiesis, with hepcidin suppression potentially facilitating the mobilisation and absorption of iron despite its increased consumption. In other studies of female long-distance runners, multiple endurance sessions within a 24-hour period or periods of intensified training resulted in a sustained increase in hepcidin. These studies also found a high proportion of athletes with depleted iron stores, which promotes the development of overt deficiency (Auersperger et al., 2013; Ishibashi et al., 2017, 2022).

The type of exercise significantly influences blood morphology and iron metabolism in female athletes, particularly during puberty. Differences between aerobic and anaerobic sports are compounded by gender, the menstrual cycle, training volume and often suboptimal iron intake.

In teenage female athletes practising aerobic sports, significantly lower red blood cell parameters (Hb, Hct, RBC, MCV) and higher transferrin concentrations were observed compared with female athletes in jumping disciplines. The simultaneous absence of differences in ferritin concentration suggests impaired functional iron metabolism whilst systemic iron stores remain intact (Osman et al., 2024).

A similar pattern of lower red blood cell parameters (Hb, Hct, RBC) and reduced ferritin concentration was observed in men practising endurance sports compared to those in strength and mixed disciplines. The pathomechanism of this phenomenon highlights the role of exercise-induced mechanical haemolysis, as indicated by the reduced haptoglobin concentration found in runners but not in cyclists (Schumacher et al., 2002).

Individuals practising strength disciplines, such as weightlifting, bodybuilding or wrestling, are less likely to suffer from iron deficiency, as their training regimens involve less of an endurance component, and the loss of this component through sweat or haemolysis is of lesser significance (Clénin et al., 2015; Yamamoto et al., 2022). The potential development of anaemia leads to a decline in maximum strength and anaerobic capacity, thereby hindering the achievement of optimal form and performance. Furthermore, insufficient iron levels in this group of athletes may prolong the time required for muscle recovery following intense exercise, which in turn necessitates longer intervals between training sessions (Damian et al., 2021). Having greater muscle mass is sometimes associated with an increased requirement for this element, as it is essential to produce myoglobin, the protein responsible for storing oxygen in the muscles. However, the overall risk of developing deficiencies is still lower in this case than among endurance athletes (Clénin et al., 2015).

For this reason, the use of iron supplements is less common among these athletes; nevertheless, it may be recommended during periods of demanding, intensive strength training if this coincides with a low intake of this micronutrient in the daily diet.

Women are a particular group of athletes in whom the previously mentioned mechanisms overlap with gender-specific factors. Female athletes, particularly adolescent girls, are at higher risk of developing iron-deficiency anaemia due to menstrual blood loss. Applying dietary restrictions can dramatically increase the risk, as this can result in a combination of physiological stress, low energy availability and a diet that limits iron bioavailability (Damian et al., 2021).

5. Clinical presentation and performance consequences

Iron deficiency, with or without anaemia, affects both performance parameters and the risk of injury, as well as bone health. In young female athletes, these effects are particularly significant due to the high demand for iron during puberty and additional loss through menstrual blood. A systematic review by Solberg and Reikvam showed that iron deficiency anaemia unequivocally reduces exercise capacity, whilst supplementation improves exercise performance, particularly in athletes with the lowest baseline iron status (Solberg & Reikvam, 2023).

In the case of iron deficiency without anaemia, the results are more varied. Some studies show an improvement in VO2 max, haematological parameters and the metabolic response to exercise following supplementation. Others indicate no clear gain in exercise capacity, despite an increase in ferritin (Solberg & Reikvam, 2023). It is emphasised, however, that low ferritin and anaemia are associated with poorer exercise tolerance, faster onset of fatigue and a decline in performance, particularly in endurance sports where oxygen transport is crucial (Blecharz et al., 2025).

Iron deficiency without anaemia is common among young female athletes and manifests itself, among other things, as fatigue and a subjective decline in performance, particularly during menstruation. Half of the female student athletes surveyed reported a decline in performance during this period (Nabeyama et al., 2020, 2023). Reviews on women's sport emphasise that even with normal haemoglobin levels, low ferritin levels may limit training adaptations and performance, which justifies active screening for and treatment of iron deficiency in this population (Blecharz et al., 2025; Solberg & Reikvam, 2023).

In a large prospective cohort of male and female British soldiers, lower ferritin concentrations were independently associated with slower 2.4 km running times, a higher risk of lower limb stress injuries, and lower bone mineral density and adverse markers of bone turnover in both sexes (O'Leary et al., 2024). However, gender-specific differences were observed. In men, a greater decline in iron stores (early-stage iron deficiency) was observed, whereas in women, a greater decline in Hb levels (late-stage iron deficiency) was observed. Higher iron stores were associated with better endurance, a lower risk of musculoskeletal injuries, higher bone mineral density, and lower concentrations of bone metabolism markers in the blood. The authors suggest that improving iron stores prior to the start of intensive training may both improve aerobic capacity and reduce the risk of injury (O'Leary et al., 2024).

6. Diagnosis in sports medicine

The diagnosis of iron metabolism disorders in sports medicine requires a move away from a simplified assessment based solely on haemoglobin (Hb) levels, particularly in the population of competitively training girls and women. Assessing haemoglobin levels alone based on general population norms shows low diagnostic sensitivity in female athletes. The literature reports that many female athletes have normal Hb levels whilst simultaneously exhibiting depletion of systemic iron stores and a reduced oxygen uptake threshold (VO2 max) (Solberg & Reikvam, 2023).

Contemporary reviews and studies on women in sport strongly emphasise that non-anaemic iron deficiency (NAID) is a common phenomenon among female athletes in endurance disciplines, constituting a hidden factor impairing performance. This condition remains undetected in routine haemoglobin (Hb) testing, despite significantly limiting the body's aerobic capacity. In the diagnosis of this syndrome, key importance is attributed to monitoring parameters such as hepcidin, ferritin and sTfR concentrations, as well as the modulating influence of the menstrual cycle phase (Alfaro-Magallanes et al., 2022; Maity & Nandy, 2026; Pedlar et al., 2018; Pengelly et al., 2025; Sim et al., 2019).

In a study conducted in Japan, 47% of female student athletes were found to have ferritin concentrations ≤ 30 ng/ml, without concomitant anaemia according to WHO criteria. A significant proportion of the respondents reported a reduction in physical performance, which was particularly pronounced during menstruation (Nabeyama et al., 2020, 2023). Consequently, for this group of athletes, it is recommended that laboratory diagnostics be expanded to include a panel of tests comprising: ferritin, serum iron, TIBC, TSAT, soluble transferrin receptor (sTfR) and reticulocyte parameters (Maity & Nandy, 2026; Solberg & Reikvam, 2023).

Review studies indicate that the effectiveness of iron supplementation is greatest at ferritin concentrations < 30 ng/ml (Solberg & Reikvam, 2025). However, in the population of women practising endurance sports, it is proposed that a higher, so-called 'athletic threshold' (< 30–35 ng/ml) be adopted as the criterion for significant deficiency, occurring regardless of normal haemoglobin levels (Maity & Nandy, 2026; Nabeyama et al., 2023; Solberg & Reikvam, 2023). Studies on young female athletes demonstrate that ferritin concentrations ≤ 30 ng/ml are highly prevalent and closely correlate with clinical symptoms of fatigue (Nabeyama et al., 2020, 2023).

It is also necessary to distinguish true iron-deficiency anaemia from so-called 'athlete's anaemia', resulting from haemodilution. In endurance sports, there is an increase in plasma volume with unchanged or even elevated erythrocyte mass. As a result, Hb and Hct are reduced, but MCV, ferritin and TSAT remain normal or high (Damian et al., 2021; Nabeyama et al., 2020, 2023). Classic studies in the field of sports haematology emphasise that in anaemia resulting from haemodilution, no signs of iron deficiency or microcytosis are observed, and the reduction in Hb is caused by increased plasma volume (Mairbäurl, 2013; Nabeyama et al., 2020, 2023). In contrast, in iron-deficiency anaemia, low ferritin, reduced TSAT, often elevated sTfR and changes in reticulocyte indices are present, indicating impaired erythropoiesis (Damian et al., 2021; Maity & Nandy, 2026; Solberg & Reikvam, 2023).

In sports medicine practice, periodic, seasonally targeted assessment of the entire iron profile is recommended for female athletes. It is important to consider the phase of the menstrual cycle and periods of increased training load, and to interpret reduced Hb cautiously in the context of plasma volume and iron storage parameters (Damian et al., 2021; Maity & Nandy, 2026; Nabeyama et al., 2020; Solberg & Reikvam, 2023).

Narrative and systematic reviews highlight that the causes of anaemia and iron deficiency in athletes are multifactorial. In addition to diet and training load, these include gastrointestinal microbleeding, exercise-induced haematuria, mechanical haemolysis, heavy menstruation and other nutritional deficiencies (Abulafia et al., 2025; Alaunyte et al., 2015; Beard & Tobin, 2000; Nabeyama et al., 2020).

7. Prevention and treatment of anaemia in athletes

Among athletes, anaemia and iron deficiency are among the most common haematological problems, particularly in endurance sports and among young female athletes during puberty. The consequences include reduced performance, impaired immune function, and even adverse effects on general health (Alaunyte et al., 2015; Beard & Tobin, 2000; Nabeyama et al., 2020, 2023; Solberg & Reikvam, 2023). Therefore, targeted monitoring, dietary modification, careful supplementation and consideration of comorbidities are crucial. Studies on elite Olympians and student-athletes show a significant prevalence of low ferritin levels in the absence of anaemia, which justifies active screening among elite athletes and young women involved in sport (Abulafia et al., 2025; Nabeyama et al., 2020, 2023; Solberg & Reikvam, 2023). These studies assessed blood count, iron, TIBC, ferritin, and vitamins B12 and folic acid (Abulafia et al., 2025; Nabeyama et al., 2023; Solberg & Reikvam, 2023). The systematic review highlights the need to go beyond haemoglobin assessment and to consider storage markers (ferritin) and functional markers when evaluating athletes, particularly in women (Alaunyte et al., 2015; Nabeyama et al., 2023; Solberg & Reikvam, 2023).

In addition to iron deficiency, other causes of anaemia in athletes include deficiencies in other nutrients (vitamin B12, folic acid), haemodilution and redistribution, and haemolysis or menstrual bleeding (Abulafia et al., 2025). Regular monitoring of iron levels is recommended, with a follow-up check 6–8 weeks after the start of treatment, as well as periodic haematological reviews (e.g. every 6 months for women, once a year for men) in athletes, particularly endurance athletes. At the same time, attention is drawn to the lack of strict ferritin thresholds requiring supplementation (Solberg & Reikvam, 2023). The concept of 'dilutional pseudoanaemia' highlights the need for serial measurements and interpretation of Hb and Ht in the context of plasma volume, rather than a single result (Abulafia et al., 2025). Monitoring vitamin D as a factor linked to iron and hepcidin status may further support prevention (Solberg & Reikvam, 2023).

The importance of dietary modifications, including the adoption of an iron-rich diet, is also emphasised. These can improve iron intake, tissue status and performance parameters (Alaunyte et al., 2015). Furthermore, in young female athletes, low iron status is mainly due to dietary choices. A vegetarian diet is particularly relevant. It is recommended to consider low-dose supplementation under medical and dietary supervision to prevent a decline in iron stores during training (Beard & Tobin, 2000). It has been shown that the benefits of supplementation are greatest when ferritin is <30 ng/mL, whereas above this threshold the effects are inconclusive. At the same time, the need to balance the benefits against the risks of adverse hepcidin responses and potential toxicity has been emphasised, which argues in favour of intermittent treatment with monitoring after 6–8 weeks (Solberg & Reikvam, 2023, 2025).

Cohort studies and reviews emphasise that supplementation should be reserved for cases of confirmed deficiency (anaemic or non-anaemic), avoiding the prophylactic administration of high doses without a diagnosis, a view also supported by warnings against the excessive use of iron preparations, including intravenous ones, in young runners without documented deficiency (Alaunyte et al., 2015; Nabeyama et al., 2020).

Although iron supplementation offers many benefits, it is also associated with certain barriers and adverse effects. The most common side effects include gastrointestinal complaints, such as nausea, bloating, and both constipation and diarrhoea, which discourage athletes from continuing to take the supplements (Clénin et al., 2015; Pengelly et al., 2025). Intravenous iron administration is suggested as an alternative to oral treatment, as it guarantees faster results, although this method requires strict medical supervision (Litton et al., 2013).

Long-term use of iron supplements, particularly in the absence of regular monitoring of iron levels, carries the risk of excessive accumulation of this element in the body. Such an excess has toxic effects, which may lead to liver damage and serious metabolic disorders (Clénin et al., 2015).

Another obstacle is an elevated concentration of hepcidin, the hormone that regulates the metabolism of this element. Its levels rise following intense physical exertion. This condition can block iron absorption in the gastrointestinal tract and consequently reduce the efficacy of supplementation, especially when it is taken at the wrong time (Kong et al., 2014).

Furthermore, optimising energy and carbohydrate intake can modify the post-exercise hepcidin response, influencing the utilisation of stored iron reserves (Solberg & Reikvam, 2023). Maintaining adequate levels of vitamins D, B12 and folic acid promotes a healthy iron status and reduces the risk of anaemia (Abulafia et al., 2024; Solberg & Reikvam, 2023).

Studies on Kendo and other Japanese disciplines indicate a significant prevalence of non-anaemic iron deficiency in women, as well as an association between hypoferritinaemia and lower energy intake and shorter training duration (Nabeyama et al., 2020, 2023). This suggests that in athletes, particularly women on restricted diets, one should actively screen for eating disorders and other conditions affecting absorption, such as coeliac disease, using individualised dietary and supplementation strategies (Alaunyte et al., 2015; Beard & Tobin, 2000; Solberg & Reikvam, 2023).

Data from cross-sectional and cohort studies and reviews indicate that effective prevention and treatment of haematological disorders in athletes should be based on targeted monitoring, including ferritin and vitamins, informed dietary modification, and cautious, short-term supplementation targeted at individuals with documented deficiencies. It is crucial to tailor recommendations to the individual, taking into account gender, sport, training load, energy intake and any coexisting nutritional or absorption disorders.

8. Discussion

The data collected highlight the issue of haematological disorders in young female athletes, pointing to the need for a thorough review of the current clinical approach. Traditional diagnostics, based mainly on the assessment of haemoglobin concentration against general population norms, prove to be far from sufficient in this specific group. This phenomenon stems from the fact that an isolated assessment of this parameter does not allow for a precise distinction between physiological, adaptive haemodilution (so-called dilutional pseudo anaemia) and the early stages of actual, pathological iron deficiency. The analysed studies clearly show that in many female elite athletes, there is a significant depletion of the body's stores of this micronutrient whilst haemoglobin levels remain apparently normal. This condition, referred to as non-anaemic iron deficiency (NAID), is currently becoming one of the most significant challenges in sports medicine. Given the high prevalence of this phenomenon, a shift in the diagnostic paradigm and the routine implementation of an expanded iron metabolism panel appear justified, with the key recommendation being to raise the sports-specific cut-off point for ferritin concentration to <30–35 ng/mL.

The multifactorial pathogenesis of the observed deficiencies in young female athletes requires careful interpretation, particularly in the context of the nature of the physical exertion undertaken. The hitherto controversial influence of training type on the haematological profile is explained by overlapping mechanisms of cellular damage and the inflammatory response. Aerobic training, unlike anaerobic training, predisposes to more severe disorders due to increased mechanical haemolysis, caused, among other things, by repeated impact of the feet on the ground or compression of capillaries in contracting muscles. Furthermore, intense endurance exercise stimulates the cytokine-hormone axis, leading to an increase in interleukin-6 concentrations and subsequent secretion of hepcidin. It has been shown that the decrease in iron absorption after exercise, along with blood loss during menstruation and often a diet with insufficient energy, creates a very bad metabolic environment in young women, greatly increasing the risk of iron deficiency.

It is important to emphasise that the clinical implications of non-anaemic iron deficiency go far beyond a decline in oxygen transport parameters and a reduction in oxygen uptake (VO_2 max). Analysis of prospective cohort data shows that low ferritin levels are an independent factor in the deterioration of musculoskeletal health. This results in an increase in subjective fatigue and a deterioration in performance times, and above all correlates with a decrease in bone mineral density and a significantly higher risk of stress injuries to the lower limbs. The sex dimorphism observed in studies of the progression of these disorders, where advanced stages of deficiency manifest more rapidly in women, further highlights the need for early, targeted preventive intervention in this group.

These observations also necessitate a critical approach to commonly used therapeutic strategies. A review of the literature clearly shows that prophylactically and empirically administering high doses of iron preparations, including the increasingly popular intravenous infusions despite a lack of documented indications, is a mistake. This practice carries the risk of toxicity and paradoxical hepcidin stimulation. Effective and safe treatment should be based on short-term (6–8 weeks) oral supplementation, which is most effective when baseline ferritin levels are below 30 ng/mL, with simultaneous, close monitoring of laboratory parameters. Furthermore, holistic care for the athlete must include a differential diagnosis of the causes of a negative energy balance. Optimising the availability of energy and carbohydrates in the diet, ruling out malabsorption syndromes (e.g. coeliac disease) and correcting the frequently co-occurring deficiencies in vitamin D, vitamin B12 and folic acid constitute the essential, non-pharmacological pillars of effective treatment and prevention of sports anaemia.

9. Conclusions

To summarise the data collected, iron deficiency, and in particular non-anaemic iron deficiency (NAID), is a common clinical problem among young female athletes, for whom gender, post-pubertal age and the specific nature of endurance exercise are the main risk factors. The pathogenesis of this phenomenon is multifactorial and includes exercise-induced haemolysis, physiological losses, micro bleeding and inflammation-induced activation of the hepcidin axis, which in sports medicine practice requires careful differentiation from physiological, adaptive dilutional pseudo anaemia. Since diagnosing solely on the basis of haemoglobin concentration is insufficiently sensitive in this group, an expanded panel of iron metabolism markers should be routinely implemented, including ferritin, sTfR and TSAT. A higher, athlete-specific cut-off point for ferritin should be taken into account, set at 30–35 ng/mL. Even without accompanying anaemia, an undiagnosed deficiency of this element leads to serious clinical consequences, such as a decline in aerobic capacity, faster onset of fatigue, reduced bone mineral density and a significantly increased risk of overuse injuries to the musculoskeletal system. For this reason, effective and safe therapeutic management should be individualised, based on dietary optimisation ensuring adequate energy availability, monitoring of co-existing deficiencies (e.g. of vitamin B12, D and folic acid, and the implementation of targeted, short-term iron supplementation based solely on documented laboratory indications, whilst strictly avoiding the routine use of high doses without confirmed deficiency.

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All authors contributed to the study conception, literature review, and manuscript preparation. All authors read and approved the final version of the manuscript.

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