



NICOLAUS COPERNICUS  
UNIVERSITY  
IN TORUŃ

**Journal of Education, Health and Sport. 2026;88:69380.**

**eISSN 2391-8306.**

<https://doi.org/10.12775/JEHS.2026.88.69380>



**Journal of Education, Health and Sport. eISSN 2450-3118**

**Journal Home Page**

<https://apcz.umk.pl/JEHS/index>

OLSZOK, Mikołaj, WIJAS, Daniel, KLUŚ, Michał, KOZDRA, Bartłomiej, MAKSELAN, Natalia, NAWRAT, Natalia, HANDZEL, Karolina, ANCZYK, Antoni and KARBOWIAK, Krzysztof. Subclinical Iron Deficiency in Athletes - Diagnostics, Consequences, and Management Strategies: A Narrative Review. *Journal of Education, Health and Sport*. 2026;88:69380. eISSN 2391-8306. <https://doi.org/10.12775/JEHS.2026.88.69380>

The journal has had 40 points in Minister of Science and Higher Education of Poland parametric evaluation. Annex to the announcement of the Minister of Education and Science of 05.01.2024 No. 32318. Has a Journal's Unique Identifier: 201159. Scientific disciplines assigned: Physical culture sciences (Field of medical and health sciences); Health Sciences (Field of medical and health sciences). Punkty Ministerialne 40 punktów. Załącznik do komunikatu Ministra Nauki i Szkolnictwa Wyższego z dnia 05.01.2024 Lp. 32318. Posiada Unikatowy Identyfikator Czasopisma: 201159. Przypisane dyscypliny naukowe: Nauki o kulturze fizycznej (Dziedzina nauk medycznych i nauk o zdrowiu); Nauki o zdrowiu (Dziedzina nauk medycznych i nauk o zdrowiu). © The Authors 2026; This article is published with open access at Licensee Open Journal Systems of Nicolaus Copernicus University in Toruń, Poland  
Open Access. This article is distributed under the terms of the Creative Commons Attribution Noncommercial License which permits any noncommercial use, distribution, and reproduction in any medium, provided the original author (s) and source are credited. This is an open access article licensed under the terms of the Creative Commons Attribution Non commercial license Share alike. (<http://creativecommons.org/licenses/by-nc-sa/4.0/>) which permits unrestricted, non commercial use, distribution and reproduction in any medium, provided the work is properly cited.  
The authors declare that there is no conflict of interests regarding the publication of this paper.  
Received: 27.02.2026. Revised: 08.03.2026. Accepted: 08.03.2026. Published: 12.03.2026.

## **Subclinical Iron Deficiency in Athletes - Diagnostics, Consequences, and Management Strategies: A Narrative Review**

**Mikołaj Olszok,**

ORCID <https://orcid.org/0009-0006-8628-9459>

E-mail [mikolaj.olszok@gmail.com](mailto:mikolaj.olszok@gmail.com)

Medical University of Silesia in Katowice Poland

15 Poniańskiego Street

40-055 Katowice

**Daniel Wijas,**

ORCID <https://orcid.org/0009-0006-0457-9904>

E-mail [danielwijas4@gmail.com](mailto:danielwijas4@gmail.com)

Medical University of Silesia in Katowice Poland  
15 Poniatowskiego Street  
40-055 Katowice

**Michał Kluś,**

ORCID <https://orcid.org/0009-0005-3695-605X>

E-mail [michalklus123@gmail.com](mailto:michalklus123@gmail.com)

Medical University of Silesia in Katowice Poland  
15 Poniatowskiego Street  
40-055 Katowice

**Bartłomiej Kozdra,**

ORCID <https://orcid.org/0009-0005-7261-6626>

E-mail [bartlomiejkozdra@gmail.com](mailto:bartlomiejkozdra@gmail.com)

Medical University of Silesia in Katowice Poland  
15 Poniatowskiego Street  
40-055 Katowice

**Natalia Makselan,**

ORCID <https://orcid.org/0009-0000-2551-5105>

E-mail [makselan.natalia@gmail.com](mailto:makselan.natalia@gmail.com)

Medical University of Silesia in Katowice Poland  
15 Poniatowskiego Street  
40-055 Katowice

**Natalia Nawrat,**

ORCID <https://orcid.org/0009-0005-2193-7286>

E-mail [nawrat72@gmail.com](mailto:nawrat72@gmail.com)

Medical University of Silesia in Katowice Poland  
15 Poniatowskiego Street  
40-055 Katowice

**Karolina Handzel,**

ORCID <https://orcid.org/0009-0004-5765-0458>

E-mail [karolinahandzel30@gmail.com](mailto:karolinahandzel30@gmail.com)

Medical University of Silesia in Katowice Poland

15 Poniatowskiego Street  
40-055 Katowice

**Antoni Anczyk,**

ORCID <https://orcid.org/0009-0008-3817-3675>

E-mail [naron333@gmail.com](mailto:naron333@gmail.com)

Medical University of Silesia in Katowice Poland  
15 Poniatowskiego Street  
40-055 Katowice

**Krzysztof Karbowski,**

ORCID <https://orcid.org/0009-0009-1332-5000>

E-mail [krzysztof.karbowski12@gmail.com](mailto:krzysztof.karbowski12@gmail.com)

Medical University of Silesia in Katowice Poland  
15 Poniatowskiego Street  
40-055 Katowice

**Corresponding Author**

Mikołaj Olszok, E-mail [mikolaj.olszok@gmail.com](mailto:mikolaj.olszok@gmail.com)

## **Abstract**

### **Background:**

Subclinical iron deficiency is common in physically active populations, especially among female and endurance athletes, and may impair oxygen transport, mitochondrial energy production, and training adaptation before anemia develops. Exercise-related mechanisms (hemolysis, gastrointestinal loss, hepcidin-mediated reduced absorption) and dietary factors contribute to chronically low iron stores.

### **Aim:**

To summarize evidence on diagnostic criteria, physiological and performance-related consequences, and management strategies for subclinical iron deficiency in athletes.

**Methods:**

A narrative review of peer-reviewed human studies was conducted using PubMed, Scopus, Web of Science, SPORTDiscus, CINAHL, and the Cochrane Library (inception-February 2025). Studies in competitive or highly trained athletes reporting diagnostic approaches, prevalence, performance or health outcomes, or management strategies were included.

**Results:**

Diagnostic criteria vary, with ferritin cut-offs of 20 - 40 µg/L most often used and limited consensus on sport-specific thresholds or routine use of transferrin saturation, soluble transferrin receptor, and hepcidin. Non-anemic iron deficiency affects 10 - 35% of male and up to 60% of female athletes, with the highest prevalence in adolescents and endurance or aesthetic sports. Low iron stores are linked to reduced endurance, lower maximal aerobic capacity, increased fatigue, and possibly blunted training adaptation, while effects on anaerobic performance are inconsistent. Management emphasizes periodic screening, dietary strategies to improve iron bioavailability, and targeted oral supplementation timed to limit hepcidin-related malabsorption; intravenous iron is reserved for selected cases.

**Conclusions:**

Subclinical iron deficiency is common, under-recognized, and clinically relevant in athletes. Standardized, sport-specific diagnostic criteria, early screening, and individualized, evidence-based interventions delivered by multidisciplinary teams are essential for effective prevention and management.

**Key words:** iron deficiency; non-anemic iron deficiency; ferritin; athletes; sports performance; hepcidin; iron supplementation; endurance training

**1. Introduction**

Subclinical iron deficiency is increasingly recognized as a critical yet often overlooked determinant of athletic performance. Iron is central to oxygen transport, mitochondrial respiration, and cellular energy production, making optimal iron availability essential for endurance, recovery, and adaptation to training in both male and female athletes (Sim et al., 2019; Nabeyama et al., 2023; Pengelly et al., 2024; Axling et al., 2020; Dutt et al., 2022;

Sawicki et al., 2023). At the same time, conventional clinical definitions of iron deficiency and anemia may fail to capture early, performance-relevant iron depletion, leading to a growing interest in refining diagnostic thresholds and management strategies specifically for sport populations (Sim et al., 2019; Pedlar et al., 2018; Pengelly et al., 2024; Galetti et al., 2021; Foy et al., 2019).

### **1.1. Iron Metabolism and Its Role in Athletic Performance**

Body iron is distributed mainly in hemoglobin, myoglobin, iron-containing enzymes (including those of the mitochondrial respiratory chain), circulating transferrin, and storage pools (ferritin and hemosiderin). Through hemoglobin and myoglobin, iron enables oxygen transport from lungs to tissues and its effective utilization in working muscle, while iron-sulfur and heme enzymes support oxidative phosphorylation and ATP production in mitochondria. Regular intense exercise increases erythropoietic drive and total iron requirements, and athletes experience additional losses via gastrointestinal microbleeding, hemolysis (e.g., foot-strike), sweat, and urine, as well as exercise-induced inflammation and hepcidin-mediated reductions in absorption. Consequently, even modest reductions in iron stores can impair oxygen delivery, oxidative enzyme function, and endurance performance before anemia develops.

### **1.2. Definition of Subclinical Iron Deficiency**

Subclinical iron deficiency in athletes usually refers to iron deficiency without anemia, in contrast to iron deficiency anemia characterized by reduced hemoglobin. Staging models distinguish: (i) iron deficiency with depleted stores but normal hemoglobin and preserved transferrin saturation (e.g., ferritin <35 µg/L, Hb >115 g/L, transferrin saturation >16%), (ii) iron-deficient non-anemia with impaired iron supply to erythropoiesis (e.g., ferritin <20 µg/L and transferrin saturation <16% with normal Hb), and (iii) overt iron-deficiency anemia with low ferritin and reduced Hb (Sim et al., 2019; Pedlar et al., 2018; Pengelly et al., 2024). In high-level female athletes, non-anemic iron deficiency is often defined by serum ferritin <30 - 40 µg/L with normal hemoglobin (Sim et al., 2019; Nabeyama et al., 2023; Pedlar et al., 2018; Pengelly et al., 2024; Axling et al., 2020). However, there is no universal consensus, and recent physiological work suggests that upregulation of iron absorption may begin at ferritin values <50 µg/L in young women, indicating incipient deficiency at higher ferritin than traditionally assumed (Pengelly et al., 2024; Galetti et al., 2021). Moreover, inflammation and training-induced plasma volume expansion complicate interpretation of ferritin and hemoglobin,

underscoring the need for athlete-specific diagnostic criteria and multi-marker approaches (e.g., including transferrin saturation, soluble transferrin receptor, and hepcidin) (Sim et al., 2019; Cappellini et al., 2020; Pedlar et al., 2018; Pengelly et al., 2024; Camaschella et al., 2020; Roemhild et al., 2021; Foy et al., 2019; Blecharz et al., 2025).

### Representative Diagnostic Thresholds in Athletes

Concept / Stage	Typical markers / thresholds (illustrative)	Citations
Iron deficiency (depleted stores)	Ferritin <30 - 35 µg/L, normal Hb, TSAT often >16%	(Sim et al., 2019; Roy et al., 2022; Pedlar et al., 2018; Pengelly et al., 2024; Axling et al., 2020)
Non-anemic iron deficiency (IDNA)	Ferritin <20 - 30 µg/L, TSAT <16 - 20%, normal Hb	(Sim et al., 2019; Pedlar et al., 2018; Pengelly et al., 2024; Packer et al., 2024)
Iron-deficiency anemia (IDA)	Low ferritin (often <12 - 20 µg/L) with reduced Hb	(Sim et al., 2019; Cappellini et al., 2020; Pengelly et al., 2024)
Incipient deficiency (physiologic)	Ferritin <50 µg/L associated with upregulated absorption, low hepcidin	(Pengelly et al., 2024; Galetti et al., 2021)

Figure 1: Commonly used and physiologic ferritin thresholds relevant to athletes.

### 1.3. Prevalence of Subclinical Iron Deficiency in Athletes

Iron deficiency, with or without anemia, is common across sports. Narrative and empirical data indicate that 15 - 35% of female and approximately 3 - 11% of male athletes show iron deficiency, with smaller cohorts reporting compromised iron stores in >50% of female and up to 30% of male athletes (Sim et al., 2019; Roy et al., 2022; Nabeyama et al., 2023; Pedlar et al., 2018; Axling et al., 2020). In adolescent and young adult competitive athletes, overall iron deficiency prevalence has been reported at ~10.9% in males and 35.9% in females, with the highest rates during adolescence and early adulthood (Roy et al., 2022; Cohen & Powers, 2024). Among university athletes in Japan, 47% of female athletes were iron-deficient but non-anemic when hypoferritinemia was defined as ferritin  $\leq$ 30 ng/mL, whereas none had anemia, underscoring the burden of subclinical deficiency (Nabeyama et al., 2023). Endurance and high-volume training appear to confer particularly high risk via greater iron losses and inflammatory responses (Sim et al., 2019; Nabeyama et al., 2023; Varillas-Delgado, 2025; Peeling et al., 2008; Cohen & Powers, 2024). Female athletes are consistently more affected than males due to menstrual blood loss, lower baseline iron stores, and sometimes lower dietary iron intake (Sim et al., 2019; Roy et al., 2022; Nabeyama et al., 2023; Pedlar et al., 2018; Axling et al., 2020; Cohen & Powers, 2024). Adolescents may have up to 30% higher iron requirements than sedentary peers, combining growth, menses, and training-related losses (Roy et al., 2022; Cohen & Powers, 2024).

## **1.4. Rationale for the Review**

Despite the clear biological rationale and substantial prevalence of iron deficiency in athletic populations, multiple gaps persist. First, diagnostic thresholds for subclinical iron deficiency in athletes remain debated, with heterogeneous cut-offs for ferritin and transferrin saturation, limited integration of hepcidin, and poor adjustment for inflammation, plasma volume shifts, sex, age, and sport-specific demands (Sim et al., 2019; Cappellini et al., 2020; Pedlar et al., 2018; Pengelly et al., 2024; Camaschella et al., 2020; Roemhild et al., 2021; Galetti et al., 2021; Foy et al., 2019). Second, the performance consequences of iron deficiency without anemia—particularly for different types of performance (endurance, strength, anaerobic power) and at varying severity of iron depletion—are incompletely characterized and sometimes inconsistent across studies (Sim et al., 2019; Roy et al., 2022; Nabeyama et al., 2023; Pedlar et al., 2018; Pengelly et al., 2024; Axling et al., 2020). Third, there is no unified framework for management strategies that balances early intervention against the risks of unnecessary supplementation or iron overload, nor for tailoring strategies by sex, age, and sport (Sim et al., 2019; Cappellini et al., 2020; Pedlar et al., 2018; Pengelly et al., 2024; Fan, 2025; Axling et al., 2020; Cohen & Powers, 2024).

A narrative synthesis that integrates contemporary insights into iron and hepcidin biology with athlete-specific epidemiology and performance data is therefore warranted. This review aims to (i) clarify definitions and diagnostics for subclinical iron deficiency in athletes, (ii) summarize its prevalence and risk profiles across sex, age, and sport type, and (iii) outline evidence-based management approaches relevant to sports scientists, clinicians, and support staff.

## **2. Methods and Results**

This section outlines the narrative search and synthesizes key findings on diagnostics, consequences, and management of subclinical iron deficiency in athletes.

### **2.1.1 Literature Search Strategy**

The literature base for this narrative review was informed by prior systematic and narrative reviews on iron and performance in athletes, particularly female and endurance athletes (Pengelly et al., 2024; Rubeor et al., 2018; Sim et al., 2019; Šmid et al., 2024; McCormick et

al., 2020; Heffernan et al., 2019; Pedlar et al., 2018). Core databases used in these works and followed here include MEDLINE/PubMed, Web of Science, Scopus, SPORTDiscus, CINAHL, EMBASE, Cochrane Library, and sport-specific resources (Pengelly et al., 2024; Rubeor et al., 2018; Sim et al., 2019; Šmid et al., 2024; Heffernan et al., 2019).

Typical keyword combinations included “iron deficiency”, “non-anemic iron deficiency”, “ferritin”, “hepcidin”, “transferrin saturation”, “soluble transferrin receptor”, “athlete\*”, “endurance”, “sports performance”, “oral iron”, and “supplementation”, connected with Boolean operators such as AND/OR (e.g., “iron deficiency AND athletes AND performance”, “ferritin OR transferrin saturation AND supplementation”) (Pengelly et al., 2024; Rubeor et al., 2018; Šmid et al., 2024; Heffernan et al., 2019).

Recent systematic reviews on female athletes and oral iron supplementation set upper bounds of July 2023 and November 2022 for full database searches, while also including earlier foundational work on iron markers, diagnostics, and guidelines from 2004 - 2021 (Pengelly et al., 2024; Rubeor et al., 2018; Sim et al., 2019; Šmid et al., 2024; Lynch et al., 2018; Peyrin-Biroulet et al., 2015; Mei et al., 2021; Suchdev et al., 2017). For this narrative review, emphasis is placed on publications from approximately 2005 onward, with inclusion of earlier landmark diagnostic and biomarker papers where necessary (Lynch et al., 2018; Wish, 2006; Peeling et al., 2008; Suchdev et al., 2017).

### **2.1.2 AI.**

AI tools were additionally applied for language editing to improve grammar, style, and clarity in the presentation of results. All uses of AI were strictly assistive and conducted under full human supervision. The final interpretation of findings, classification of reasoning errors, and formulation of conclusions were performed exclusively by human experts in clinical medicine and formal logic. The role of AI was limited to supporting efficiency in data processing, pattern recognition, and linguistic refinement, and did not replace human judgment at any stage of the analytical process.

## **2.2. Inclusion and Exclusion Criteria**

Evidence was drawn from observational cohorts, interventional trials (particularly randomized controlled trials of iron supplementation), as well as high-quality systematic and narrative reviews relevant to iron status and performance in athletic or highly active populations

(Pengelly et al., 2024; Rubeor et al., 2018; Sim et al., 2019; Šmid et al., 2024; McCormick et al., 2020; Heffernan et al., 2019; Pedlar et al., 2018).

Eligible populations included competitive athletes (youth to adult) or clearly physically active individuals (e.g.,  $\text{VO}_2\text{max} >45 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$  or  $\geq 5 \text{ h}\cdot\text{week}^{-1}$  training) with documented iron indices (Pengelly et al., 2024; Rubeor et al., 2018; Sim et al., 2019; Roy et al., 2022; Šmid et al., 2024). Studies confined to chronic disease states (e.g., chronic kidney disease) or non-athletic general populations were used primarily to inform biomarker interpretation, not performance effects (Lynch et al., 2018; Wish, 2006; Mei et al., 2021; Suchdev et al., 2017).

Most modern sport-specific reviews restricted studies to English-language full-text publications, excluding editorials, letters, commentaries, and abstracts without primary data (Pengelly et al., 2024; Rubeor et al., 2018; Šmid et al., 2024; Heffernan et al., 2019). Grey literature and non-peer-reviewed sources were generally excluded.

## **2.3. Diagnostic Approaches to Subclinical Iron Deficiency**

### **2.3.1. Biochemical Markers**

Routine assessment in athletes typically includes serum ferritin, hemoglobin (Hb), and transferrin saturation (TSAT), often supplemented by soluble transferrin receptor and increasingly hepcidin (Pengelly et al., 2024; Sim et al., 2019; Roy et al., 2022; Šmid et al., 2024; Kielbik & Witkowska-Piłaszewicz, 2025; Lynch et al., 2018; Pedlar et al., 2018; Nabeyama et al., 2023; Peeling et al., 2008).

#### **Ferritin**

Ferritin reflects iron stores but is an acute-phase protein, rising with inflammation and intensive exercise (Sim et al., 2019; Roy et al., 2022; Kielbik & Witkowska-Piłaszewicz, 2025; Lynch et al., 2018; Nabeyama et al., 2023; Suchdev et al., 2017). In athletes, “Stage 1 iron deficiency” is often defined as ferritin  $<35 \mu\text{g/L}$  with normal Hb and TSAT  $>16\%$  (Sim et al., 2019; Kielbik & Witkowska-Piłaszewicz, 2025). More severe non-anemic deficiency (IDNA) is characterized by ferritin  $<20 \mu\text{g/L}$  and TSAT  $<16\%$  (Pengelly et al., 2024; Rubeor et al., 2018; Sim et al., 2019). Systematic reviews in female athletes and supplementation trials frequently use sFer  $<40 \mu\text{g/L}$  as an inclusion criterion, with evidence that performance benefits are clearest when ferritin is  $\leq 20 \mu\text{g/L}$  (Pengelly et al., 2024; Rubeor et al., 2018; Šmid et al., 2024; Heffernan et al., 2019). Physiologic analyses suggest early iron-deficient erythropoiesis may begin at ferritin around 25

$\mu\text{g/L}$  in women and that hepcidin/sTfR-based thresholds may indicate early deficiency at  $\leq 50$   $\mu\text{g/L}$  (Kiełbik & Witkowska-Piłaszewicz, 2025; Mei et al., 2021; Tarancón-Díez et al., 2022).

### **Hemoglobin (Hb)**

Hb is central to defining iron-deficiency anemia, but in athletes is affected by training-induced plasma volume expansion, altitude, and environmental adaptation, potentially leading to “sports anemia” without true iron depletion (Sim et al., 2019; Kiełbik & Witkowska-Piłaszewicz, 2025; Pedlar et al., 2018). Normal or “low-normal” Hb does not exclude tissue iron deficiency or performance-relevant IDNA (Pengelly et al., 2024; Sim et al., 2019; Kiełbik & Witkowska-Piłaszewicz, 2025; Pedlar et al., 2018).

### **Transferrin Saturation (TSAT)**

TSAT reflects circulating iron readily available for erythropoiesis. Cut-offs  $<16 - 20\%$  are widely used to define impaired supply and to distinguish Stage 2 IDNA from simple low stores (Pengelly et al., 2024; Rubeor et al., 2018; Sim et al., 2019; Kiełbik & Witkowska-Piłaszewicz, 2025; Peyrin-Biroulet et al., 2015). Some heart failure and guideline data indicate TSAT is more closely related to exercise capacity than ferritin alone (Wish, 2006; Lee et al., 2025).

### **Soluble Transferrin Receptor (sTfR)**

sTfR reflects bone marrow iron demand, with increases indicating iron-restricted erythropoiesis and being less influenced by inflammation than ferritin (Roy et al., 2022; Lynch et al., 2018; Nabeyama et al., 2023; Wish, 2006; Mei et al., 2021; Suchdev et al., 2017). In athletic cohorts, sTfR helps to distinguish **latent (tissue) deficiency** from prelatent low stores and can refine staging beyond ferritin alone (Roy et al., 2022; Kiełbik & Witkowska-Piłaszewicz, 2025). The sTfR/hepcidin ratio has been proposed as a sensitive indicator of early deficiency, correlating strongly when ferritin is  $\leq 50$   $\text{ng/mL}$  (Tarancón-Díez et al., 2022).

### **Hepcidin**

Hepcidin is the master iron-regulatory hormone, upregulated by inflammation and iron sufficiency, and suppressed by iron deficiency and hypoxia (Sim et al., 2019; Kiełbik & Witkowska-Piłaszewicz, 2025; Lynch et al., 2018; Peeling et al., 2008). Exercise acutely elevates hepcidin, transiently reducing iron absorption; this response is attenuated in iron-deficient athletes, consistent with homeostatic up-regulation of absorption (Sim et al., 2019; Kiełbik & Witkowska-Piłaszewicz, 2025; Peeling et al., 2008). While still mostly research-based, hepcidin helps interpret ferritin and TSAT in the context of training and

inflammation, and may guide timing of supplementation (Sim et al., 2019; Kiełbik & Witkowska-Piłaszewicz, 2025; McCormick et al., 2020; Peeling et al., 2008).

### **2.3.2. Interpretation Challenges in Athletes**

Athletes present several interpretation challenges for standard iron markers. Ferritin rises as an acute-phase reactant with infections, inflammation, and after intense training, which can mask deficiency if not adjusted for inflammatory markers or collection timing (Sim et al., 2019; Roy et al., 2022; Kiełbik & Witkowska-Piłaszewicz, 2025; Lynch et al., 2018; Nabeyama et al., 2023; Peeling et al., 2008; Suchdev et al., 2017). Similarly, hemoglobin and red cell indices are affected by training-induced hypervolemia and heat adaptation, leading to lower concentrations (“pseudo-anemia”) without reduced red cell mass or impaired performance (Sim et al., 2019; Kiełbik & Witkowska-Piłaszewicz, 2025; Pedlar et al., 2018).

Cross-sectional data from athletic and non-athletic populations show that inflammation (often reflected by C-reactive protein and  $\alpha$ 1-acid glycoprotein) can materially distort the prevalence of iron deficiency estimates when using ferritin alone, sometimes changing estimates by >20 percentage points in children and >8 percentage points in women (Lynch et al., 2018; Suchdev et al., 2017). Consequently, several sport-focused reviews emphasize standardized blood collection (morning, rested, hydrated, away from hard sessions) and use of multiple markers (ferritin, TSAT, sTfR,  $\pm$  hepcidin) rather than single-marker cut-offs (Sim et al., 2019; Roy et al., 2022; Kiełbik & Witkowska-Piłaszewicz, 2025; Pedlar et al., 2018; Nabeyama et al., 2023; Peeling et al., 2008; Suchdev et al., 2017).

## **2.4. Consequences of Subclinical Iron Deficiency**

### **2.4.1. Effects on Physical Performance**

#### **Aerobic capacity**

Systematic evidence in high-level female athletes indicates that non-anemic iron deficiency can reduce endurance performance by approximately 3 - 4%, with decrements in maximal aerobic capacity and time-to-exhaustion (Pengelly et al., 2024; Sim et al., 2019; Šmid et al., 2024; Heffernan et al., 2019). When IDNA athletes receive iron supplementation (typically 16 - 100 mg elemental iron/day for 6 - 18 weeks),  $VO_2$ max has improved by ~6 - 15% in those with clearly low baseline ferritin ( $\leq 20 - 25 \mu\text{g/L}$ ), while benefits are absent or minimal when baseline ferritin is higher ( $\approx 28 - 30 \mu\text{g/L}$ ) (Pengelly et al., 2024; Rubeor et al., 2018; Šmid et

al., 2024; Heffernan et al., 2019). Meta-analytic data in mixed-sex athletes show small but positive effects of oral iron on VO<sub>2</sub>max, again more pronounced at low pre-supplementation ferritin ( $\leq 12 \mu\text{g/L}$ ) (Šmid et al., 2024).

### **Fatigue, recovery, and training adaptation**

Subclinical iron deficiency is linked to increased fatigue, reduced training capacity, impaired muscle function and stress management, and poorer competition results even before anemia develops (Sim et al., 2019; Šmid et al., 2024; Heffernan et al., 2019; Pedlar et al., 2018). Experimental and observational data suggest that low iron stores impair oxidative enzymes and respiratory proteins, limiting mitochondrial ATP production and contributing to slower recovery and diminished adaptation to endurance and altitude training (Pengelly et al., 2024; Sim et al., 2019; Kielbik & Witkowska-Piłaszewicz, 2025; Pedlar et al., 2018). Supplementing athletes with low pre-altitude ferritin ( $< 35 \mu\text{g/L}$ ) during altitude exposure enhances hematological adaptation, underlining the role of adequate iron in training adaptation (Sim et al., 2019).

### **Strength and anaerobic performance**

Evidence for effects on isokinetic strength and anaerobic power is less consistent; reductions of  $-23\%$  to small gains ( $+4\%$ ) have been reported in ID athletes, with iron supplementation showing variable effects ( $-5\%$  to  $+9\%$ ), again influenced by baseline deficiency severity and study power (Pengelly et al., 2024; Heffernan et al., 2019).

## **2.4.2. Health Consequences**

### **Immune function**

Iron deficiency and low energy availability (REDs) are both associated with immune perturbations. Although data specific to subclinical deficiency in athletes are limited, iron is essential for immune cell proliferation and function, and deficiency may predispose to fatigue, frequent minor illness, and impaired recovery (Sim et al., 2019; Šmid et al., 2024; Heffernan et al., 2019; Mountjoy et al., 2023). Exercise-induced inflammation, hepcidin up-regulation, and recurrent low ferritin in athletes suggest a complex interplay between iron, immune responses, and training stress (Sim et al., 2019; Kielbik & Witkowska-Piłaszewicz, 2025; Peeling et al., 2008).

### **Cognitive and psychological effects**

In non-athletic populations, iron deficiency without anemia is linked to impairments in

attention, cognition, and mood, especially in young women (Lynch et al., 2018; Mei et al., 2021). Given the cognitive demands of high-level sport and reports of fatigue, poor concentration, and decreased stress tolerance in iron-deficient athletes, similar subclinical effects are plausible but under-researched in strictly athletic cohorts (Sim et al., 2019; Šmid et al., 2024; Heffernan et al., 2019; Pedlar et al., 2018; Mountjoy et al., 2023).

### **Injury risk and broader health**

Relative Energy Deficiency in Sport (REDs) consensus statements emphasize that low energy availability, menstrual dysfunction, and micronutrient deficits (including iron) contribute to impaired bone health, increased injury risk, and reduced performance (Mountjoy et al., 2023). While direct data connecting subclinical iron deficiency alone to musculoskeletal injury are scarce, chronic fatigue, impaired adaptation, and co-existing nutrient deficits likely increase overall injury and illness vulnerability in athletes with persistent low iron (Sim et al., 2019; Šmid et al., 2024; Pedlar et al., 2018; Mountjoy et al., 2023; Lee et al., 2025).

## **2.5. Management and Prevention Strategies**

### **2.5.1. Nutritional Interventions**

#### **Dietary iron sources and heme vs. non-heme iron**

Initial management of mild or prelatent deficiency prioritizes dietary strategies: increasing intake of iron-rich foods and optimizing overall energy intake (Sim et al., 2019; Roy et al., 2022; Šmid et al., 2024; McCormick et al., 2020; Heffernan et al., 2019; Pedlar et al., 2018; Nabeyama et al., 2023). Heme iron from meat, poultry, and fish has substantially higher bioavailability than non-heme iron from plant sources and fortified foods, and is particularly important for at-risk groups such as female endurance athletes and adolescents (Sim et al., 2019; Roy et al., 2022; Šmid et al., 2024; Heffernan et al., 2019; Nabeyama et al., 2023). Observational data in Japanese university athletes highlight that insufficient energy intake is associated with hypoferritinemia, while non-heme-heavy diets may limit absorption, even when nominal iron intake is high (Roy et al., 2022; Nabeyama et al., 2023).

#### **Factors influencing absorption**

Vitamin C enhances non-heme iron absorption, whereas phytates (in whole grains, legumes), polyphenols (tea, coffee), and calcium can inhibit it when co-ingested (Sim et al., 2019; McCormick et al., 2020; Lynch et al., 2018; Heffernan et al., 2019; Nabeyama et al., 2023). Timing iron-rich meals away from high-calcium foods and tea/coffee, and ensuring adequate

carbohydrate and energy availability (to avoid hepcidin elevation under LEA) are recommended (Sim et al., 2019; McCormick et al., 2020; Mountjoy et al., 2023; Peeling et al., 2008).

## **2.5.2. Supplementation Protocols**

### **Indications for supplementation**

Most sport-focused reviews recommend progressing to oral iron supplementation when ferritin falls below ~20 - 30 µg/L (particularly with TSAT <16 - 20%), or when clear symptoms or performance decrements accompany low stores, and especially in preparation for altitude or heavy training blocks (Pengelly et al., 2024; Rubeor et al., 2018; Sim et al., 2019; Šmid et al., 2024; McCormick et al., 2020; Heffernan et al., 2019; Pedlar et al., 2018). Evidence indicates that benefits on performance and hematologic indices are greatest when baseline ferritin is ≤12 - 20 µg/L and limited when ferritin is in the low-normal range (~25 - 30 µg/L) (Pengelly et al., 2024; Rubeor et al., 2018; Šmid et al., 2024; Heffernan et al., 2019).

### **Dosing strategies**

Effective oral iron protocols in athletes have used 16 - 100 mg elemental iron/day (often as ferrous sulfate) for 6 - 8 weeks, with greater effects on ferritin and performance at higher doses and lower baseline ferritin (Pengelly et al., 2024; Sim et al., 2019; Šmid et al., 2024; Heffernan et al., 2019). Recent treatment-strategy refinements propose morning dosing, ideally within 30 min after morning exercise, and for athletes with gastrointestinal sensitivity, alternate-day dosing or lower doses to enhance fractional absorption and reduce side effects (Sim et al., 2019; McCormick et al., 2020; Peeling et al., 2008). High single daily doses (e.g., 130 mg/day) may not further improve status when baseline ferritin is already normal and can increase side effects (Šmid et al., 2024; Heffernan et al., 2019). Intravenous iron is generally reserved for severe deficiency, intolerance/non-response to oral supplements, or time-critical situations (e.g., major championships) (Sim et al., 2019; McCormick et al., 2020; Pedlar et al., 2018; Peyrin-Biroulet et al., 2015).

## **2.5.3. Monitoring and Screening in Athletes**

Regular screening and longitudinal monitoring are central to prevention. Prevalence data in adolescent and young adult athletes (10.9% of males and 35.9% of females iron-deficient in a German cohort; 47% hypoferritinemia in Japanese female university athletes) support at least annual screening, with more frequent testing (2 - 3 times/year) in high-risk groups such as

female endurance and aesthetic sport athletes, adolescents, those with heavy menstrual bleeding, history of deficiency, or planned altitude training (Sim et al., 2019; Roy et al., 2022; Kielbik & Witkowska-Piłaszewicz, 2025; Pedlar et al., 2018; Nabeyama et al., 2023; Lee et al., 2025).

Recommended panels typically include ferritin, Hb, full blood count, TSAT or serum iron/TIBC, and, where possible, sTfR and inflammatory markers (CRP, AGP) to aid interpretation (Sim et al., 2019; Roy et al., 2022; Kielbik & Witkowska-Piłaszewicz, 2025; Lynch et al., 2018; Pedlar et al., 2018; Nabeyama et al., 2023; Suchdev et al., 2017). Sports clubs and medical teams are advised to standardize blood collection (rested, morning, hydrated, no intense training in preceding 24 - 48 h) and to integrate iron status into broader REDs and menstrual health surveillance, nutrition counselling, and training-load management (Sim et al., 2019; Kielbik & Witkowska-Piłaszewicz, 2025; Pedlar et al., 2018; Nabeyama et al., 2023; Mountjoy et al., 2023; Peeling et al., 2008; Lee et al., 2025).

### Key Aspects of Diagnosis and Management in Athletes

Domain	Key points for athletes	Citations
Core markers	Use ferritin, Hb, TSAT; add sTfR ± hepcidin where possible	(Pengelly et al., 2024; Sim et al., 2019; Roy et al., 2022; Šmid et al., 2024; Kielbik & Witkowska-Piłaszewicz, 2025; Lynch et al., 2018; Pedlar et al., 2018; Nabeyama et al., 2023; Peeling et al., 2008; Tarancón-Díez et al., 2022; Suchdev et al., 2017)
Key cut-offs	Performance benefits most evident when ferritin $\leq$ 12 - 20 $\mu$ g/L; early deficiency may begin $\leq$ 25 - 50 $\mu$ g/L	(Pengelly et al., 2024; Rubeor et al., 2018; Sim et al., 2019; Šmid et al., 2024; Kielbik & Witkowska-Piłaszewicz, 2025; Heffernan et al., 2019; Mei et al., 2021; Tarancón-Díez et al., 2022)
Interpretation issues	Adjust for inflammation, training load, hypervolemia; avoid relying on ferritin or Hb alone	(Sim et al., 2019; Roy et al., 2022; Kielbik & Witkowska-Piłaszewicz, 2025; Lynch et al., 2018; Pedlar et al., 2018; Nabeyama et al., 2023; Peeling et al., 2008; Suchdev et al., 2017)
Performance effects	IDNA reduces endurance 3 - 4%; VO <sub>2</sub> max and performance improve 2 - 20% after targeted supplementation	(Pengelly et al., 2024; Rubeor et al., 2018; Sim et al., 2019; Šmid et al., 2024; Heffernan et al., 2019; Pedlar et al., 2018)
First-line management	Optimize diet (heme iron, energy, vitamin C), address LEA/REDs	(Sim et al., 2019; Roy et al., 2022; Šmid et al., 2024; McCormick et al., 2020; Heffernan et al., 2019; Nabeyama et al., 2023; Mountjoy et al., 2023; Peeling et al., 2008; Lee et al., 2025)
Supplementation	16 - 100 mg elemental iron/day for 6 - 8 weeks when clearly indicated; consider timing/alternate-day dosing	(Pengelly et al., 2024; Rubeor et al., 2018; Sim et al., 2019; Šmid et al., 2024; McCormick et al., 2020; Heffernan et al., 2019; Pedlar et al., 2018; Peeling et al., 2008)
Screening	Annual to 2 - 3 $\times$ /year in high-risk groups; standardized sampling conditions	(Sim et al., 2019; Roy et al., 2022; Kielbik & Witkowska-Piłaszewicz, 2025; Pedlar et al., 2018; Nabeyama et al., 2023; Lee et al., 2025; Suchdev et al., 2017)

**Figure 1:** Summary of key diagnostic and management themes for athletes.

### **3. Discussion**

#### **3.1. Clinical and Practical Implications**

Early identification of subclinical iron deficiency is crucial in athletes, as performance decrements and impaired adaptation to training may occur before overt anemia develops. Detecting low iron stores at this stage allows targeted interventions that can preserve maximal oxygen transport capacity, mitochondrial function, and neuromuscular performance, thereby preventing unexplained fatigue, reduced training quality, and increased illness susceptibility during congested competition periods.

From a practical standpoint, integrating iron status monitoring into routine sports medicine screening facilitates individualized training and recovery planning. Periodic assessment of ferritin, hemoglobin, and complementary markers enables coaches and clinicians to adjust training loads, altitude exposure, and competition schedules for at-risk athletes. In cases of declining iron indices, temporary modification of training intensity, optimization of dietary iron intake, and, when indicated, supplementation can be implemented proactively, minimizing time lost from training and reducing the likelihood of more severe deficiency requiring prolonged rehabilitation.

#### **3.2. Limitations of Current Evidence**

The available literature on subclinical iron deficiency in athletes is constrained by several methodological limitations. Many studies use small, heterogeneous samples, lack control groups, or apply cross-sectional designs, which restrict the ability to infer causality between iron status and performance outcomes. Moreover, variability in training status, dietary habits, menstrual function, and environmental conditions is often insufficiently controlled, introducing potential confounding.

A further challenge is the heterogeneity of diagnostic criteria used to define subclinical iron deficiency. Studies differ in ferritin cut-off values, in whether hemoglobin and transferrin saturation are incorporated, and in the extent to which inflammatory markers are considered. This inconsistency complicates comparisons across studies and may contribute to divergent estimates of prevalence and impact. Additionally, the frequent reliance on single time-point

measurements ignores the dynamic nature of iron metabolism in response to training cycles, acute exercise, and illness, limiting the ecological validity of current findings.

### **3.3. Future Research Directions**

Future research should prioritize the development and validation of sport-specific reference ranges for iron-related biomarkers that account for training volume, sex, age, and discipline (e.g., endurance vs. power sports). Establishing consensus thresholds for subclinical iron deficiency, ideally incorporating indices such as soluble transferrin receptor and hepcidin alongside ferritin and hemoglobin, would enhance diagnostic precision and comparability between studies.

Longitudinal studies in elite athletes are needed to elucidate the temporal relationship between iron status, training load, and performance. Prospective cohort designs following athletes across seasons, altitude camps, and periods of intensified training would clarify critical windows for screening and intervention, as well as identify individual susceptibility profiles. Interventional trials comparing different nutritional, supplementation, and monitoring strategies - while rigorously controlling for inflammation and exercise-induced plasma volume shifts - are also warranted to define evidence-based protocols for preventing and managing subclinical iron deficiency in high-performance sport.

## **4. Conclusions**

Subclinical iron deficiency is a prevalent yet frequently underdiagnosed condition in athletes, particularly in endurance disciplines and among female competitors. Its insidious nature - often occurring without overt anemia - means that meaningful decrements in performance and well-being can develop before standard clinical thresholds are reached.

Early, sport-specific screening protocols that go beyond hemoglobin alone and incorporate ferritin, transferrin saturation, and, where available, additional markers such as soluble transferrin receptor or hepcidin, are crucial to identifying at-risk athletes before performance deteriorates. Individualized management strategies, including tailored nutritional counseling, evidence-based supplementation when indicated, and adjustments in training load, may help prevent performance decline and reduce potential health complications such as increased fatigue, impaired immune function, and heightened injury risk.

Effective prevention and treatment require close multidisciplinary cooperation. Sports physicians, dietitians, exercise physiologists, and coaches should work together to implement routine monitoring, interpret iron indices within the specific context of training and competition, and design practical interventions that are compatible with the demands of elite sport. Establishing clear, sport- and sex-specific reference ranges and integrating iron status assessment into regular medical evaluations can help bridge the gap between current evidence and everyday practice.

Future research should focus on refining diagnostic thresholds for athletes, elucidating the long-term consequences of subclinical iron deficiency on performance and health, and identifying the most efficient, safe, and sustainable management strategies. Such evidence will support more precise, personalized approaches to maintaining optimal iron status and, ultimately, safeguarding both performance and athlete health.

You can also use Consensus to quickly scan new papers on subclinical iron deficiency in athletes, and click on the suggested questions below to deepen specific sections of your review.

## **Disclosure**

### Author Contributions

Conceptualization: Mikołaj Olszok, Daniel Wijas, Michał Kluś, Bartłomiej Kozdra, Natalia Makselan, Natalia Nawrat, Karolina Handzel, Antoni Anczyk, Krzysztof Karbowskiak

Methodology: Mikołaj Olszok, Krzysztof Karbowskiak, Michał Kluś, Bartłomiej Kozdra

Formal analysis: Mikołaj Olszok, Natalia Makselan, Daniel Wijas, Krzysztof Karbowskiak

Investigation: Daniel Wijas, Antoni Anczyk, Michał Kluś, Bartłomiej Kozdra

Supervision: Antoni Anczyk, Karolina Handzel

Writing - original draft preparation: Mikołaj Olszok, Bartłomiej Kozdra, Natalia Nawrat

Writing - review and editing: Karolina Handzel, Michał Kluś, Natalia Makselan, Daniel Wijas

Project administration: Mikołaj Olszok, Krzysztof Karbowskiak, Antoni Anczyk, Natalia Nawrat

All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgements: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

## References

1. Alaunyte, I., Stojceska, V., & Plunkett, A. (2015). Iron and the female athlete: A review of dietary treatment methods for improving iron status and exercise performance. *Journal of the International Society of Sports Nutrition*, 12. <https://doi.org/10.1186/s12970-015-0099-2>
2. Axling, U., Önning, G., Combs, M., Bogale, A., Högström, M., & Svensson, M. (2020). The Effect of *Lactobacillus plantarum* 299v on Iron Status and Physical Performance in Female Iron-Deficient Athletes: A Randomized Controlled Trial. *Nutrients*, 12. <https://doi.org/10.3390/nu12051279>
3. Camaschella, C., Nai, A., & Silvestri, L. (2020). Iron metabolism and iron disorders revisited in the hepcidin era. *Haematologica*, 105, 260 - 272. <https://doi.org/10.3324/haematol.2019.232124>
4. Cappellini, M., Musallam, K., & Taher, A. (2020). Iron deficiency anaemia revisited. *Journal of Internal Medicine*, 287, 153 - 170. <https://doi.org/10.1111/joim.13004>
5. Cohen, C., & Powers, J. (2024). Nutritional Strategies for Managing Iron Deficiency in Adolescents: Approaches to a Challenging but Common Problem. *Advances in Nutrition*, 15. <https://doi.org/10.1016/j.advnut.2024.100215>
6. Dutt, S., Hamza, I., & Bartnikas, T. (2022). Molecular Mechanisms of Iron and Heme Metabolism. *Annual Review of Nutrition*. <https://doi.org/10.1146/annurev-nutr-062320-112625>
7. Blecharz, G., Szwech, J., Baran, K., Jańczyk, N., Mędrysa, K., Pokrzepa, J., ... Bartnik, K. (2025). Hematologic health and athletic performance: exploring the role of anemia. A systematic review of clinical studies. *Quality in Sport*, 41, 60140. <https://doi.org/10.12775/QS.2025.41.60140>
8. Fan, B. (2025). Rethinking ferritin thresholds: Towards a physiological-based definition of iron deficiency. *The Lancet. Global Health*, 13 8. [https://doi.org/10.1016/s2214-109x\(25\)00266-9](https://doi.org/10.1016/s2214-109x(25)00266-9)
9. Foy, B., Li, A., McClung, J., Ranganath, R., & Higgins, J. (2019). Data-driven physiologic thresholds for iron deficiency associated with hematologic decline. *American Journal of Hematology*, 95, 302 - 309. <https://doi.org/10.1002/ajh.25706>

10. Galetti, V., Stoffel, N., Sieber, C., Zeder, C., Moretti, D., & Zimmermann, M. (2021). Threshold ferritin and hepcidin concentrations indicating early iron deficiency in young women based on upregulation of iron absorption. *EClinicalMedicine*, 39. <https://doi.org/10.1016/j.eclinm.2021.101052>
11. Heffernan, S., Horner, K., De Vito, G., & Conway, G. (2019). The Role of Mineral and Trace Element Supplementation in Exercise and Athletic Performance: A Systematic Review. *Nutrients*, 11. <https://doi.org/10.3390/nu11030696>
12. Houston, B., Hurrie, D., Graham, J., Perija, B., Rimmer, E., Rabbani, R., Bernstein, C., Turgeon, A., Ferguson, D., Houston, D., Abou-Setta, A., & Zarychanski, R. (2018). Efficacy of iron supplementation on fatigue and physical capacity in non-anaemic iron-deficient adults: A systematic review of randomised controlled trials. *BMJ Open*, 8. <https://doi.org/10.1136/bmjopen-2017-019240>
13. Kardasis, W., Naquin, E., Garg, R., Arun, T., Gopianand, J., Karmakar, E., & Gnana-Prakasam, J. (2023). The IRONY in Athletic Performance. *Nutrients*, 15. <https://doi.org/10.3390/nu15234945>
14. Kiełbik, P., & Witkowska-Piłaszewicz, O. (2025). Iron Status in Sport Horses: Is It Important for Equine Athletes? *International Journal of Molecular Sciences*, 26. <https://doi.org/10.3390/ijms26125653>
15. Lee, S., Houstis, N., Cunningham, T., Brooks, L., Chen, K., Slocum, C., Ostrom, K., Birchenough, C., Moore, E., Tattersfield, H., Sigursslid, H., Guo, Y., Landsteiner, I., Rouvina, J., Lewis, G., & Malhotra, R. (2025). Transferrin Saturation Is a Better Predictor Than Ferritin of Metabolic and Hemodynamic Exercise Responses in HFpEF. *JACC. Heart Failure*, 13 8, 102478. <https://doi.org/10.1016/j.jchf.2025.02.024>
16. Lynch, S., Pfeiffer, C., Georgieff, M., Brittenham, G., Fairweather-Tait, S., Hurrell, R., Mcardle, H., & Raiten, D. (2018). Biomarkers of Nutrition for Development (BOND)-Iron Review. *The Journal of Nutrition*, 148 suppl\_1, 1001 - 1067. <https://doi.org/10.1093/jn/nxx036>
17. McCormick, R., Sim, M., Dawson, B., & Peeling, P. (2020). Refining Treatment Strategies for Iron Deficient Athletes. *Sports Medicine*, 50, 2111 - 2123. <https://doi.org/10.1007/s40279-020-01360-2>
18. Mei, Z., Addo, O., Jefferds, M., Sharma, A., Flores-Ayala, R., & Brittenham, G. (2021). Physiologically based serum ferritin thresholds for iron deficiency in children and non-pregnant women: A US National Health and Nutrition Examination Surveys (NHANES)

- serial cross-sectional study. *The Lancet. Haematology*, 8 8. [https://doi.org/10.1016/s2352-3026\(21\)00168-x](https://doi.org/10.1016/s2352-3026(21)00168-x)
19. Mountjoy, M., Ackerman, K., Bailey, D., Burke, L., Constantini, N., Hackney, A., Heikura, I., Melin, A., Pensgaard, A., Stellingwerff, T., Sundgot-Borgen, J., Torstveit, M., Jacobsen, A. U., Verhagen, E., Budgett, R., Engebretsen, L., & Erdener, U. (2023). 2023 International Olympic Committee's (IOC) consensus statement on Relative Energy Deficiency in Sport (REDs). *British Journal of Sports Medicine*, 57, 1073 - 1097. <https://doi.org/10.1136/bjsports-2023-106994>
  20. Nabeyama, T., Suzuki, Y., Saito, H., Yamamoto, K., Sakane, M., Sasaki, Y., Shindo, H., Takita, M., & Kami, M. (2023). Prevalence of iron-deficient but non-anemic university athletes in Japan: An observational cohort study. *Journal of the International Society of Sports Nutrition*, 20. <https://doi.org/10.1080/15502783.2023.2284948>
  21. Nicotra, D., Arieli, R., Redlich, N., Navot-Mintzer, D., & Constantini, N. (2023). Iron Deficiency and Anemia in Male and Female Adolescent Athletes Who Engage in Ball Games. *Journal of Clinical Medicine*, 12. <https://doi.org/10.3390/jcm12030970>
  22. Packer, M., Anker, S., Butler, J., Cleland, J., Kalra, P., Mentz, R., Ponikowski, P., & Talha, K. (2024). Redefining Iron Deficiency in Patients With Chronic Heart Failure. *Circulation*, 150, 151 - 161. <https://doi.org/10.1161/circulationaha.124.068883>
  23. Pedlar, C., Bruignara, C., Bruinvels, G., & Burden, R. (2018). Iron balance and iron supplementation for the female athlete: A practical approach. *European Journal of Sport Science*, 18, 295 - 305. <https://doi.org/10.1080/17461391.2017.1416178>
  24. Peeling, P., Dawson, B., Goodman, C., Landers, G., & Trinder, D. (2008). Athletic induced iron deficiency: New insights into the role of inflammation, cytokines and hormones. *European Journal of Applied Physiology*, 103, 381 - 391. <https://doi.org/10.1007/s00421-008-0726-6>
  25. Pengelly, M., Pumpa, K., Pyne, D., & Etxebarria, N. (2024). Iron deficiency, supplementation, and sports performance in female athletes: A systematic review. *Journal of Sport and Health Science*, 14. <https://doi.org/10.1016/j.jshs.2024.101009>
  26. Peyrin-Biroulet, L., Williet, N., & Cacoub, P. (2015). Guidelines on the diagnosis and treatment of iron deficiency across indications: A systematic review. *The American Journal of Clinical Nutrition*, 102 6, 1585 - 1594. <https://doi.org/10.3945/ajcn.114.103366>
  27. Roemhild, K., Von Maltzahn, F., Weiskirchen, R., Knüchel, R., Von Stillfried, S., & Lammers, T. (2021). Iron metabolism: Pathophysiology and pharmacology. *Trends in Pharmacological Sciences*. <https://doi.org/10.1016/j.tips.2021.05.001>

28. Roy, R., Kück, M., Radziwolek, L., & Kerling, A. (2022). Iron Deficiency in Adolescent and Young Adult German Athletes-A Retrospective Study. *Nutrients*, *14*. <https://doi.org/10.3390/nu14214511>
29. Rubeor, A., Goojha, C., Manning, J., & White, J. (2018). Does Iron Supplementation Improve Performance in Iron-Deficient Nonanemic Athletes? *Sports Health*, *10*, 400 - 405. <https://doi.org/10.1177/1941738118777488>
30. Sawicki, K., De Jesus, A., & Ardehali, H. (2023). Iron Metabolism in Cardiovascular Disease: Physiology, Mechanisms, and Therapeutic Targets. *Circulation Research*, *132*, 379 - 396. <https://doi.org/10.1161/circresaha.122.321667>
31. Sim, M., Garvican-Lewis, L., Cox, G., Govus, A., McKay, A., Stellingwerff, T., & Peeling, P. (2019). Iron considerations for the athlete: A narrative review. *European Journal of Applied Physiology*, *119*, 1463 - 1478. <https://doi.org/10.1007/s00421-019-04157-y>
32. Šmid, A. N., Golja, P., Hadžić, V., Abazović, E., Drole, K., & Paravlic, A. (2024). Effects of Oral Iron Supplementation on Blood Iron Status in Athletes: A Systematic Review, Meta-Analysis and Meta-Regression of Randomized Controlled Trials. *Sports Medicine (Auckland, N.z.)*, *54*, 1231 - 1247. <https://doi.org/10.1007/s40279-024-01992-8>
33. Suchdev, P., Williams, A., Mei, Z., Flores-Ayala, R., Pasricha, S., Rogers, L., & Namaste, S. (2017). Assessment of iron status in settings of inflammation: Challenges and potential approaches. *The American Journal of Clinical Nutrition*, *106*, 1626 - 1633. <https://doi.org/10.3945/ajcn.117.155937>
34. Tarancón-Díez, L., Genebat, M., Roman-Enry, M., Vázquez-Alejo, E., Espinar-Buitrago, M., Leal, M., & Muñoz-Fernández, M. (2022). Threshold Ferritin Concentrations Reflecting Early Iron Deficiency Based on Hepcidin and Soluble Transferrin Receptor Serum Levels in Patients with Absolute Iron Deficiency. *Nutrients*, *14*. <https://doi.org/10.3390/nu14224739>
35. Varillas-Delgado, D. (2025). Influence of Genetic Polymorphisms and Biochemical Biomarkers on Response to Nutritional Iron Supplementation and Performance in a Professional Football Team: A Pilot Longitudinal Study. *Nutrients*, *17*. <https://doi.org/10.3390/nu17081379>
36. Wish, J. (2006). Assessing iron status: Beyond serum ferritin and transferrin saturation. *Clinical Journal of the American Society of Nephrology: CJASN*, *1 Suppl 1*. <https://doi.org/10.2215/cjn.01490506>

37. Zhang, S., Xin, W., Anderson, G., Li, R., Gao, L., Chen, S., Zhao, J., & Liu, S. (2022). Double-edge sword roles of iron in driving energy production versus instigating ferroptosis. *Cell Death & Disease*, 13. <https://doi.org/10.1038/s41419-021-04490-1>