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Glycemic control in endurance athletes with type 1 diabetes - a literature review

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Abstract

Background: Physical activity is vital for type 1 diabetes management, yet endurance sports carry a high risk of rapid blood glucose fluctuations. Fear of hypoglycemia remains a primary barrier to regular training. Modern technologies, including continuous glucose monitoring (CGM) and automated insulin delivery (AID), significantly improve standards of care, athletic performance, and quality of life.

Aim: This study analyzes scientific literature on glycemic control strategies for endurance athletes with type 1 diabetes, emphasizing the impact of modern technologies and nutritional interventions on exercise safety.

Materials and methods: A literature review of 48 publications was conducted. The analysis included guidelines from international societies (ADA, EASD, ISPAD), clinical trials, and systematic reviews evaluating CGM, insulin pumps, closed-loop systems, and nutritional interventions.

Results: Safe endurance exercise requires proactive basal insulin adjustment and precisely planned carbohydrate intake. CGM allows real-time tracking of glycemic trends, though sensor lag time during exercise must be considered. AID, including hybrid closed-loop systems, optimizes metabolic control during and after training. Supported by education, these tools effectively reduce the fear of hypoglycemia and improve athletes' quality of life.

Conclusions: With proper glycemic control, type 1 diabetes is no longer an obstacle to competitive endurance sports, including ultramarathons. Integrating diabetes technologies with personalized nutritional strategies ensures athlete safety. Future developments should focus on refining closed-loop algorithms for variable exercise workloads.

Keywords: type 1 diabetes, endurance sports, continuous glucose monitoring (CGM), exercise-induced hypoglycemia, automated insulin delivery.

Introduction:

Physical activity is an integral and key component of the comprehensive management of type 1 diabetes (T1D), bringing numerous cardiovascular and metabolic benefits to patients [11, 34]. Practicing sports, particularly in endurance disciplines, poses a significant challenge for patients with type 1 diabetes (T1D) due to difficulties in maintaining stable glycemia [10, 35]. Under physiological conditions in healthy individuals, the body precisely regulates the secretion of insulin and glucagon in response to exercise [24, 46]. However, in individuals with type 1 diabetes (T1D), these mechanisms are impaired, predisposing them to rapid fluctuations in blood glucose levels, including health- and life-threatening hypoglycemia [24, 35, 46].

The risk of hypoglycemia during and after prolonged physical activity is one of the most critical clinical issues in sports medicine [13, 39]. This phenomenon directly translates into the psychological sphere—the so-called Fear of Hypoglycemia (FoH), which is widely recognized as the primary barrier limiting the initiation and continuation of regular training by patients with type 1 diabetes [6, 9, 36]. This fear, combined with objective difficulties in appropriately adjusting insulin doses and carbohydrate intake, often leads to the avoidance of exercise or the intentional maintenance of hyperglycemia prior to training for safety reasons [6, 12, 15]. Such precautionary behaviors negatively impact overall metabolic control, motivation, and the quality of life of patients with type 1 diabetes [9, 15, 21].

Over the past decade, tremendous progress has been made in diabetes technologies, revolutionizing the approach to safe sports participation for individuals with type 1 diabetes [1, 27]. The widespread introduction of continuous glucose monitoring (CGM) systems has enabled athletes to track blood glucose trends in real time and make proactive therapeutic decisions without the need to interrupt exercise [1, 19, 37]. Furthermore, the rapid development of personal insulin pumps and automated insulin delivery (AID) systems, such as hybrid closed-loop systems, has created new opportunities for the precise modification of basal insulin infusion in response to energy expenditure [8, 20, 29]. Studies indicate that the utilization of these modern technological solutions not only improves physiological safety but also significantly reduces psychological burden, allowing athletes with type 1 diabetes (T1D) to successfully compete in extremely demanding events, including ultramarathons [21, 41, 45].

Glycemic optimization in endurance athletes is a highly individualized process that requires the seamless integration of knowledge from exercise physiology, pharmacotherapy, and sports nutrition [11, 16, 34].

The aim of this paper is to review the latest literature concerning glycemic control strategies in athletes with type 1 diabetes participating in endurance disciplines. This study analyzes the effectiveness and limitations of modern technologies (CGM, automated insulin delivery systems) and dietary recommendations, evaluating their impact on patient safety, athletic performance, and overall quality of life in the context of the demands of contemporary sports.

Methodology

This study was prepared based on the methodology of a systematic literature review, focusing on scientific publications indexed in key biomedical databases: PubMed, Scopus, Web of Science, and Google Scholar. The literature search process was conducted from January 2020 to May 2026. The search strategy relied on combining keywords using Boolean operators. The following English and Polish terms were utilized: "type 1 diabetes", "endurance athletes", "continuous glucose monitoring", "insulin pump", "fear of hypoglycemia", "cukrzyca typu 1", "sporty wytrzymałościowe", "ciągłe monitorowanie glikemii", and "lęk przed hipoglikemią".

Articles meeting the following criteria were included in the analysis: (1) original research papers, (2) review articles and meta-analyses, (3) official guidelines and position statements from scientific societies, including the European Association for the Study of Diabetes (EASD), the American Diabetes Association (ADA), and the International Society for Pediatric and Adolescent Diabetes (ISPAD), and (4) publications concerning the population of athletes (both amateur and professional) with type 1 diabetes engaged in endurance sports. Particular emphasis was placed on the latest reports published between 2024 and 2026 to ensure the currency of the presented data, especially in the context of rapidly advancing diabetes technologies [21, 45, 47].

The initial selection involved screening titles and abstracts for their relevance to the study objective. In the second stage, the full texts of the selected publications were analyzed to assess their scientific and methodological quality. Ultimately, 48 references were qualified for the final review, forming the basis for formulating the results and conclusions. The collected data underwent a qualitative synthesis, allowing the results to be structured into thematic subsections.

Results

Physiological response to exercise and pharmacotherapy adjustment strategies

Based on the analyzed literature, it has been demonstrated that the mechanisms of glycemic regulation during physical exercise in individuals with type 1 diabetes (T1D) differ significantly from the processes occurring in a healthy individual. Under physiological conditions, the response to physical exercise involves a decrease in insulin secretion by pancreatic beta cells and an increased secretion of glucagon and catecholamines, which stimulates hepatic glucose production, protecting against hypoglycemia [24, 35, 46]. In patients with type 1 diabetes (T1D), the level of circulating insulin in the blood (derived from exogenous injections) does not spontaneously decrease during training [24]. Elevated insulin concentrations, combined with increased glucose uptake by contracting muscles, lead to a rapid drop in glycemia during and after endurance (aerobic) exercise, drastically increasing the risk of severe hypoglycemia [10, 36, 46].

A review of the available literature unequivocally demonstrates that maintaining normoglycemia in endurance athletes requires the implementation of proactive therapeutic strategies. According to the position statements of major scientific societies (ADA, EASD, ISPAD), the optimal strategy relies on two pillars: insulin dose reduction and a precisely planned carbohydrate intake [2, 11, 17, 27]. Studies indicate that reducing basal insulin by 50–80% at 60–90 minutes prior to planned activity in patients using continuous subcutaneous insulin infusion (CSII) significantly lowers the risk of early hypoglycemia [25]. Furthermore, for exercise lasting longer than 60 minutes, an additional intake of 30 to 60 grams of carbohydrates per hour of activity is recommended, depending on the training intensity and current active insulin levels (IOB – Insulin on Board) [7, 14, 38].

Table 1. Guidelines for pharmacotherapy and nutrition adjustments in endurance sports for patients with T1D.

Exercise phase	Insulin adjustment	Nutritional strategy - Carbohydrates
Pre-exercise	Basal rate reduction by 50–80% at 60–90 minutes before the start (in CSII) or meal bolus reduction.	A low glycemic index meal consumed 1–3 hours before training.
During exercise	Maintenance of the reduced basal rate; target blood glucose level raised to approx. 150 mg/dL.	Intake of 30–60 g of fast-acting carbohydrates per hour of exercise.

Post-exercise	Nighttime basal rate reduction by approx. 20% to protect against delayed-onset hypoglycemia.	Consumption of a recovery meal containing complex carbohydrates and protein within 2 hours post-training.

Based on data gathered in: Colberg SR, et al., Physical Activity/Exercise and Diabetes: A Position Statement of the American Diabetes Association; Moser O, et al., Glucose management for exercise using continuous glucose monitoring (CGM) and intermittently scanned CGM (isCGM) systems in type 1 diabetes; Riddell MC, et al., Exercise management in type 1 diabetes: a consensus statement; Scott SN, et al., Post-exercise recovery for the endurance athlete with type 1 diabetes: a consensus statement.

The complexity of glycemic management is compounded by the phenomenon of late-onset hypoglycemia, which can occur up to 24 hours after the completion of endurance exercise [13]. This mechanism is associated with the increased replenishment of muscle and hepatic glycogen stores, as well as heightened tissue sensitivity to insulin [13, 39]. To minimize this risk, current guidelines emphasize the necessity of reducing the nighttime basal rate by approximately 20% on the night following intense training, alongside an adequate intake of meals rich in low-glycemic-index carbohydrates during the post-exercise recovery period [39, 43].

The literature also describes the use of low-dose glucagon injections to prevent declines in blood glucose levels. Studies, including those conducted by Lundemose et al., suggest that this experimental strategy may be a safe and effective method for the treatment and prevention of exercise-induced hypoglycemia during moderate-intensity physical activity. It reduces the need to consume large quantities of carbohydrates, which is often associated with gastrointestinal discomfort in athletes [23].

Diabetes technologies and the safety and quality of exercise

The breakthrough in care for athletes with type 1 diabetes (T1D) is inextricably linked to the popularization of continuous glucose monitoring (CGM) systems. An analysis of the reviewed literature indicates that the use of CGM is currently the gold standard and the foundation for optimizing therapy in physically active individuals [1, 27]. A key advantage of these devices, extending beyond the mere convenience of eliminating repeated fingerstick testing, is the ability to analyze glycemic trends—the direction and rate of changes in glucose concentrations in real time [1, 19, 37].

Clinical studies have demonstrated that the use of continuous glucose monitoring (CGM) systems allows for the earlier detection of impending hypoglycemia, enabling early carbohydrate intervention prior to the actual onset of clinical symptoms [33, 37]. The authors of expert consensus statements (EASD, ISPAD) emphasize that during exercise, therapeutic decisions should not rely solely on absolute glycemic values (e.g., 110 mg/dL), but primarily on the analysis of glycemic trend indicators. For instance, at a level of 110 mg/dL, a stable trend allows for the continuation of exercise without intervention, whereas a rapidly falling trend constitutes an absolute indication for the urgent consumption of fast-acting carbohydrates [27].

The use of CGM during intense endurance sports is also associated with certain limitations. These systems measure glucose concentrations in the interstitial fluid rather than directly in the blood [4, 5, 26]. Under conditions of rapid glycemic fluctuations induced by sudden energy expenditure, a physiological delay (so-called lag time) occurs, ranging from 5 to even 15 minutes [4, 5]. Studies conducted by Biagi et al. [5] and Moser et al. [26] indicate a slight decrease in the accuracy of continuous glucose monitoring (CGM) sensors during high-intensity physical exercise compared to resting conditions. Furthermore, in extreme and combat sports, athletes also encounter technical issues, such as the risk of sensor detachment due to profuse sweating or mechanical damage [1, 19]. Nevertheless, the general scientific consensus clearly indicates that the benefits of using continuous glucose monitoring (CGM) systems in sports outweigh these drawbacks [27, 41].

Table 2. Comparison of glucose monitoring and insulin delivery methods in the context of endurance sports.

Technology	Main advantages in sports	Challenges and limitations
Blood glucose meter (SMBG)	High measurement accuracy, no physiological delay.	Necessity to interrupt exercise, lack of glycemic trend indicators.
CGM systems	Trend analysis (arrows), predictive alarms, no fingersticks required while in motion.	Measurement delay (lag time) of approx. 5–15 min, risk of sensor detachment due to sweat.
Hybrid Closed-Loop (AID)	Automatic suspension of basal insulin infusion prior to hypoglycemia, improvement in TIR (Time in Range).	Reactive operation of algorithms, necessity to activate the "exercise" mode 90 minutes in advance.

Based on data gathered in: Abdulrahman A, et al., Use of continuous glucose monitoring for sport in type 1 diabetes; Houlder SK, et al., Continuous Glucose Monitoring and Exercise in Type 1 Diabetes: Past, Present and Future; Paldus B, et al., Strengths and Challenges of Closed-Loop Insulin Delivery During Exercise in People With Type 1 Diabetes: Potential Future Directions; Tagougui S, et al., Artificial Pancreas Systems and Physical Activity in Patients with Type 1 Diabetes: Challenges, Adopted Approaches, and Future Perspectives.

The next stage in the evolution of type 1 diabetes (T1D) treatment in sports is the integration of continuous glucose monitoring (CGM) systems with personal insulin pumps, which led to the development of automated insulin delivery (AID) systems, including hybrid closed-loop systems [8, 42]. A review of publications confirms that these systems, through the automatic reduction or complete suspension of basal insulin infusion based on the algorithmic prediction of declining glycemia, currently represent the most effective tool in the prevention of exercise-induced hypoglycemia [20, 29]. As recent studies indicate, the use of the "exercise target" mode in hybrid pumps—which raises the target blood glucose value from, for example, 100 mg/dL to 150 mg/dL for the duration of the activity—significantly increases Time in Range (TIR) and limits the time spent in hypoglycemia, thereby reducing the need for exogenous carbohydrate intake during the training itself [8, 29, 31].

The use of automated insulin delivery (AID) systems in endurance sports (e.g., road cycling, marathons) requires appropriate prior training of the patient. The activation of the exercise mode should occur at least 90 minutes before the planned start of physical activity to allow for a significant reduction of active insulin circulating in the blood (IOB - Insulin on Board), previously delivered as part of the algorithm's automated interventions [20, 42].

Nutritional strategies and insulin dosage adjustments

Proper management of endurance exercise in athletes with type 1 diabetes (T1D) relies on a precise balance between carbohydrate intake and insulin dose modifications. According to international expert consensuses, the golden rules of peri-exercise insulin therapy require interventions at three key stages: before, during, and after training [34]. The primary pre-exercise strategy recommended for patients using insulin pumps is the reduction of the basal insulin infusion (basal rate) by 50–80% at 60 to 90 minutes prior to the planned start [25, 34]. If a pre-workout meal is consumed, the standard prandial bolus should be reduced by 25–75%, depending on the planned intensity and duration of the exercise. This action aims to maximally reduce the level of circulating active insulin (IOB - Insulin on Board) at the onset of activity [34, 38]. Following the completion of endurance exercise, the primary goal becomes protection against delayed-onset hypoglycemia. This typically requires a reduction of the bolus for the recovery meal by approximately 50% and a mandatory reduction of the nighttime basal rate by 20% [39].

A significant challenge discussed in the literature is optimal nutritional strategies. Classic carbohydrate loading (carbo-loading), commonly utilized by marathon runners or cyclists to achieve muscle glycogen supercompensation in the days preceding a competition, presents a serious clinical problem in diabetic individuals [7, 40]. This is because an increased carbohydrate intake requires the administration of proportionally higher doses of exogenous insulin. This results in the maintenance of high levels of circulating active insulin (IOB - Insulin on Board) just before the competition, which, upon the initiation of intense exercise, drastically increases the risk of early and severe hypoglycemia [7]. For this reason, it is recommended that pre-race meals be based on low-glycemic-index carbohydrates, which allows for milder insulin response curves [43].

Crucial for maintaining performance during prolonged exercise is continuous energy replenishment. According to guidelines, an athlete should consume 30 to 60 grams of carbohydrates for every hour of physical activity [14, 38]. The most popular solution in endurance sports is highly concentrated energy gels; however, their use in patients with type 1 diabetes (T1D) is associated with a specific paradox examined in the literature. The consumption of a fast-acting gel with maximally reduced (or suspended) basal insulin can lead to a sudden glucose spike and secondary hyperglycemia, which impairs the body's aerobic capacity [38, 40]. Conversely, in a situation where the level of active insulin in the blood is still high, the glucose from the gel is rapidly driven into the working muscles, failing to effectively raise circulating blood sugar levels.

This forces athletes with type 1 diabetes (T1D) to modify the standard nutritional strategies utilized by healthy individuals. Experts recommend the so-called micro-dosing of carbohydrates (e.g., consuming 10–15 grams every 15–20 minutes) instead of a one-time intake of large portions in the form of a whole gel or isotonic drink. Such a "drip-feed" administration of energy substrates prevents rapid glycemic spikes and allows for significantly more stable metabolic control during multi-hour competitions, such as ultramarathons [7, 40].

Psychological aspects, fear of hypoglycemia, and quality of life (QoL)

Alongside the physiological and technological challenges associated with glycemic control, psychological aspects are a key issue in the care of athletes with type 1 diabetes (T1D). The accumulated literature unequivocally indicates that the fear of hypoglycemia (FoH) constitutes the most significant barrier preventing patients, including athletes with many years of experience, from regular and fully engaging participation in physical activity [6, 9, 12, 36]. The fear of experiencing a hypoglycemic episode—both during intense exercise and in the form of unpredictable, delayed-onset nocturnal hypoglycemia—leads to significant psychological discomfort, lowering overall quality of life (QoL) and motivation to initiate and continue training [15, 21].

A persistently high level of fear of hypoglycemia (FoH) can result in athletes implementing suboptimal, conservative adaptive strategies. Athletes often consciously and deliberately maintain a state of hyperglycemia prior to starting training or consume excessive amounts of carbohydrates as a precaution. On the one hand, this action temporarily protects against hypoglycemia, but on the other hand, it leads to a chronic deterioration of metabolic control (an increase in the percentage of glycated hemoglobin – HbA1c) and a decline in physical capacity, which is of crucial importance in endurance sports [9, 36]. As researchers note, this continuous compromise between medical safety and athletic performance is a major source of frustration and burnout in this patient group [15].

Table 3. Consequences of fear of hypoglycemia (FoH) in sports and technological preventive strategies.

Consequence / Manifestation of FoH	Impact on the athlete	Technological preventive strategy
Intentional pre-exercise hyperglycemia	Decreased aerobic capacity, chronic deterioration of metabolic control (higher HbA1c).	Use of predictive CGM alarms and activating the "exercise target" in AID systems to build trust without artificially raising glucose.
Pre-emptive overconsumption of carbohydrates	Gastrointestinal discomfort, rapid glycemic fluctuations during exercise.	Monitoring active insulin (IOB) on the pump and micro-dosing carbohydrates based on real-time CGM trend arrows.
Fear of delayed-onset nocturnal hypoglycemia	Sleep disturbances, impaired post-workout recovery, chronic stress.	Utilization of Predictive Low Glucose Management (PLGM) algorithms to automatically suspend basal insulin delivery during the night.
Avoidance of intense physical activity	Lowered overall quality of life (QoL), frustration, and athletic burnout.	Remote sharing of real-time CGM data with coaches or family members to increase the sense of safety.

Based on data gathered in: Cigrovski Berkovic M, et al., Fear of hypoglycemia, a game changer during physical activity in type 1 diabetes mellitus patients; Brazeau AS, et al., Barriers to physical activity among patients with type 1 diabetes; Roberts AJ, et al., Association between fear of hypoglycemia and physical activity in youth with type 1 diabetes; Speight J, et al., Impact of glycaemic technologies on quality of life and related outcomes in adults with type 1 diabetes; Vauthier JC, et al., Diabetes Technologies in Ultra-Endurance Type 1 Diabetes: Qualitative Study.

The introduction of modern diabetes technologies plays a fundamental role in mitigating the aforementioned psychological barriers. A review of studies confirms that the use of continuous glucose monitoring (CGM) and automated insulin delivery (AID) systems directly translates into a significant reduction in the fear of hypoglycemia [28, 41]. The ability to set personalized predictive alarms (warning of a projected drop in glucose levels 20–30 minutes prior to its actual occurrence) provides athletes with an essential sense of control and safety. This allows them to freely execute their training plans without the need to constantly focus on the subjective symptoms of blood sugar fluctuations [30, 41].

Particularly interesting and up-to-date data is provided by recent qualitative studies conducted among ultra-endurance athletes with type 1 diabetes (T1D). As demonstrated by Vauthier et al. [45], in extreme disciplines (e.g., ultramarathons, long-distance cycling, triathlons), continuous glucose monitoring (CGM) technology and smart insulin pumps not only facilitate monitoring but actually determine the possibility of safely starting and completing a competition. The authors emphasize that the reduction of cognitive load, resulting from the automation of decision-making processes by hybrid pump systems, significantly improves the quality of life for athletes with type 1 diabetes (T1D). This allows them to engage in safe and equitable competition with athletes without metabolic disorders [21, 41, 45].

Discussion

The growing popularity of endurance sports, such as marathons, road cycling, and triathlons, presents new challenges for sports medicine specialists and diabetologists caring for patients with type 1 diabetes (T1D). A review of the accumulated literature unequivocally indicates that the former view discouraging individuals with type 1 diabetes (T1D) from undertaking prolonged, extreme physical exertion is no longer valid [10, 11]. Nevertheless, achieving peak performance while maintaining strict metabolic control remains a complex process based on individualized strategies [16].

Most authorities unanimously support the reduction of the basal insulin dose prior to physical training as the most effective method for preventing hypoglycemia in athletes with type 1 diabetes [25, 27]. However, the medical community is not in full agreement regarding the ideal timing of this intervention. The EASD/ISPAD guidelines suggest reducing the basal rate 60–90 minutes before the planned activity [27], yet some researchers indicate that in certain elite athletes—characterized by high variability in insulin absorption due to altered blood flow through the subcutaneous tissue during exercise—basal reduction may be necessary as early as 120 minutes before starting the exercise [13]. Such preemptive action requires immense discipline and rigorous training planning from the athlete, which in the reality of amateur sports can be difficult to achieve and often leads to therapeutic errors.

A significant gap in current knowledge, requiring further research, is the standardization of nutritional recommendations during exercise that precisely account for the current level of circulating active insulin (IOB). Although guidelines indicate the need to consume 30 to 60 grams of carbohydrates per hour, this amount is often insufficient during intense physical training (e.g., ultramarathons), where energy demands multifold exceed standard algorithms [7, 40]. Furthermore, an excessive carbohydrate intake—serving as a sort of "protective shield" against hypoglycemia (driven by FoH)—carries the risk of hyperglycemic fluctuations and severe gastrointestinal distress, directly impairing the athlete's performance at crucial moments of competition [38]. In this context, the previously mentioned promising studies on the use of microdoses of glucagon [23] represent an interesting direction, offering hope for a complete shift in the approach to preventing hypoglycemia during prolonged physical exertion.

The greatest achievement of modern sports diabetology, universally emphasized in the analyzed literature, is the widespread implementation of continuous glucose monitoring (CGM) and automated insulin delivery (AID) systems. These systems have led to the popularization of competitive sports among patients with type 1 diabetes (T1D). However, viewing technology as a universal and infallible solution should be approached with caution. An insufficiently highlighted problem in many publications is the physiological delay (lag time) in measuring glucose concentrations in the interstitial fluid relative to the circulating blood, which can be misleading and dangerous, especially during interval training, where blood sugar levels are subject to rapid fluctuations [4, 5, 26]. Furthermore, current hybrid pump (AID) algorithms respond to declining glycemia reactively—i.e., they reduce insulin delivery only when the sensor registers a distinct drop. During sudden and unplanned energy expenditure, this reaction (despite the activation of the "exercise target" mode) often proves to be delayed [20, 29].

The future of glycemic control in athletes with diabetes most likely lies in the development of so-called bihormonal systems (delivering insulin and glucagon simultaneously) and the full integration of hybrid systems with vital sign monitors (e.g., accelerometers or sports heart rate monitors) [22, 42]. This would allow the insulin pump to instantly "read" the increase in heart rate and the onset of physical exertion, thereby enabling an immediate, automatic change in insulin delivery parameters even before blood glucose levels drop.

In conclusion, the approach to optimizing athletic performance in patients with type 1 diabetes has evolved from highly restrictive models toward flexible and individualized risk management. Awareness, appropriate education, and the athlete's close collaboration with a multidisciplinary medical team, supported by advanced technology, currently constitute the highest standard of care (Quality of Care), guaranteeing an improvement in the overall quality of life (QoL) at every stage of the training cycle.

Conclusion

A review of the current scientific literature demonstrates that type 1 diabetes (T1D) no longer constitutes a medical barrier precluding participation in competitive endurance sports, including extreme disciplines such as ultramarathons or long-distance cycling. However, safe and effective participation in this type of competition requires strict planning and the preemptive adjustment of pharmacotherapy based on individualized strategies. The gold standard for hypoglycemia prevention remains the preemptive reduction of the basal insulin infusion by 50–80% at least 60–90 minutes prior to the planned training. This action, strictly combined with an appropriately balanced carbohydrate intake during exercise and modified therapy during the recovery period, constitutes the foundation of protecting the patient against early and delayed-onset hypoglycemia.

The key tool determining the effectiveness of the aforementioned strategies is modern diabetes technology. Continuous glucose monitoring (CGM) systems have fundamentally changed the paradigm of care, allowing athletes to make rapid therapeutic decisions based on the analysis of glycemic trends, rather than just absolute values. Although the physiological measurement delay during situations of rapid changes in energy expenditure must be kept in mind, the integration of continuous glucose monitoring (CGM) with automated insulin delivery (AID) systems is considered the greatest achievement of modern sports diabetology. The appropriately early activation of exercise features in pumps equipped with hybrid closed-loop algorithms allows for an effective reduction in the level of active insulin (IOB), which maximizes the Time in Range (TIR) metric.

The application of advanced technologies plays an invaluable role in the psychological sphere, effectively mitigating the fear of hypoglycemia (FoH). The ability to rely on predictive alarms and smart algorithms significantly reduces the cognitive load on athletes. This sense of metabolic safety directly improves the quality of life (QoL) for athletes with T1D, reducing the risk of burnout and allowing them to fully execute their training plans on par with healthy individuals.

Despite undeniable progress, current systems are still characterized by a certain degree of reactivity, basing their operation on changes in glucose levels that have already occurred. Conclusions drawn from the latest research indicate that the future of sports diabetology will require the integration of insulin pumps with biometric vital sign monitors (e.g., heart rate monitors). This would allow for the dynamic modification of insulin infusion from the very first second of commencing physical exertion. Highly promising directions that warrant further exploration also include bihormonal closed-loop systems and the experimental use of glucagon microdoses. In the future, these may provide a safe alternative that is less burdensome on the gastrointestinal tract than the necessity of continuous carbohydrate consumption during long-distance endurance events.

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Declaration of the use of generative AI and AI

In preparing this work, the authors used Google Gemini to improving language and readability. After using this tool, the authors reviewed and edited the content as necessary and accept full responsibility for the substantive content of the publication.

References

Abdulrahman A, Manhas J, Linane H, Gurney M, Fitzgerald C, O'Sullivan E. Use of continuous glucose monitoring for sport in type 1 diabetes. BMJ Open Sport Exerc Med. 2018;4(1):e000432. Published 2018 Dec 17. doi:10.1136/bmjsem-2018-000432. https://doi.org/10.1136/bmjsem-2018-000432

Adolfsson P, Riddell MC, Taplin CE, et al. ISPAD Clinical Practice Consensus Guidelines 2018: Exercise in children and adolescents with diabetes. Pediatr Diabetes. 2018;19 Suppl 27:205-226. doi:10.1111/pedi.12755. https://doi.org/10.1111/pedi.12755

Bally L, Zueger T, Buehler T, et al. Metabolic and hormonal response to intermittent high-intensity and continuous moderate intensity exercise in individuals with type 1 diabetes: a randomised crossover study. Diabetologia. 2016;59(4):776-784. doi:10.1007/s00125-015-3854-7. https://doi.org/10.1007/s00125-015-3854-7

Bauhaus H, Erdogan P, Braun H, Thevis M. Continuous Glucose Monitoring (CGM) in Sports-A Comparison between a CGM Device and Lab-Based Glucose Analyser under Resting and Exercising Conditions in Athletes. Int J Environ Res Public Health. 2023;20(15):6440. Published 2023 Jul 25. doi:10.3390/ijerph20156440. https://doi.org/10.3390/ijerph20156440

Biagi L, Bertachi A, Quirós C, et al. Accuracy of Continuous Glucose Monitoring before, during, and after Aerobic and Anaerobic Exercise in Patients with Type 1 Diabetes Mellitus. Biosensors (Basel). 2018;8(1):22. Published 2018 Mar 9. doi:10.3390/bios8010022. https://doi.org/10.3390/bios8010022

Brazeau AS, Rabasa-Lhoret R, Strychar I, Mircescu H. Barriers to physical activity among patients with type 1 diabetes. Diabetes Care. 2008;31(11):2108-2109. doi:10.2337/dc08-0720. https://doi.org/10.2337/dc08-0720

Cavallo M, De Fano M, Barana L, et al. Nutritional Management of Athletes with Type 1 Diabetes: A Narrative Review. Nutrients. 2024;16(6):907. Published 2024 Mar 21. doi:10.3390/nu16060907. https://doi.org/10.3390/nu16060907

Christiansen M, Bartee A, Lalonde A, et al. Performance of an Automated Insulin Delivery System: Results of Early Phase Feasibility Studies. Diabetes Technol Ther. 2021;23(3):187-194. doi:10.1089/dia.2020.0318. https://doi.org/10.1089/dia.2020.0318

Cigrovski Berkovic M, Bilic-Curcic I, La Grasta Sabolic L, Mrzljak A, Cigrovski V. Fear of hypoglycemia, a game changer during physical activity in type 1 diabetes mellitus patients. World J Diabetes. 2021;12(5):569-577. doi:10.4239/wjd.v12.i5.569. https://doi.org/10.4239/wjd.v12.i5.569

Colberg SR, Laan R, Dassau E, Kerr D. Physical activity and type 1 diabetes: time for a rewire?. J Diabetes Sci Technol. 2015;9(3):609-618. doi:10.1177/1932296814566231. https://doi.org/10.1177/1932296814566231

Colberg SR, Sigal RJ, Yardley JE, et al. Physical Activity/Exercise and Diabetes: A Position Statement of the American Diabetes Association. Diabetes Care. 2016;39(11):2065-2079. doi:10.2337/dc16-1728. https://doi.org/10.2337/dc16-1728

Finn M, Sherlock M, Feehan S, Guinan EM, Moore KB. Adherence to physical activity recommendations and barriers to physical activity participation among adults with type 1 diabetes. Ir J Med Sci. 2022;191(4):1639-1646. doi:10.1007/s11845-021-02741-w. https://doi.org/10.1007/s11845-021-02741-w

Fitzpatrick R, Davison G, Wilson JJ, McMahon G, McClean C. Exercise, type 1 diabetes mellitus and blood glucose: The implications of exercise timing. Front Endocrinol (Lausanne). 2022;13:1021800. Published 2022 Sep 28. doi:10.3389/fendo.2022.1021800. https://doi.org/10.3389/fendo.2022.1021800

Francescato MP, Stel G, Stenner E, Geat M. Prolonged exercise in type 1 diabetes: performance of a customizable algorithm to estimate the carbohydrate supplements to minimize glycemic imbalances. PLoS One. 2015;10(4):e0125220. Published 2015 Apr 28. doi:10.1371/journal.pone.0125220. https://doi.org/10.1371/journal.pone.0125220

Fried L, Chetty T, Cross D, et al. The Challenges of Being Physically Active: A Qualitative Study of Young People With Type 1 Diabetes and Their Parents. Can J Diabetes. 2021;45(5):421-427. doi:10.1016/j.jcjd.2020.09.010. https://doi.org/10.1016/j.jcjd.2020.09.010

Grightmire B, Alkabbani W, Gamble JM. Peak performance: Putting type 1 diabetes management recommendations for athletes to the test. Am J Med Open. 2022;7:100011. Published 2022 Mar 11. doi:10.1016/j.ajmo.2022.100011. https://doi.org/10.1016/j.ajmo.2022.100011

Holt RIG, DeVries JH, Hess-Fischl A, et al. The management of type 1 diabetes in adults. A consensus report by the American Diabetes Association (ADA) and the European Association for the Study of Diabetes (EASD). Diabetologia. 2021;64(12):2609-2652. doi:10.1007/s00125-021-05568-3. https://doi.org/10.1007/s00125-021-05568-3

Horton WB, Subauste JS. Care of the Athlete With Type 1 Diabetes Mellitus: A Clinical Review. Int J Endocrinol Metab. 2016;14(2):e36091. Published 2016 Mar 26. doi:10.5812/ijem.36091. https://doi.org/10.5812/ijem.36091

Houlder SK, Yardley JE. Continuous Glucose Monitoring and Exercise in Type 1 Diabetes: Past, Present and Future. Biosensors (Basel). 2018;8(3):73. Published 2018 Aug 3. doi:10.3390/bios8030073. https://doi.org/10.3390/bios8030073

Jayawardene DC, McAuley SA, Horsburgh JC, et al. Closed-Loop Insulin Delivery for Adults with Type 1 Diabetes Undertaking High-Intensity Interval Exercise Versus Moderate-Intensity Exercise: A Randomized, Crossover Study. Diabetes Technol Ther. 2017;19(6):340-348. doi:10.1089/dia.2016.0461. https://doi.org/10.1089/dia.2016.0461

J Cockcroft E, Chithuranjan D, Narendran P, C Andrews R, P Dias R. Quality of life and physical activity in type 1 diabetes. BMC Pediatr. 2025;25(1):345. Published 2025 May 1. doi:10.1186/s12887-025-05632-6. https://doi.org/10.1186/s12887-025-05632-6

Lee AS, Johnson NA, McGill MJ, et al. Effect of High-Intensity Interval Training on Glycemic Control in Adults With Type 1 Diabetes and Overweight or Obesity: A Randomized Controlled Trial With Partial Crossover. Diabetes Care. 2020;43(9):2281-2288. doi:10.2337/dc20-0342. https://doi.org/10.2337/dc20-0342

Lundemose SB, Laugesen C, Ranjan AG, Nørgaard K. Exploring low-dose glucagon for exercise-induced hypoglycaemia in type 1 diabetes: A randomised controlled trial. Diabet Med. 2025;42(4):e15512. doi:10.1111/dme.15512. https://doi.org/10.1111/dme.15512

Mallad A, Hinshaw L, Schiavon M, et al. Exercise effects on postprandial glucose metabolism in type 1 diabetes: a triple-tracer approach. Am J Physiol Endocrinol Metab. 2015;308(12):E1106-E1115. doi:10.1152/ajpendo.00014.2015. https://doi.org/10.1152/ajpendo.00014.2015

McAuley SA, Horsburgh JC, Ward GM, et al. Insulin pump basal adjustment for exercise in type 1 diabetes: a randomised crossover study. Diabetologia. 2016;59(8):1636-1644. doi:10.1007/s00125-016-3981-9. https://doi.org/10.1007/s00125-016-3981-9

Moser O, Mader JK, Tschakert G, et al. Accuracy of Continuous Glucose Monitoring (CGM) during Continuous and High-Intensity Interval Exercise in Patients with Type 1 Diabetes Mellitus. Nutrients. 2016;8(8):489. Published 2016 Aug 10. doi:10.3390/nu8080489. https://doi.org/10.3390/nu8080489

Moser O, Riddell MC, Eckstein ML, et al. Glucose management for exercise using continuous glucose monitoring (CGM) and intermittently scanned CGM (isCGM) systems in type 1 diabetes: position statement of the European Association for the Study of Diabetes (EASD) and of the International Society for Pediatric and Adolescent Diabetes (ISPAD) endorsed by JDRF and supported by the American Diabetes Association (ADA). Diabetologia. 2020;63(12):2501-2520. doi:10.1007/s00125-020-05263-9. https://doi.org/10.1007/s00125-020-05263-9

Natale P, Chen S, Chow CK, et al. Patient experiences of continuous glucose monitoring and sensor-augmented insulin pump therapy for diabetes: A systematic review of qualitative studies. J Diabetes. 2023;15(12):1048-1069. doi:10.1111/1753-0407.13454. https://doi.org/10.1111/1753-0407.13454

Paldus B, Morrison D, Lee M, Zaharieva DP, Riddell MC, O'Neal DN. Strengths and Challenges of Closed-Loop Insulin Delivery During Exercise in People With Type 1 Diabetes: Potential Future Directions. J Diabetes Sci Technol. 2023;17(4):1077-1084. doi:10.1177/19322968221088327. https://doi.org/10.1177/19322968221088327

Patton SR, Clements MA. Psychological Reactions Associated With Continuous Glucose Monitoring in Youth. J Diabetes Sci Technol. 2016;10(3):656-661. Published 2016 May 3. doi:10.1177/1932296816638109. https://doi.org/10.1177/1932296816638109

Perkins BA, Turner LV, Riddell MC. Applying technologies to simplify strategies for exercise in type 1 diabetes. Diabetologia. 2024;67(10):2045-2058. doi:10.1007/s00125-024-06229-x. https://doi.org/10.1007/s00125-024-06229-x

Reddy R, Wittenberg A, Castle JR, et al. Effect of Aerobic and Resistance Exercise on Glycemic Control in Adults With Type 1 Diabetes. Can J Diabetes. 2019;43(6):406-414.e1. doi:10.1016/j.jcjd.2018.08.193. https://doi.org/10.1016/j.jcjd.2018.08.193

Rickels MR, Peleckis AJ, Dalton-Bakes C, et al. Continuous Glucose Monitoring for Hypoglycemia Avoidance and Glucose Counterregulation in Long-Standing Type 1 Diabetes. J Clin Endocrinol Metab. 2018;103(1):105-114. doi:10.1210/jc.2017-01516. https://doi.org/10.1210/jc.2017-01516

Riddell MC, Gallen IW, Smart CE, et al. Exercise management in type 1 diabetes: a consensus statement. Lancet Diabetes Endocrinol. 2017;5(5):377-390. doi:10.1016/S2213-8587(17)30014-1. https://doi.org/10.3390/ijerph16244890

Riddell MC, Scott SN, Fournier PA, et al. The competitive athlete with type 1 diabetes. Diabetologia. 2020;63(8):1475-1490. doi:10.1007/s00125-020-05183-8. https://doi.org/10.1007/s00125-020-05183-8

Roberts AJ, Taplin CE, Isom S, et al. Association between fear of hypoglycemia and physical activity in youth with type 1 diabetes: The SEARCH for diabetes in youth study. Pediatr Diabetes. 2020;21(7):1277-1284. doi:10.1111/pedi.13092. https://doi.org/10.1111/pedi.13092

Schubert-Olesen O, Kröger J, Siegmund T, Thurm U, Halle M. Continuous Glucose Monitoring and Physical Activity. Int J Environ Res Public Health. 2022;19(19):12296. Published 2022 Sep 28. doi:10.3390/ijerph191912296. https://doi.org/10.3390/ijerph191912296

Scott S, Kempf P, Bally L, Stettler C. Carbohydrate Intake in the Context of Exercise in People with Type 1 Diabetes. Nutrients. 2019;11(12):3017. Published 2019 Dec 10. doi:10.3390/nu11123017. https://doi.org/10.3390/nu11123017

Scott SN, Fontana FY, Cocks M, et al. Post-exercise recovery for the endurance athlete with type 1 diabetes: a consensus statement. Lancet Diabetes Endocrinol. 2021;9(5):304-317. doi:10.1016/S2213-8587(21)00054-1. https://doi.org/10.1016/S2213-8587(21)00054-1

Silva Daniel NV, Esteves Dos Santos N, Gobatto CA, Hoffmann LM, Esteves AM, Belli T. Nutritional Strategies of an Athlete with Type 1 Diabetes Mellitus During a 217-km Ultramarathon. Wilderness Environ Med. 2022;33(1):128-133. doi:10.1016/j.wem.2021.11.005. https://doi.org/10.1016/j.wem.2021.11.005

Speight J, Choudhary P, Wilmot EG, et al. Impact of glycaemic technologies on quality of life and related outcomes in adults with type 1 diabetes: A narrative review. Diabet Med. 2023;40(1):e14944. doi:10.1111/dme.14944. https://doi.org/10.1111/dme.14944.

Tagougui S, Taleb N, Molvau J, Nguyen É, Raffray M, Rabasa-Lhoret R. Artificial Pancreas Systems and Physical Activity in Patients with Type 1 Diabetes: Challenges, Adopted Approaches, and Future Perspectives. J Diabetes Sci Technol. 2019;13(6):1077-1090. doi:10.1177/1932296819869310. https://doi.org/10.1177/1932296819869310

Thomas DE, Brotherhood JR, Brand JC. Carbohydrate feeding before exercise: effect of glycemic index. Int J Sports Med. 1991;12(2):180-186. doi:10.1055/s-2007-1024664. https://doi.org/10.1055/s-2007-1024664

Tonoli C, Heyman E, Roelands B, et al. Type 1 diabetes-associated cognitive decline: a meta-analysis and update of the current literature. J Diabetes. 2014;6(6):499-513. doi:10.1111/1753-0407.12193. https://doi.org/10.1111/1753-0407.12193

Vauthier JC, Choley L, Arduini D, Mas P, Kabuth B. Diabetes Technologies in Ultra-Endurance Type 1 Diabetes: Qualitative Study. J Med Internet Res. 2026;28:e86815. Published 2026 May 8. doi:10.2196/86815. https://doi.org/10.2196/86815

Yardley JE, Kenny GP, Perkins BA, et al. Resistance versus aerobic exercise: acute effects on glycemia in type 1 diabetes. Diabetes Care. 2013;36(3):537-542. doi:10.2337/dc12-0963. https://doi.org/10.2337/dc12-0963

Zanardo E, Quinto G, Battista F, et al. Acute effects of physical exercise on cognitive function and neurotrophins in patients with type 1 diabetes: A systematic review. Heliyon. 2025;11(4):e42456. Published 2025 Feb 5. doi:10.1016/j.heliyon.2025.e42456. https://doi.org/10.1016/j.heliyon.2025.e42456

Zimmer RT, Aberer F, Schierbauer J, et al. Performance of real-time continuous glucose monitoring during track and field training in adolescents with type 1 diabetes. Dokładność ciągłego monitorowania stężenia glukozy w czasie rzeczywistym podczas treningu lekkoatletycznego u młodzieży z cukrzycą typu 1. Pediatr Endocrinol Diabetes Metab. 2024;30(4):211-220. doi:10.5114/pedm.2024.146685. https://doi.org/10.5114/pedm.2024.146685