Female Athlete Physiology: Addressing Gaps in Injury Prevention, Training, and Recovery

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ABSTRACT

The physiology of female athletes presents unique challenges in terms of injury prevention, training, and recovery. Although more women are getting involved in sports, the majority of studies are male-centered, leaving a significant gap in information about assessing the needs of female athletes. Hormonal changes, especially during the menstrual cycle, also affect performance and risk for injury and recovery processes, with female players much more prone to injuries such as anterior cruciate ligament ruptures and stress fractures. In addition, relative energy deficiency in sport (REDs) is associated with poor muscle recovery, nutrient deficits, and a higher risk of musculoskeletal injuries. This review fills the existing gaps in the current literature by highlighting the need for sex-specific studies, individualized training programs, and nutrition practices. The absence of high-quality randomized controlled trials and an insufficient number of women in sports science research cannot be allowed. Research should personalize interventions that take into account hormonal changes and enhance long-term performance and recovery among female athletes.

Keywords: Female athlete physiology, Injury prevention, Menstrual cycle impact, Reds, Sex-specific training

Background and Introduction

Underrepresentation of Female Athletes in Sports Science

The issue of underrepresentation of female athletes in the field of sports science remains a vital one. There is a significant gap in the detection of female-specific physiological responses to training, injury, and recovery, largely due to the fact that only 35% of participants in sports science studies are women. The current prevailing preference for male-dominated medical, nutritional, and training protocols suggests a disparity in scientific studies. Some scientists justify this disparity, blaming it on the complexity of female physiological conditions, including the menstrual cycle. However, this only emphasizes the efficacy of studies that target female athletes to optimize performance and injury prevention.[1] In addition to this problem, women are also underrepresented and face bias in sport and exercise medicine (SEM). Although women contribute almost half of the world's population, they are underrepresented and show a negative bias in SEM. This has led to a shortage of female-specific research and guidelines, resulting in fewer opportunities for the discipline to address the needs of female athletes.[2] Studies regarding the cardiovascular health of female athletes are also scarce, and their effects are often assessed from a male-centric perspective. This gap is particularly evident during pregnancy and lactation, when specific physiological changes occur, affecting performance. The incorporation of female athletes, especially during these stages, is crucial for generating accurate and viable recommendations regarding health.[3] As shown in Figure 1, the suggested methods for enhancing the recognition of females as sports researchers, as well as addressing sex-specific knowledge deficits in sports performance and their impact on cardiovascular health, are presented.[3]

Historical Biases and Overlooked Variables in Training/Recovery Protocols

In the history of the sports sciences, female athletes were often overlooked, which led to significant gaps in the development of appropriate training and recovery protocols. Despite the fact that women currently account for nearly 50% of participants in the Olympics and other major sporting events, not enough studies in the field of sports science and sports medicine have included women in their research.[4] For instance, the menstrual cycle is one of the factors often neglected in sports science, particularly in performance monitoring. It usually lasts 28 days and has two major phases, namely the follicular phase and the luteal phase, with the division in between being the ovulatory phase (see Figure 2).[4] This underrepresentation, in part, results from the physiological complexities of female athletes that demand more sophisticated study designs and lengthy research durations. Consequently, training protocols based on research predominantly conducted by men do not adequately address the unique needs of women, particularly in terms of their physiological and nutritional needs.[5] In addition, there is a lack of sex-specific research audits that have prevented the establishment of accurate, evidence-based protocols for female athletes.[6] This bias persists even in the monitoring of training loads, recovery, and well-being, and these models are commonly male-centric. In other words, techniques such as GPS tracking and perceived exertion ratings (both common practices for monitoring) may fail to completely quantify some of the intricacies in physiology pertaining to female athletes. Such voids are exacerbated by the existence of confirmation bias in sports science, where testing may not recognize or underestimate findings that seek to contradict the usual male-centric perspectives.[7] Eliminating these biases and incorporating more female-specific research into training and recovery regimens is essential in maximizing the performance and well-being of female athletes.
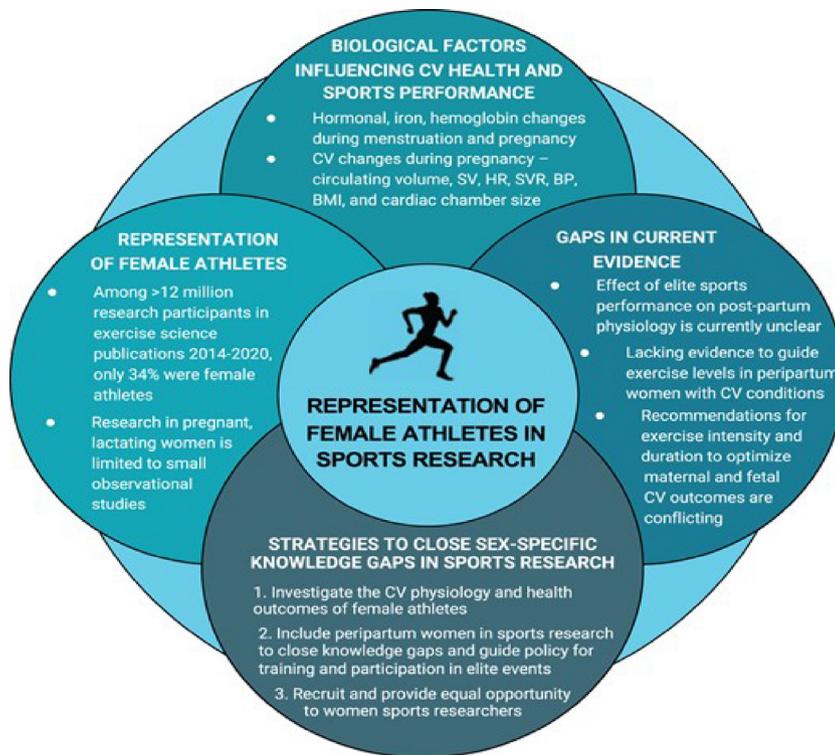
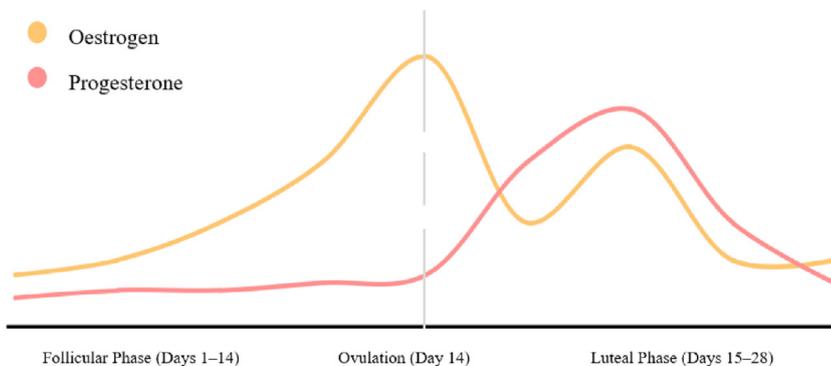Fig 1 | Sex-specific gaps and inclusion strategies in sports research[3]

Fig 2 | Phases of the female menstrual cycle relevant to sports monitoring[4]

Research Objectives

• To investigate sex-specific physiological and biomechanical factors that contribute to injury risk in female athletes.

• To critically review evidence-based training protocols tailored for female physiology, including hormonal and musculoskeletal considerations.

• To examine recovery strategies that optimize rehabilitation outcomes in female athletes, accounting for sex-based differences in metabolism and endocrine response.

• To highlight current gaps in sports science research and medical practice related to female athletes.

• To propose recommendations for future research and applied practice to ensure equitable athlete support systems.

Significance of the Review

This review has substantial value in developing knowledge of sex-specific factors influencing performance, injury, and recovery in female athletes. As noted by Temm et al., the training load and recovery monitoring of female athletes is insufficiently studied, especially in younger populations.[4] In addition, as Madigan points out, historical biases in sports nutrition research made it impossible to fully understand the needs of female athletes.[5] By filling these gaps, the review aims to establish more precise and evidence-based protocols for development, ensuring that female athletes receive equitable support and optimal care in training and recovery procedures.

Female-Specific Physiology in Sport

Menstrual Cycle and Athletic Performance

The menstrual cycle is one of the most significant physiological factors that can affect female performance. Hormones in the cycle may affect several areas of physical and cognitive performance. Castanier et al. highlighted the role of menstrual phases, such as the follicular and luteal phases, in both physical and mental health, and the hormonal changes in these phases have the potential to affect cognitive activity and the strength and endurance of an individual.[8] Specifically, this phase is characterized by low levels of estrogen and progesterone, during which one may experience a decline in exercise performance, especially in strength-related exercises. On the other hand, a luteal phase with an elevated level of progesterone can promote greater endurance and abilities for fatigue resistance due to the body's augmented ability to use fat.[9] Moreover, Figure 3 reveals the variation of female sex hormones, namely estrogen, progesterone, FSH, and LH, which denote the subphases of a eumenorrheic menstrual cycle.[9] Moreover, individual differences are high, where some athletes who record considerable fluctuations in performance even have stable heads, unlike others whose performance is less affected by the menstrual cycle. Furthermore, the authors, after analyzing data from 35 studies, found that even though the phases of the menstrual cycle do influence performance, the inter-individual variation is significant.[10] The research noted that in the case of endurance and strength tests, only minor differences between the menstrual phases were revealed, while for back squat tests, during the ovulatory phase, a significant difference was recorded because the 1RM (one-repetition maximum) values increased by about 3.4 kg.[10] This fact is supportive of the concept of individual training protocols, which take into consideration such hormonal shifts, with athletes being able to maximize performance outcomes.

Hormonal Influence on Musculoskeletal Health and Psychological Factors

The musculoskeletal system of female athletes is also affected differently by the fluctuation of sex hormones during the menstrual cycle. Estrogen and
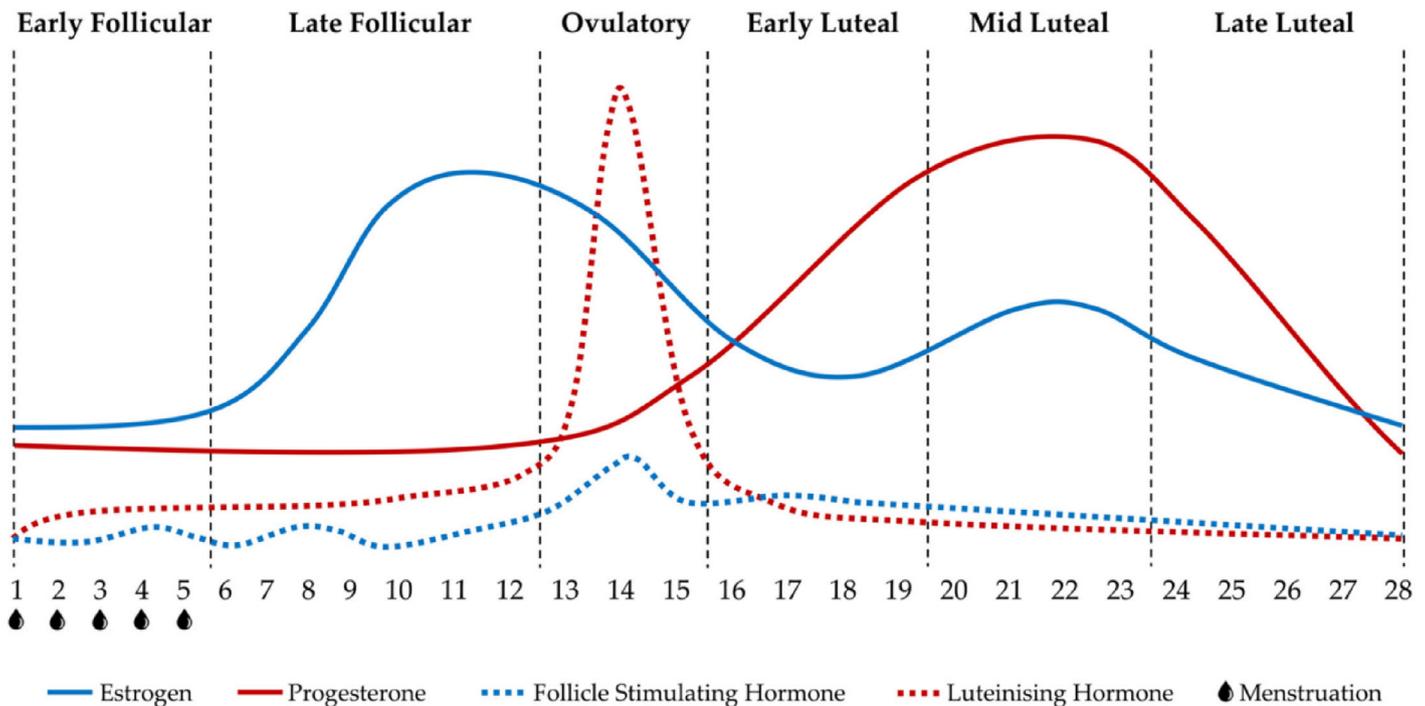
Fig 3 | Hormonal variations across a eumenorrheic menstrual cycle[9]

progesterone also have important functions in terms of bone health, muscle function, and joint stability. In the follicular phase, the amount of estrogen is high, and it may help to improve muscle strength and the cardiovascular system.[8] However, the luteal phase, which has been associated with elevated levels of progesterone, may cause a less favorable condition for muscle strength while enhancing endurance through increased fat oxidation.[9] In addition, Carmichael et al.'s research emphasized the requirement of particular training protocols that include musculoskeletal considerations under the influence of hormonal changes. Protocols related to such hormonal changes can maximize performance results, minimize the risk of injuries, and enhance the general well-being of athletes.[10] Additionally, Kildalsen studied the effect of the menstrual cycle on the performance of female handball players, and it was revealed that the athletes performed better during the follicular phase when estrogen levels were high, a condition associated with better endurance and agility.[11] Nevertheless, considerable individual variability was stressed in the study, indicating the need for an individualized training program. Similarly, McNulty et al. performed a systematic review and meta-analysis, finding that the reduction in performance was trivial in the early follicular phase.[12] Figure 4 represents a network diagram of the pairwise effect sizes of six menstrual cycle phases: early follicular, late follicular, ovulatory, early luteal, mid-luteal, and late luteal. Composed on the basis of data from 73 studies, it includes both direct and indirect effects. Notwithstanding minor performance differences from one phase to another, they concluded that individual responses to hormonal fluctuations

are different, which necessitates the development of personalized training programs for female athletes.

Injury Epidemiology in Female Athletes

Impact of Relative Energy Deficiency in Sport (REDs) and Anterior Cruciate Ligament (ACL)

REDs has a greater prevalence among females than males, thus making them highly predisposed to knee injury.[13] REDs are caused by excessive energy imbalance where the caloric intake does not match the energy requirements of exercise, causing physiological impairment, such as hormonal problems and limited ability to recover back to normal physiological function.[13] According to research, female athletes with sport-related eating disorders are at high risk of suffering from ACL tears, patellar tendinopathy, patellofemoral pain syndrome, and impaired musculoskeletal repair mechanisms.[13] Deficiencies of hormones, especially anabolic ones, hinder muscle and tendon healing, and a lack of consuming essential nutrients (such as collagen and vitamin D) contributes to the deterioration of microtraumas.[13] The link between REDs and knee injuries is, therefore, of great concern due to the fact that this group of athletes is already predisposed to an increased baseline risk of ACL injuries at up to eight times greater than males.[14] Females experience noncontact ACL injuries in 63% of cases, compared to 50% in males, highlighting the importance of neuromuscular and hormonal factors.[15] In addition, disordered eating and low energy availability (LEA) are present in 44% and 53% of female athletes, increasing REDs-related injury risks.[16] These results underline the requirement of early screening and intervention to
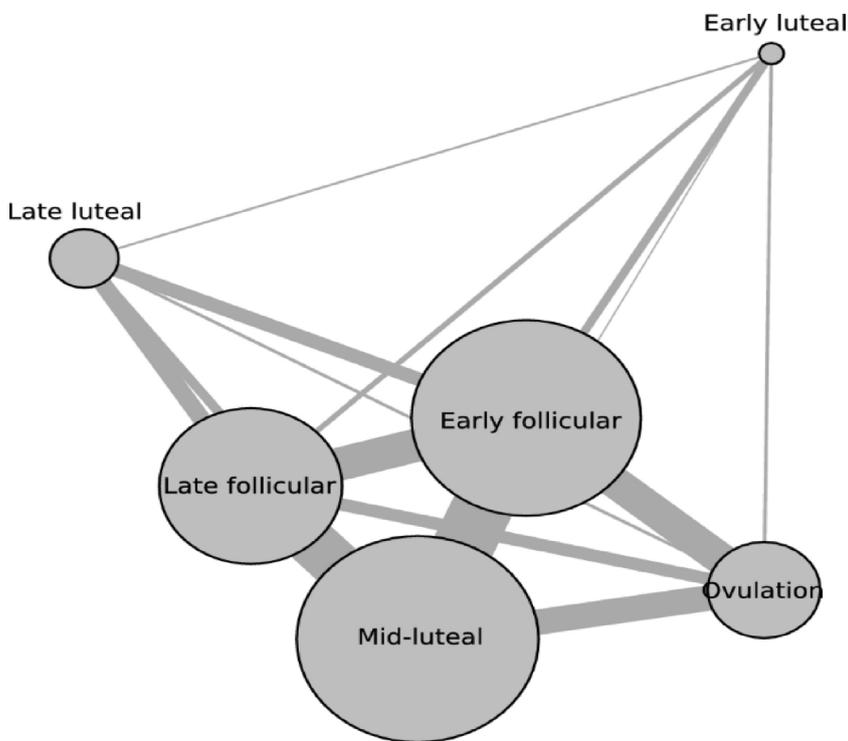
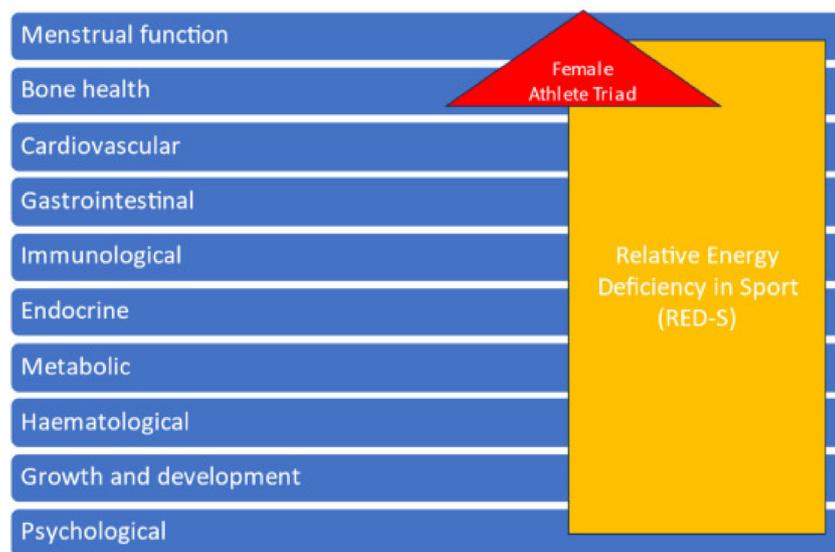**Fig 4 | Network of pairwise effect sizes across menstrual cycle phases**[12]

Fig 5 | Health impacts of REDs beyond the female athlete triad[13]

may increase the risk of injuries, especially musculoskeletal injuries, ACL tears, and stress fractures, by disturbing the recovery of muscle, bone health, and neuromuscular function.[16] While during both training (0.04 per 1,000 player-hours) and competition (87 per 1,000 player-hours), the noncontact ACL injuries were reported in various frequencies, the high incidence during competitions (0.48 per 1,000 player-hours) as compared to the training occasions Figure 6 is based on a systematic review and meta-analysis about non-contact ACL injury epidemiology in team ball sports: variables selected include sex, age, sport type, participation level, and exposure type.[15] Changes in the levels of estrogen throughout the menstruation cycle influence ligament laxity and neuromuscular control that affect ACL losses.[17] While the study suggests the protective nature of OCs, two studies did not show a significant correlation, lending support for further studies to be conducted.[17] The level of competition and age are equally important factors that influence an individual's vulnerability to injuries. Even though hormonal contraceptives can lessen the risk of injuries due to their ability to control the estrogen-associated laxity of ligaments, the effects of contraceptives on athletic performance are under debate.[18] Precise prevention procedures, such as neuromuscular training and hormonal control, can be used to address injury imbalances among female athletes.

Evidence-Based Training Strategies for Female Physiology

Sex-Specific Resistance Training Programming

It is well known in modern sports science that women exhibit similar relative strength gains to men using resistance training (a 15−30% difference in 8−12-week programs). However, hormonal pathways to these changes differ (and the anabolic part of these changes acts through estrogen, testosterone, growth hormone, and IGF-I).[19] Muscular strength refers to the highest force generated at a particular movement, which depends on such aspects as the type of muscle action, range of movement, rate of contraction, and amount of physiological characteristics. Strength gains are dependent on neural drive, the type and size of muscle fiber, hormonal levels, and exercise specificity (see Figure 7). These sex-specific dynamics affect the training response at all levels—for example, the rate of muscle hypertrophy in women averages 1−1.5% per month, compared to 1.5−2% in men; substrate utilization patterns differ, with women exhibiting 15−20% greater fat oxidation during exercise; and recovery needs may also vary, with women potentially requiring longer or different recovery protocols. Emerging female-specific programming models are calling for a shift from acute, performance-based periodization to adaptation-capacity models that account for hormonal fluctuations. Current guidelines recommend a change in training loads by 5−10% during the phases of the menstrual cycle with greater emphases on high-volume work in the follicular phase (days 1−14) and higher intensity

prevent long-term musculoskeletal injury in female athletes. Figure 5 demonstrates the health effects of REDs, indicating extensions to the female athlete triad on a wide range of physiological and psychological outcomes (psychological effects may both lead to and occur due to REDs).[13]

Eating Disorders and Contraceptive Use

Professional women athletes have an increased risk for eating disorders (16%) and LEA (53%), which are conditions that may have severe adverse effects on their overall health and performance.[16] These factors, combined with changes in hormone levels,
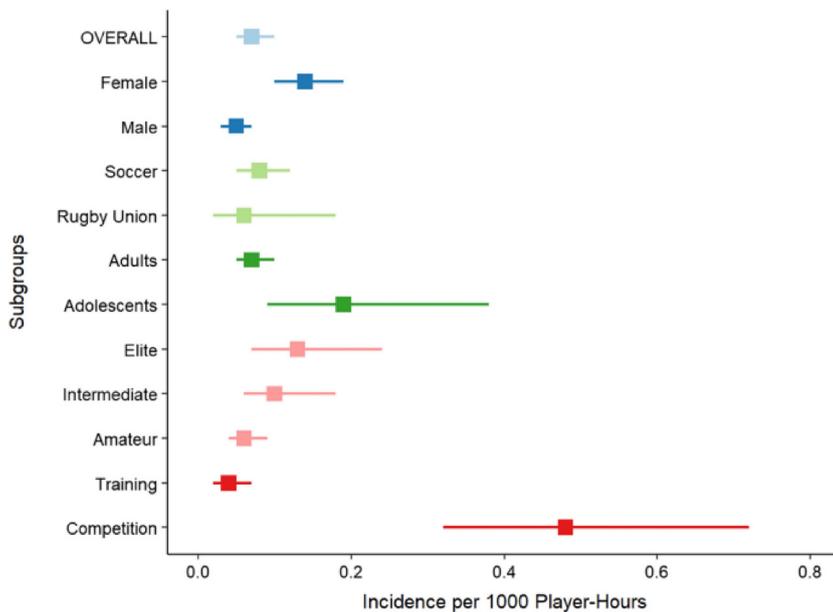
Fig 6 | Epidemiology of noncontact ACL injuries in team ball sports[15]

Fig 7 | Key factors affecting strength adaptation in women's resistance training[19]

work in the luteal phase (days 15−28).[20,21] The active IMPACT clinical trial (*n* = 120) will provide conclusive evidence regarding three approaches to training: emphasized follicular phase (80% of high-intensity training in follicular), luteal-phase emphasized, and traditional non-phase-specific training.[21] According to the preliminary data, phase-optimized training may enhance the training efficiency by 12−15% and, at the same time, can help to decrease the risk of overtraining.[20,21] Such approaches help to eliminate historical differences in research carried out on female athletes since, prior to 2010, such athletes only accounted for less than 30% of participants in exercise physiology studies.[19,20]

Menstrual-Cycle-Phase-Optimized Resistance Training for Female Athletes

Menstrual-cycle-phase-optimized resistance training for female athletes shows limited evidence in current research. A scoping review encompassed 1,942 studies, from which 14 studies (8 primary studies) were ultimately included in the review.[22] These follicular-phase training protocols also had secondary health benefits, as there were calculated reductions in dysmenorrhea symptoms among participants. Deng et al. conducted a systematic review and meta-analysis to determine the effect of physical training on performance in female tennis players, reviewing nine studies with 222 participants. Muscle power, strength, agility, serve velocity, and serve accuracy increased with a very large effect size after physical training, ranging from 0.65 to 1.14.[23] However, the research provides some conflicting results. One of the studies included showed that strength gains during follicular and luteal phase training were not different. Another important finding was that underweight athletes improved strength measures by 15−20% more when luteal phase training was focused.[22] Another major gap in this study is that no studies have been conducted to examine the use of menstrual cycle phase training for rehabilitation purposes after ACL reconstruction (ACLR). This is especially important, considering that female athletes exhibit long-term deficits in quadriceps strength following ACLR, and resistance training is currently considered the cornerstone of rehabilitation by the best available evidence-based guidelines across all countries.

Recovery and Rehabilitation Considerations

Nutritional Considerations for Recovery in Female Athletes

Nutrition is very important when it comes to perfecting the recovery process and ensuring that female athletes perform at their best after getting injured. Holtzman and Ackerman highlight the belief that women have individual physiological needs caused by hormonal cycles, and therefore, special nutritional strategies are needed to cope with muscle healing and inflammation reduction. The energy and fluid intake need to be carefully regulated, particularly within the first 48 hours after the injury, when fueling is essential for synthesizing and healing muscles.[24] Moreover, Knappenberger pointed out that after injury, athletes need to pay attention to consuming enough calories to avoid muscle atrophy and contribute to tissue rebuilding. This is especially the case since trauma or surgery might lead to the need for additional calories (by up to 20%)—which are not met with low caloric intake (see Figure 8).[25] In addition, Larrosa et al. concluded that carbohydrate-rich diets and the consumption of protein multiple times a day significantly improve recovery, where the intake of protein above 25 g/meal promotes muscle anabolism. Such dieting strategies are particularly important for female athletes, who must manage the pressure of physical recovery amidst hormonal fluctuations.[26]

Rehabilitation Strategies for Female Athletes

Female athletes' rehabilitation requires an individualized approach to the recovery process, as it must
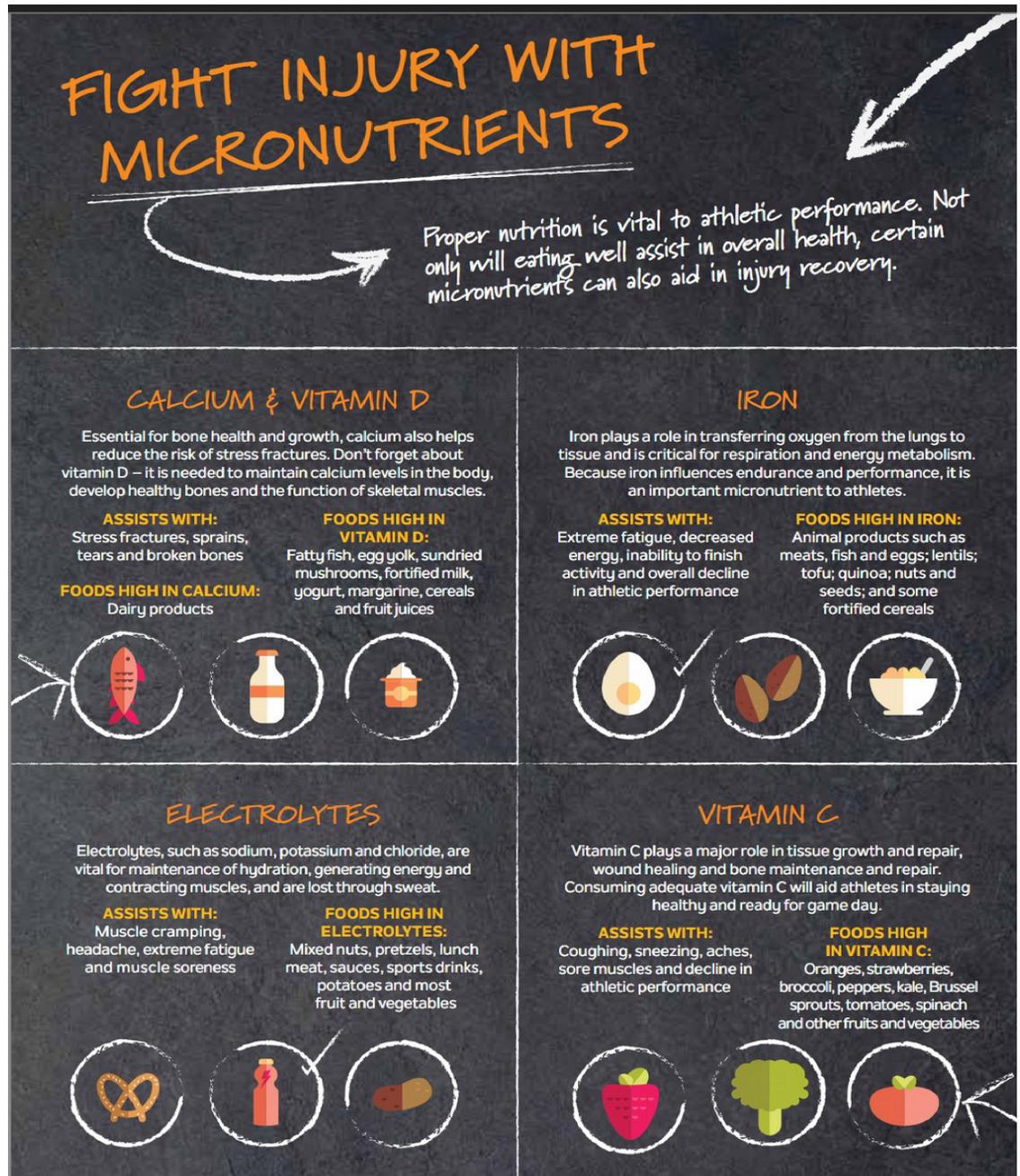
Fig 8 | Nutrition chart[25]

account for their distinctive anatomical, hormonal, and psychological characteristics. An increase in injuries has accompanied an increase in the number of female athletes, and hence, more sex-specific rehabilitation strategies have been needed. Gianakos et al. described this. These strategies should consider factors of hormonal influences (changes in laxity of ligaments during menstrual cycles) in dictating joint stability and recovery from injuries.[27] In addition, Schroeder et al. mentioned that the rehabilitation programs for female athletes should also take into account the psychological aspects of the recovery from injury, as mental health difficulties, such as anxiety and depression are strongly prevalent among females because of hormonal changes and societal

influence.[28] Vuletić and Bøe also added that when aging female athletes become older, changes in bone mineral density and muscle mass increase their risk of musculoskeletal injuries, underlining the need for specific strengthening and stretching training aimed at rehabilitation to prevent long-term decline in performance and enhance overall performance.[29] Such holistic and personalized rehabilitation plans can improve recovery tremendously and ensure safety in return to sports.

Research Gaps and Challenges
The lack of high-quality randomized controlled trials (RCTs) focusing solely on female athletes is one of the key issues in developing research on female athletes.

Traditionally, most studies have used male-dominated data, which is then generalized to female athletes without considering the potential for inconclusive findings regarding their performance, injury occurrences, and recovery techniques.[13,24] According to Holtzman and Ackerman, the physiological response of female athletes to training and recovery from injury is significantly different from that of males; however, the subject has been largely neglected in examinations, with a preference for male-based studies.[24] This extrapolation of male-generated data to female populations stalls the ability to form customized interventions that would maximize the health and performance of female athletes. One of the other main barriers to enhancing research among female athletes is the lack of funding and engagement in sex-specific studies. The lack of inclusion of women in clinical trials and sports science research results in an information gap regarding their specific athletic requirements.[26] This inadequacy of funds for female-specific sports science also reduces the possibility of carrying out large-scale, high-standard research that could be translated into evidence-based practices for female athletes.[27] To bridge these gaps, there is a need for more specific funding and a higher input of female athletes, as well as prioritized efforts toward the inclusion of women's physiological variables in further research.

Future Directions and Recommendations

Future studies among female athletes should, therefore, be sex-based studies that take into consideration the physiological, hormonal, and mental factors relating to their performance and well-being. As pointed out by Gamble, there is an urgent need to future-proof female athletes by accommodating their unique differences and developing customized training and recovery programs built on high-quality, female-focused research.[30] Currently, most data on training, recovery, and injury prevention are derived from male populations, which may not be applicable to females.[31] This generalization narrows our knowledge of how female athletes react to training and the best way of preventing injuries such as ACL tears and stress fractures to which female athletes are at a disproportionate risk.[32] Future research may determine the role of hormonal changes and nutritional requirements during the menstrual cycle to personalize performance-enhancement strategies. For this purpose, future research should involve longitudinal RCTs to test the effectiveness of training interventions and recovery protocols among female athletes, with special attention to those that integrate hormonal phases. In addition, if more funding and an increase in the participation of female athletes are not provided in studies, these gaps can never be filled, and the findings may not be applicable, meaning they will be of no value to them.

Conclusion

This review highlights the crucial importance of sex-specific research in enhancing our understanding of the unique physiological, hormonal, and psycho-logical processes involved in the performance, injury risk, and recovery of female athletes. Although female athletes are exposed to higher risks of injuries like ACL tears, knee injuries, and disordered eating, most of the present data was retrieved from the male population and, thus, cannot be used for the female population. Lack of good-quality RCTs, generalization of male-derived data, and a lack of funds and participation in sex-specific research are some of the major challenges identified. To overcome these gaps, future research should focus on sex-specific interventions, training protocols specific to women, and nutritional approaches that take into account menstrual cycles and hormonal changes. Additionally, increasing female athlete participation in research and securing specific funding will be crucial in designing evidence-based practices that promote performance, protect against injury, and maintain long-term health. Ultimately, promoting more inclusive research will maximize the treatment and assistance offered to all female athletes worldwide.

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