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The Role of Modern Technologies in Managing Glycemia During Physical Activity in Patients with Type 1 Diabetes – A Literature Review

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ABSTRACT

Introduction: Regular physical activity is a fundamental component of therapy for type 1 diabetes (T1D), offering multidimensional benefits: from improved insulin sensitivity and weight control to reduced cardiovascular risk and enhanced psychological well-being. Despite these proven advantages, the fear of hypoglycemia remains the primary barrier preventing patients from engaging in regular exercise. **Aim**: The aim of this study is to provide a comprehensive review of current literature regarding the use of modern diabetes technologies - specifically Continuous Glucose Monitoring (CGM/FGM) systems and Advanced Hybrid Closed Loop (AHCL) insulin delivery systems - in the context of various forms of physical activity. **Methods**: A systematic search of the literature was conducted using PubMed, Google Scholar and Web of Science databases. The review prioritized clinical trials, meta-analyses, and consensus guidelines published between 2007 and 2024, with a special focus on the rapid technological advancements observed in the 2020–2024. **Results**: The analysis indicates that modern technologies have revolutionized the approach to exercise in T1D. CGM systems allow for proactive trend-based decision-making, while AHCL systems effectively mitigate hypoglycemia risk through automated insulin suspension. However, the efficacy of these tools is dependent on the type of exercise (aerobic vs. anaerobic) and requires specific patient education regarding "exercise modes" and nutritional strategies. **Conclusion**: While modern technology significantly reduces the cognitive burden of diabetes management during sports, it does not eliminate physiological challenges entirely. Future research should focus on dual-hormone systems and algorithms dedicated to high-intensity interval sports.

Keywords: Type 1 Diabetes, Physical Activity, Continuous Glucose Monitoring, Hybrid Closed Loop, Hypoglycemia, Exercise Physiology

1. Introduction

Type 1 diabetes (T1D) is a chronic autoimmune condition characterized by the destruction of pancreatic beta cells and absolute insulin deficiency. The management of T1D is a complex balancing act involving exogenous insulin administration, dietary management and physical activity. Historically, physical activity was considered a "double-edged sword" for patients with T1D. While it is widely recommended by major diabetes associations - including the American Diabetes Association (ADA) and the International Society for Pediatric and Adolescent Diabetes (ISPAD) - as an essential part of a healthy lifestyle, it presents many metabolic challenges.

Epidemiological data shows that a large percentage of patients with T1D do not meet the recommended physical activity guidelines of 150 minutes of activity per week. As shown by studies by Brazeau et al. (2008), the fear of hypoglycemia is the strongest barrier preventing patients from participating in sports. This fear is not unfounded; exercise increases glucose uptake by skeletal muscles significantly, often outpacing hepatic glucose production, which, in the presence of active exogenous insulin, leads to rapid glycemic drops.

The problem of exercise management remains relevant even in the era of modern technology. A recent large-scale survey study by Romine et al. (2023) highlighted that despite access to advanced equipment, many patients still do not exercise due to a lack of trust in automated algorithms during extreme exertion or the unpredictability of glycemic responses. This indicates a gap between technological capability and patient confidence.

Managing exercise glycemia is widely regarded by clinicians as one of the most difficult challenges in diabetology (Riddell et al., 2017). The problem arises from the fact that different types of exercise manifest opposing glycemic responses. Furthermore, the pharmacokinetics of subcutaneous insulin is often different from physiological secretion, which leads to iatrogenic hyperinsulinemia during exercise.

The last decade has brought many new solutions to these problems. The transition from capillary blood glucose monitoring to Continuous Glucose Monitoring (CGM) and the evolution from Multiple Daily Injections (MDI) to Advanced Hybrid Closed Loop (AHCL) systems have created new opportunities. The introduction of systems that not only suspend insulin but also deliver automated correction boluses is changing the treatment and everyday life of patients with diabetes. This review aims to show the latest technologies, offering a practical perspective on their efficacy, limitations, and future directions.

2. Materials and Methods

A comprehensive narrative review of the literature was conducted. The search strategy involved the use of electronic databases: PubMed/MEDLINE and Google Scholar. The search was limited to articles published in English between January 2007 and early 2024 to ensure the relevance of data regarding rapidly evolving technologies.

Inclusion Criteria:

- Randomized Controlled Trials (RCTs) and observational studies involving humans with Type 1 Diabetes.
- Studies focusing on physical activity, exercise physiology, or sports performance.
- Articles evaluating the performance of CGM, FGM (Flash Glucose Monitoring), CSII (Continuous Subcutaneous Insulin Infusion), and AHCL systems.
- Consensus statements and clinical practice guidelines from recognized diabetes organizations (ADA, EASD, ISPAD).

Exclusion Criteria:

- Animal studies.
- Studies focusing exclusively on Type 2 Diabetes.
- Case reports (unless describing novel technological phenomena).
- Articles published prior to 2007, unless they were seminal works describing fundamental physiological mechanisms.

Keywords used for the search included combinations of: "Type 1 Diabetes", "Exercise", "Continuous Glucose Monitoring", "Flash Glucose Monitoring", "Hybrid Closed Loop", "Artificial Pancreas", "Hypoglycemia", "Insulin Sensitivity", and "Automated Insulin Delivery".

3. Physiological Challenges: The Battle of Hormones

To understand the role of technology, one must first appreciate the underlying physiology. In a healthy individual, glucose homeostasis during exercise is maintained by a precise neuroendocrine feedback loop. As muscle glucose uptake increases, insulin secretion from the pancreas decreases rapidly (almost to zero), and counter-regulatory hormones (glucagon, catecholamines, cortisol, growth hormone) are released to stimulate hepatic glucose production (glycogenolysis and gluconeogenesis).

In T1D, this regulation is disrupted on multiple levels:

1. **Relative Hyperinsulinemia:** Exogenous insulin absorbed from subcutaneous tissue cannot be "turned off" instantly. Even if a pump is suspended, the insulin already on board (IOB) continues to act, promoting glucose uptake into cells and inhibiting glucose production by the liver.
2. **Impaired Glucagon Response:** Individuals with long-standing T1D often lose the ability to secrete glucagon in response to hypoglycemia, further compromising their defense mechanisms.
3. **Blunted Catecholamine Response:** Repeated episodes of hypoglycemia can lead to Hypoglycemia-Associated Autonomic Failure (HAAF), reducing the adrenergic response to exercise.

Aerobic vs. Anaerobic Metabolism

The glycemic response is strictly dependent on the energy pathway used during effort.

- **Aerobic Exercise:** Activities such as long-distance running, cycling, or swimming rely primarily on oxidative phosphorylation. These activities significantly increase insulin sensitivity and glucose consumption, typically leading to a drop in blood glucose levels.
- **Anaerobic Exercise:** High-intensity efforts such as weightlifting, sprinting, or martial arts stimulate a massive release of catecholamines (epinephrine and norepinephrine). These hormones stimulate hepatic glucose release that often exceeds muscle uptake. As proven by Yardley et al. (2013), this can result in stable glycemia or even transient hyperglycemia during and after the workout.

The HIIT Paradigm

A meta-analysis by Zhu et al. (2022) offers a compelling perspective on High-Intensity Interval Training (HIIT). By alternating anaerobic bursts with aerobic recovery, HIIT creates a protective buffer against immediate hypoglycemia, making it generally safer than continuous moderate-intensity exercise. Yet, this stability comes with a trade-off: the surge in counter-regulatory hormones often triggers delayed hyperglycemia, necessitating a proactive approach to post-exercise insulin dosing rather than standard reduction.

Late-Onset Hypoglycemia (LOH)

Beyond the workout itself, Gomez et al. (2015) draw attention to the risk of Late-Onset Hypoglycemia. The metabolic demand of replenishing muscle glycogen stores creates a 'glucose sink' effect that persists for 6–15 hours, frequently resulting in nocturnal drops. In this context, automated delivery proves superior. Paldus et al. (2022) demonstrated that modern closed-loop systems effectively mitigate this risk by dynamically reducing basal insulin overnight as the sensor detects the downward trend, protecting the athlete during sleep

4. Continuous Glucose Monitoring (CGM) Systems in Sports

CGM systems have transitioned from being a supplementary tool to the standard of care for active T1D patients. Unlike traditional glucometers (SMBG) which provide a static "snapshot," CGMs offer dynamic insights into glycemic trends.

Trend Arrows as a Therapeutic Compass

A key tool in hypoglycemia prevention is trend analysis. According to the EASD/ISPAD position statement (Moser et al., 2020), therapeutic decisions should be based on the direction of the trend arrow. For instance, a glucose level of 110 mg/dL is safe if the trend is stable, but requires immediate carbohydrate ingestion if the arrow points explicitly downwards (Table 1).

Table 1. Algorithm for management prior to aerobic exercise based on CGM readings and trend arrows (adapted from Moser et al., 2020).

Glycemia Level (mg/dL)	**Trend Arrow on Sensor**	**Recommended Action Before Start**
< 90 mg/dL	Any trend	**DO NOT START EXERCISE.** Consume 15–20 g of glucose, wait until glucose rises > 90 mg/dL and stabilizes.
90 – 126 mg/dL	⬇ (Dropping)	Consume 10–20 g of carbohydrates (e.g., banana, gel). Delay start by 10 min.
90 – 126 mg/dL	➡ (Stable)	Consume 10 g of carbohydrates (if exercise > 30 min). You may start.
126 – 180 mg/dL	➡ (Stable)	Optimal moment to start. Usually requires no extra carbohydrates (for exercise up to 60 min).
180 – 270 mg/dL	⬆ (Rising)	You may start. Consider a gentle insulin correction if exercise is light.
> 270 mg/dL	Any trend	Check ketones. If elevated (>0.6 mmol/L or 1.5 mmol/L), do not exercise. Correct with insulin and hydrate.

Technological Limitations in Sports

However, technology is not a perfect substitute for physiology. Vigers et al. (2022) highlighted that despite the improved precision (MARD) of modern sensors like the Dexcom G6, the issue of 'lag time' persists. Since sensors measure glucose in interstitial fluid rather than blood, rapid aerobic exercise can create a significant delay—often 10–15 minutes—between the actual blood glucose drop and the sensor reading. Clinically, this implies a sensor could display a safe 100 mg/dL while the athlete is already hypoglycemic at 70 mg/dL. Another practical challenge is 'compression hypoglycemia,' frequently encountered in contact sports or during recovery sleep. Direct pressure on the sensor site restricts local perfusion, triggering a false low alarm. It is crucial for athletes to distinguish this technical artifact from true hypoglycemia to avoid consuming unnecessary carbohydrates.

5. Personal Insulin Pumps and Dose Reduction

Before the era of automation, the primary strategy for Continuous Subcutaneous Insulin Infusion (CSII) users was the manual reduction of basal rates.

Studies by Davey et al. (2013) confirmed that reducing the basal rate by 50–80% significantly reduces the risk of hypoglycemia. However, the timing is critical. Insulin analogs (lispro, aspart) have a peak action time of 60–90 minutes. A newer approach proposed by Moser et al. (2021) suggests that for highly insulin-sensitive patients, basal reduction should occur 90–120 minutes before the start of the activity. Reducing the basal rate at the onset of exercise is often ineffective for the first hour of training due to the insulin already circulating in the system.

6. Era of Automation: Hybrid Closed Loops (AHCL)

The introduction of Advanced Hybrid Closed Loop (AHCL) systems represents the most significant breakthrough in recent years. These systems use control algorithms (PID or MPC – Model Predictive Control) to automatically adjust basal insulin and, in some systems, deliver correction boluses based on CGM predictions.

Clinical Efficacy

The latest reports from 2021–2023 provide robust evidence of their efficacy. A study by Aronson et al. (2023) regarding the MiniMed 780G system showed that in physically active individuals, this system maintains Time in Range (TIR) >70% even on days with intense training. The system's ability to perform "micro-corrections" every 5 minutes allows for tighter control without the constant need for patient intervention.

Similar results for tubeless systems (Omnipod 5) were presented by Sherr et al. (2022). In their study, the adaptive algorithm played a key role by reducing insulin delivery based on trend predictions, significantly reducing the number of rescue carbohydrate interventions.

The Role of "Exercise Modes"

Most modern systems (Control-IQ, SmartGuard, Omnipod 5) feature a dedicated "Exercise Mode" or "Activity Mode". This function typically:

1. Increases the target glucose level (e.g., to 140–150 mg/dL).
2. Suspends automated correction boluses.
3. Reduces basal insulin delivery.
   However, a challenge identified by Desjardins et al. (2021) is the user behavior. Patients who activate "Exercise Mode" only at the moment of starting training often still experience hypoglycemia because the system does not have time to "wash out" the active insulin. Education emphasizing the "90-minute rule" for mode activation is crucial.

Do-It-Yourself (DIY) Systems

It is impossible to discuss modern technology without mentioning the Open Source (DIY) community. Systems such as AndroidAPS or Loop allow for high customization, including setting specific temporary targets for different sports. While not FDA/CE approved, these systems are widely used by athletes. They offer features often unavailable in commercial pumps, such as "Unannounced Meals" or ultra-sensitive exercise detections using accelerometer data from smartphones or smartwatches, though formal clinical trials in this area are still emerging.

7. Nutritional Support in the Tech Era

Technology effectively reduces the need for carbohydrate supplementation, but does not eliminate it. In addition to classic studies by Campbell (2013) on low-glycemic index meals, new light is shed on this topic by McCarthy et al. (2023). These authors analyzed the efficacy of "rescue carbs" in closed-loop users.

Their conclusions indicate that with an active AID (Automated Insulin Delivery) system, the amount of carbohydrates needed to recover from hypoglycemia is lower (approx. 5–10g) than in standard therapy (15–20g). This is because the system automatically suspends insulin often 30 minutes before the actual drop occurs. Consuming the standard 20g of glucose in this scenario often leads to "rebound hyperglycemia," as the glucose hits the bloodstream just as insulin levels are minimal.

Table 2. Comparison of efficacy and limitations of diabetes technologies in the context of physical activity.

Technology Type	Main Sports Support Functions	Advantages in Physical Activity Context	Limitations and Challenges
SMBG + Pen (MDI)	Basic measurement.	Reliability; no device on the body (important for contact sports).	Lack of trends; need to interrupt training; active basal insulin cannot be suspended.
CGM / FGM	Trend arrows; Alarms.	Predictive decisions; insight without finger pricking; sharing data with coaches.	Lag time (Vigers 2022); signal loss in water; compression hypoglycemia.
Pump (CSII)	Temp Basal Rate (TBR).	Precise basal reduction; extended bolus for post-exercise meals.	Risk of ketoacidosis upon disconnection; pump placement issues.
Closed Loop (AHCL)	Auto-suspension; Exercise Mode; Auto-Bolus.	Highest TIR (Aronson 2023); fewer nocturnal hypoglycemias; reduced mental burden.	Requires activating sport mode in advance; different "rescue carb" strategy; fear of auto-bolus during anaerobic effort.

8. Specific Sports Considerations

Water Sports

Swimming presents a unique challenge. While many pumps (e.g., Omnipod) are waterproof, Bluetooth signals do not travel well through water. This breaks the communication between the sensor and the pump/phone, effectively turning off the "Closed Loop" functionality during the swim. Patients must rely on pre-swim insulin adjustments and reconnect immediately after exiting the water to allow the algorithm to catch up.

Contact Sports

In disciplines like rugby, judo, or basketball, the risk of device dislodgement is high. Many players choose to disconnect their tubed pumps (e.g., MiniMed, Tandem) for the duration of the match. This, however, introduces the risk of hyperglycemia and ketosis if the disconnection lasts longer than 1–2 hours. The "untethered regimen" (combining pump basal with long-acting insulin injections) is sometimes used as a strategy for tournament days.

9. Discussion

Literature analysis, including the latest works from 2020–2024, indicates a dynamic evolution of recommendations. AHCL systems are becoming the new gold standard. As noted by Taleb et al. (2022), this technology changes "active diabetes management" into "passive surveillance," reducing the patient's mental burden.

This psychological aspect is crucial. The reduction of "diabetes distress" allows patients to focus on athletic performance rather than safety. The assurance that the system will suspend insulin if a drop is predicted allows for more confident participation in endurance events.

Limitations and Future Directions

As it is pointed out by Paldus et al. (2022), technology does not eliminate physiology. The phenomenon of increased insulin sensitivity after exercise still occurs, and algorithms - despite their advancement - still struggle to predict sudden changes during interval efforts.

The future likely belongs to bi-hormonal systems (insulin + glucagon) and ultra-rapid insulins. A dual-hormone pump could theoretically administer micro-doses of glucagon to prevent hypoglycemia during exercise without the need for carbohydrate ingestion, mimicking the physiology of a healthy pancreas. Until such systems are commercially available, the hybrid closed loop remains the most advanced tool in the therapeutic arsenal.

10. Conclusions

1. **Update of Standards:** AHCL systems demonstrate higher efficacy (Time in Range) in sports than traditional pumps and MDI, as confirmed by clinical trials from 2022–2023. They are a safety net against hypoglycemia.
2. **Nutritional Paradigm Shift:** Users of modern systems require smaller amounts of carbohydrates for hypoglycemia correction. The "15-15 rule" needs to be adapted to prevent rebound hyperglycemia.
3. **Timing is Key:** A key element of success is activating sports modes in automated systems sufficiently early (approx. 90 min before exercise) to allow insulin levels to drop.
4. **Education:** Technology is not autonomous. Patients require education on how different exercise intensities affect sensor accuracy and algorithm performance.

Disclosure

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

Conflict of Interest

The authors declare no conflict of interest.

Declaration on the use of AI:

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