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Review

Aerobic Exercise-Based Metabolic Rehabilitation in Type 1 Diabetes: Physiology, Prevention, and Personalized Management in the Era of Automated Insulin Delivery

Felice Strollo [1], Marzia Bongiovanni [2], Natalia Visalli [3] and Maja Cigrovski Berkovic [4,*] on behalf of the AMD Lazio Region Study Group on Exercise in Diabetes [†]

[1] Endocrinology Department, IRCCS San Raffaele Roma, 00166 Rome, Italy; felix.strollo@gmail.com
[2] University Diabetes Unit, Santa Maria Goretti Hospital, 04100 Latina, Italy; bongiovannimarzia@yahoo.it
[3] Diabetes and Nutrition Unit, ASL Roma 1, 00193 Rome, Italy; visallitoto@gmail.com
[4] Department for Sport and Exercise Medicine, Faculty of Kinesiology, University of Zagreb, 10000 Zagreb, Croatia
* Correspondence: maja.cigrovskiberkovic@gmail.com
† Membership of the AMD Lazio Region Study Group on Exercise in Diabetes is provided in Appendix B.

Abstract

Background and Objectives: Regular exercise is an integral component of type 1 diabetes (T1D) care, yet its sustained practice is often limited by fear of hypoglycemia, uncertainty regarding insulin and carbohydrate adjustments, and the complexity of integrating exercise physiology with contemporary diabetes technology. This clinically oriented narrative review examines aerobic exercise in T1D within a preventive and rehabilitative framework, with emphasis on practical management in the era of continuous glucose monitoring (CGM) and automated insulin delivery (AID). **Methods**: A structured PubMed/MEDLINE search was conducted across five prespecified domains: exercise physiology; insulin and carbohydrate adaptation; exercise-associated and nocturnal hypoglycemia; CGM and AID during physical activity; and cardiovascular, preventive, and rehabilitation-related outcomes. **Results**: During aerobic exercise, the inability of exogenous insulin concentrations to fall as rapidly as endogenous insulin secretion creates a dynamic interaction among insulin on board, muscle glucose uptake, hepatic glucose production, carbohydrate availability, exercise characteristics, and counter-regulatory responses. **Conclusions**: Current evidence supports anticipatory, individualized strategies that combine exercise-related glucose targets, appropriate insulin adjustment, judicious carbohydrate intake, CGM trend interpretation, and post-exercise surveillance. Special attention is required for delayed and nocturnal hypoglycemia. Beyond acute glycemic management, sustained physical activity is associated with improved cardiorespiratory fitness, metabolic health, quality of life, and lower long-term cardiovascular risk. We propose exercise-based metabolic rehabilitation as a longitudinal, individualized approach that uses education, physiological understanding, and technology to support safe, confident, and sustained participation in physical activity. AID should therefore be viewed as a powerful component of, rather than a substitute for, personalized exercise management.

Keywords: type 1 diabetes; exercise; physical activity; metabolic rehabilitation; prevention; automated insulin delivery; continuous glucose monitoring; personalized management

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1. Introduction: Exercise Beyond Glycemic Control

Physical exercise has been regarded as a cornerstone of diabetes care since the earliest decades of modern diabetology. Elliot P. Joslin included exercise among the essential components of diabetes management together with nutrition, pharmacological treatment, and education [1]. In contemporary type 1 diabetes (T1D), regular physical activity is likewise considered an integral component of care, with potential benefits extending beyond glycemic control to physical fitness, psychological well-being, health-related quality of life, and long-term cardiovascular health [2–7].

Despite these benefits, participation in physical activity remains challenging for many people with T1D. Fear of hypoglycemia, uncertainty about insulin and carbohydrate adjustments, and limited confidence among families, coaches, and exercise professionals can all act as barriers to participation [8]. These barriers are particularly relevant because exercise itself changes glucose utilization and insulin sensitivity, while exogenous insulin cannot reproduce the rapid physiological fall in circulating insulin that occurs during aerobic exercise in individuals without diabetes.

Within this context, regular exercise can be viewed not merely as a lifestyle recommendation but as a component of long-term therapeutic management. In this review, we use the term exercise-based metabolic rehabilitation to describe a structured, individualized approach aimed at preserving functional capacity, facilitating safe and sustained participation in physical activity, and supporting prevention of diabetes-related cardiometabolic complications. This use of the term does not imply that exercise "rehabilitates" pancreatic beta-cell function or replaces insulin therapy; rather, it emphasizes restoration and maintenance of metabolic and functional health through appropriately supported physical activity in line with the WHO/ICF emphasis on functioning and participation [9].

The aim of this narrative review is therefore to summarize the physiological basis of aerobic exercise management in T1D and translate this knowledge into practical principles for insulin use, carbohydrate intake, continuous glucose monitoring (CGM), and automated insulin delivery (AID). Particular attention is given to personalization, because the preventive and rehabilitative value of exercise can be realized only when people with T1D are able to participate safely and consistently.

Rather than proposing another exercise-management algorithm, this review integrates contemporary physiological and technology-based recommendations within a broader concept of exercise-based metabolic rehabilitation, in which successful management is defined not only by avoidance of acute dysglycemia but also by sustained participation, functional capacity, autonomy, and long-term cardiometabolic health.

The scope was intentionally limited to predominantly aerobic exercise because this modality is characterized by a relatively consistent tendency toward increased peripheral glucose utilization and glucose lowering in the presence of circulating exogenous insulin, thereby posing distinctive challenges for insulin and carbohydrate management. Resistance, high-intensity interval, sprint, and other predominantly anaerobic activities may elicit substantially different glycemic and counter-regulatory responses and would require separate treatment beyond the focused clinical purpose of this review [10–12]. The integrated clinical framework adopted throughout the review is summarized in Figure 1.

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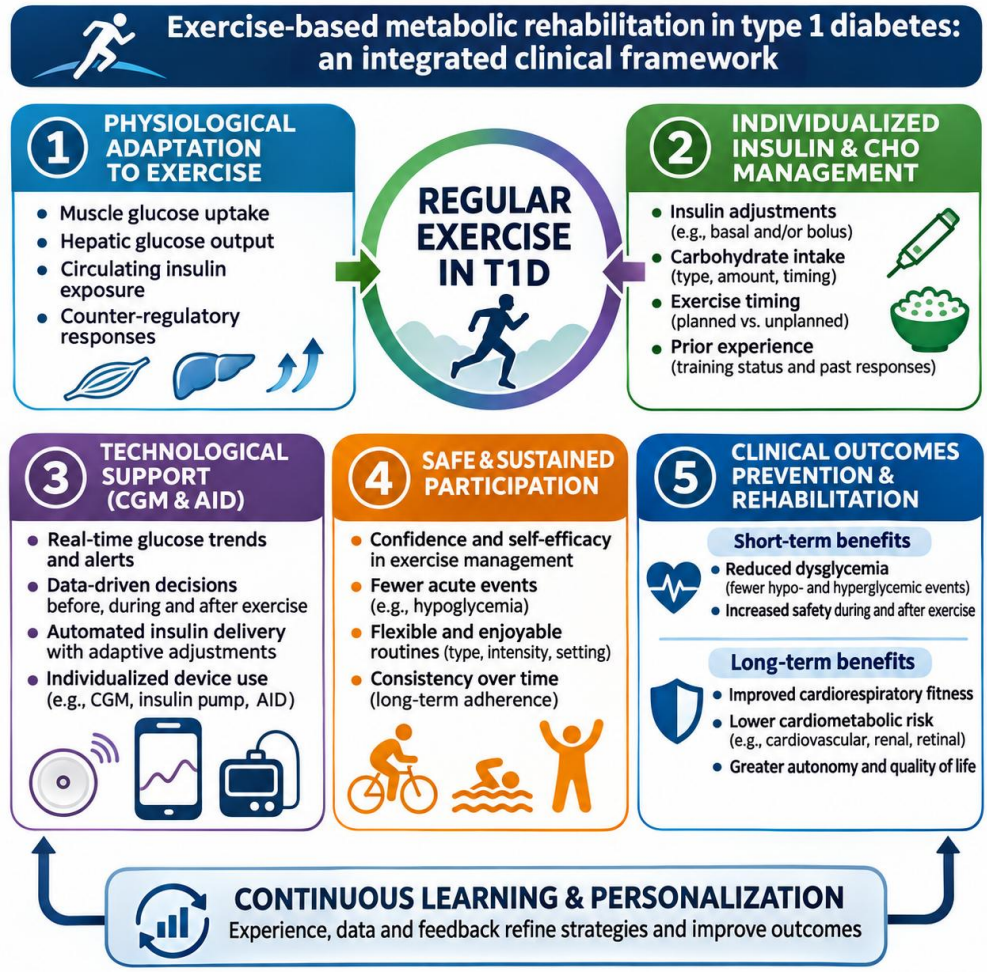


Figure 1. Exercise-based metabolic rehabilitation in type 1 diabetes: an integrated clinical framework. The figure summarizes the continuous pathway linking physiological adaptation, individualized insulin and carbohydrate management, CGM/AID-supported decision-making, sustained participation, and long-term preventive and rehabilitative outcomes. The feedback loop emphasizes progressive personalization based on repeated exercise experience [6,7,10,12–14].

2. Literature Search and Narrative Synthesis

A structured PubMed/MEDLINE search was performed on 9 August 2026 to support this clinically oriented narrative review. The search was organized around five prespecified domains reflecting the scope of the manuscript: (1) physiological responses to aerobic exercise in T1D; (2) insulin and carbohydrate adaptation before, during, and after exercise; (3) exercise-associated, delayed, and nocturnal hypoglycemia; (4) continuous glucose monitoring (CGM) and automated insulin delivery (AID) during physical activity; and (5) cardiovascular risk, prevention, and rehabilitation-related implications of regular physical activity in T1D.

Only English-language human studies were eligible for inclusion. No lower publication-date limit was imposed because earlier landmark physiological and clinical studies were considered potentially relevant.

Titles and abstracts retrieved were screened for direct relevance to the clinical questions addressed in this review. Priority was given to international consensus or position statements, systematic reviews and meta-analyses, randomized or controlled clinical studies, large observational cohorts, and original physiological studies that materially informed current exercise-management principles. Publications focused exclusively on type 2 diabetes, reports without direct relevance to exercise management

in T1D, conference abstracts without a full report, duplicate publications, and papers providing no additional clinically relevant information beyond higher-level evidence were not retained. Reference lists of major consensus statements and selected reviews were also examined to identify landmark studies not captured by the targeted searches.

Because the aim was clinical interpretation rather than exhaustive evidence quantification, the review was designed as a structured narrative synthesis and not as a systematic review. Accordingly, no formal risk-of-bias assessment, PRISMA flow diagram, or meta-analysis was undertaken. Evidence was synthesized thematically and interpreted in the context of the authors' long-standing clinical experience in the education and management of physically active people with T1D. In greater detail, search and selection transparency were as follows: M.B. and N.V. conducted the literature search and relevance screening separately, and discussed inclusion criteria at the end of the whole process to overcome potential conflicting decisions with methodological oversight from F.S. and M.C.B. Searches used on 9 August 2026 were restricted to English-language records and were screened for direct relevance to the clinical scope of this narrative review after a gradual selection process depicted in Figure 2. The complete PubMed search framework used for reproducibility is provided in Appendix A. Following this sequential selection process, 23 publications were retained and included in the final reference list, representing the evidence base used to develop the present narrative review.

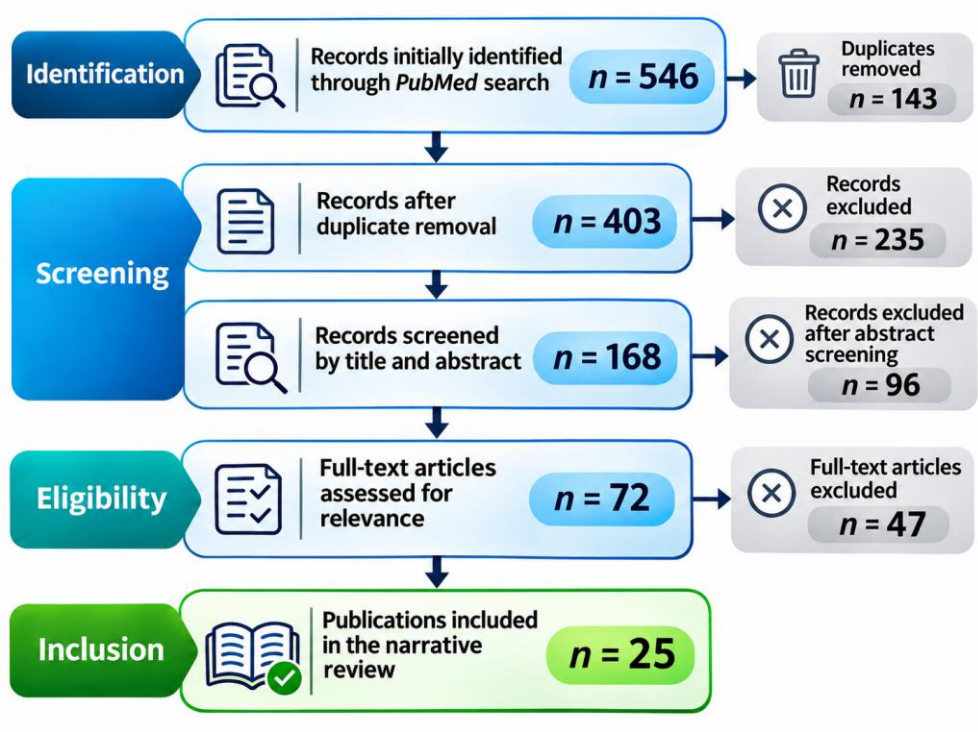


Figure 2. Article selection process flowchart.

As a non-systematic narrative review, this synthesis is vulnerable to selective retrieval and interpretation, does not formally appraise study quality, and integrates the authors' clinical experience; therefore, it should not be read as a comprehensive or quantitatively graded evidence assessment.

3. Why Aerobic Exercise Is Metabolically Different in Type 1 Diabetes

During aerobic exercise, contracting skeletal muscle markedly increases glucose uptake. In people without diabetes, this increased peripheral demand is accompanied by a rapid reduction in endogenous insulin secretion and coordinated counter-regulatory

responses that help preserve circulating glucose while allowing hepatic glucose production and mobilization of alternative fuels. In T1D, circulating insulin is determined by previously administered exogenous insulin and cannot fall with the same physiological speed. Consequently, the balance among insulin levels still remaining active in blood (insulin on board (IOB), an estimate of residual glucose-lowering insulin activity calculated from prior insulin delivery and the assumed insulin-action profile, applicable to AID, conventional pumps, and injection therapy). We underline that IOB is a model-derived estimate of residual insulin action, not a measured circulating insulin concentration. Because of its inherent functional meaning, it is relevant to adopting a suitable strategy for adaptation to exercise intensity and duration, while taking into account hepatic glucose output, muscle glucose uptake, carbohydrate availability, and counter-regulatory hormones to achieve the most stable glucose level possible [10]. In greater detail, counter-regulation depends on glucagon and sympathoadrenal responses the rise of which during exercise may be impaired in T1D due to antecedent hypoglycemia, thus increasing susceptibility to subsequent hypoglycemia. Liver and muscle glycogen availability, nutritional status, habitual training, and biological sex may modify substrate selection and glucose trajectories, although individual variability is substantial [10,12]. These mechanisms reinforce the need to interpret exercise responses longitudinally rather than infer a universal response from exercise intensity alone.

The direction and magnitude of glucose change are not uniform across exercise modalities. Prolonged moderate-intensity aerobic activity commonly lowers glucose, whereas high-intensity, intermittent, resistance, or predominantly anaerobic exercise may produce a smaller initial decline or even a transient rise in glucose as a consequence of a high catecholamine output driving hepatic glucose release. Training status, antecedent exercise, time of day, recent meals, starting glucose, and active insulin further modify these responses [10,12]. Accordingly, exercise management in T1D should be based on expected physiology rather than on a single glucose threshold or a rigid universal algorithm.

This physiological variability is clinically important. A strategy that prevents hypoglycemia during one session may promote hyperglycemia during another because of differences in exercise intensity, timing, insulin exposure, stress, or other contextual factors, while excessive carbohydrate intake can trigger subsequent automated insulin delivery and thereby contribute to a later fall in glucose. For this reason, the most useful framework is anticipatory and adaptive: estimate the likely metabolic direction of the planned activity, minimize avoidable excess insulin on board, monitor glucose trends, and refine the strategy through repeated experience.

4. Preparing for Aerobic Exercise: Glucose, Insulin on Board, and Carbohydrate Availability

Consensus guidance commonly uses a pre-exercise glucose range of approximately 7.0–10.0 mmol/L (126–180 mg/dL) as a practical starting range for many aerobic activities, with individual adjustments according to hypoglycemia risk and exercise context. When exercise follows a meal, illustrative prandial bolus reductions of approximately 25–75% have been described in specific protocols; they are not universal recommendations and depend on duration, intensity, insulin on board, and treatment modality [12–14]. These principles also apply to multiple daily injections and non-automated pump therapy, although neither offers the same automated higher-target function as AID. Sensor glucose may lag behind blood glucose, particularly during rapid change; a delay of roughly 5–15 min is often present, but it varies with sensor, physiology, and conditions. Symptoms or unexpected sensor readings warrant capillary confirmation when feasible [14].

The literature underpinning practical recommendations has evolved from capillary glucose monitoring to real-time CGM and, more recently, to AID-specific guidance [10,13,15,16]. Preparation should begin before exercise rather than the moment activity starts. When aerobic exercise is planned, recent insulin administration with IOB, meal or recent carbohydrate intake timing, anticipated directionality with intensity and duration, and previous responses to similar sessions should be considered together. Also, the athlete should always take great account of the fact that, despite absolute CGM data with glucose trend arrows being extremely helpful for overall exercise management, during exercise, especially when glucose is falling quickly, as witnessed by the rate of change, interstitial glucose can lag behind blood glucose. This is clinically relevant because relying exclusively on the displayed sensor value, rather than the direction/rate of change, can dangerously delay carbohydrate intervention.

For planned aerobic activity, which is expected to lower glucose, current AID guidance supports raising the glucose target in advance—ideally about 1–2 h before exercise when circumstances and the device permit—particularly when activity will occur with meaningful insulin on board [13]. When exercise follows a carbohydrate-containing meal, a reduction in the pre-exercise meal bolus may also be appropriate. By contrast, activities other than aerobic exercise that are expected to raise glucose usually do not require elevation of the glucose target. These principles should be individualized rather than applied mechanically because starting glucose and trend, exercise type, and prior experience materially affect risk.

Carbohydrate intake is similarly context-dependent. Small amounts of rapidly absorbed carbohydrate may be used when glucose is low or falling, whereas unnecessary large carbohydrate loads should be avoided because they may cause hyperglycemia and, in AID users, stimulate additional insulin delivery. The objective is to match carbohydrate intake to physiological need while anticipating the response of the specific AID system [13–15].

5. Automated Insulin Delivery Around Exercise

AID systems represent a major advance in T1D management because they continuously adapt insulin delivery in response to sensor glucose and system-specific algorithms. Their use can reduce the burden of day-to-day glucose management, but exercise remains a demanding context because insulin pharmacokinetics are slower than the rapid metabolic changes induced by muscular activity. An algorithm can respond to measured and predicted glucose trajectories, yet it may not fully know the context of the upcoming activity, the athlete's intended intensity, the amount of recent carbohydrate intake, or the individual response learned over years of training.

The 2025 EASD/ISPAD position statement provides the most comprehensive contemporary framework for AID management around physical activity [13]. Subsequent real-world and randomized evidence has reinforced the importance of anticipatory rather than purely reactive strategies [16–18]. For planned aerobic exercise, an exercise-related higher glucose target is generally most effective when activated before activity; when exercise has to occur soon after a meal, reduction of the prandial bolus may be particularly relevant to reducing hypoglycemia risk. For unplanned activity, immediate activation of the higher target and judicious use of rapidly absorbed carbohydrate may be necessary. Whenever possible, scheduling aerobic exercise during periods of relatively low insulin on board can simplify management [13].

Importantly, AID use during exercise should not be framed as a binary choice between "automation" and "manual control." The clinically relevant question is how to use the available technology in a manner consistent with the physiology of the activity and the user's documented response. In selected circumstances, some experienced users

may temporarily modify or disengage automation; such approaches may be reasonable when based on documented individual responses, but they should neither be generalized nor assumed to be superior to remaining in automated mode. They are better understood as individualized adaptations requiring knowledge of insulin action, carbohydrate metabolism, device behavior, and personal exercise responses.

6. Practical Strategies: Benefits, Limitations, and the Need for Individualization

The principal strategies used to reduce exercise-associated dysglycemia act on three modifiable domains: insulin exposure, carbohydrate availability, and exercise timing or structure as depicted in Figure 3.

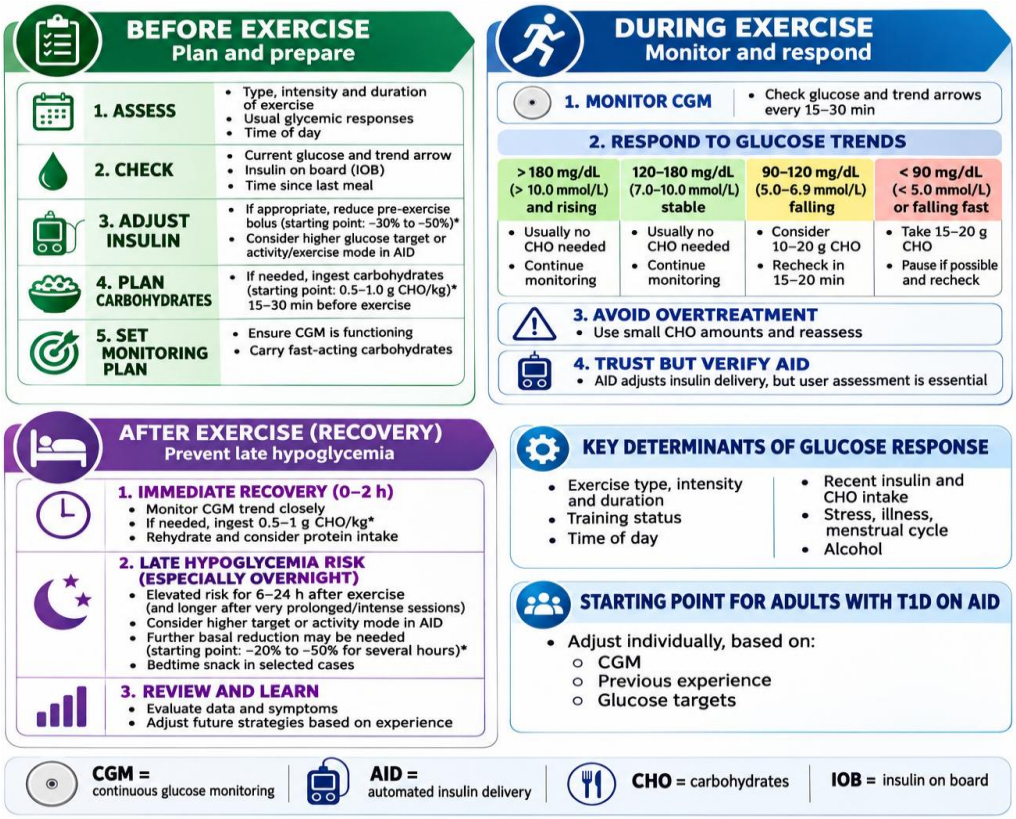


Figure 3. Practical management of planned aerobic exercise in people with type 1 diabetes using automated insulin delivery. The framework integrates preparation, CGM-guided monitoring, insulin and carbohydrate adaptation, recovery, and prevention of delayed or nocturnal hypoglycemia. Numerical values are intended as starting points and require individualization according to treatment modality, exercise characteristics, real-time data, and prior response [11–13]. The values shown are illustrative, protocol-dependent examples, not fixed prescriptions, and each athlete should keep in mind that individual needs, temporary insulin-sensitivity changes, and different contexts can strongly influence their last-minute choices.

Reducing a pre-exercise bolus or basal insulin exposure can decrease the need for supplemental carbohydrate and lower hypoglycemia risk, but these approaches require advance planning and may increase pre-exercise glucose. Carbohydrate supplementation is particularly useful for prolonged or unplanned activity but, when excessive, may impair weight-management goals, cause gastrointestinal symptoms, or provoke secondary insulin delivery in AID users. Brief high-intensity efforts or resistance exercise

may attenuate a glucose decline in selected settings, but their effect is not sufficiently predictable to substitute for individualized monitoring [13,19–21].

These trade-offs illustrate why practical recommendations should be treated as starting points for structured experimentation rather than fixed prescriptions. Training sessions provide an opportunity to identify reproducible patterns under safer conditions than competition. Recording starting glucose, trend, insulin on board, insulin adjustments, carbohydrate intake, exercise duration and intensity, and subsequent glucose response can progressively transform experience into an individualized management strategy. The feasibility of these strategies depends on whether exercise is planned. Planned sessions allow advance adjustments to insulin exposure and carbohydrate availability, whereas unplanned sessions generally require immediate glucose-trend assessment, device-specific action where available, and cautious carbohydrate supplementation [12–14].

The main practical options with benefits/limitations and supporting evidence are summarized in Table 1.

Table 1. Practical exercise-management strategies in T1D: potential benefits and limitations.

Strategy	Potential Benefit	Important Limitation/Context	Supporting Evidence
Reduce pre-exercise meal bolus	May reduce insulin on board and lower hypoglycemia risk during aerobic exercise.	Requires planning; magnitude depends on meal timing, exercise type, and individual response.	[12,20] Controlled trial; consensus
Use AID exercise/higher target	May reduce automated insulin delivery before and during glucose-lowering exercise.	Most effective when activated sufficiently before planned activity; device-specific behavior varies.	[13,19] Position statement; RCT
Adjust basal insulin exposure	May reduce hypoglycemia risk when automation is not used or when device-specific strategies permit.	Requires advance planning; excessive reduction can increase hyperglycemia/ketosis risk.	
Rapid-acting carbohydrate during exercise	Useful for low or falling glucose and for prolonged/unplanned activity.	Excess intake can cause hyperglycemia, gastrointestinal symptoms, and additional reactive AID insulin delivery.	
Post-exercise insulin/carbohydrate adaptation	May reduce delayed/nocturnal hypoglycemia and support recovery	Needs individualization; fixed percentage reductions should not be generalized.	
Brief high-intensity/resistance effort	May attenuate glucose decline in selected circumstances.	Response is variable: monitoring or individualized insulin/CHO planning are needed.	

7. Delayed and Nocturnal Hypoglycemia

The risk of exercise-associated hypoglycemia does not end when exercise stops. Increased insulin sensitivity and post-exercise restoration of muscle glycogen can persist for hours, creating a clinically important risk of delayed and nocturnal hypoglycemia [10,21–23]. Recent real-world T1DEXI data in adults confirm that nocturnal hypoglycemia is more frequent after exercise days and identify preceding time below range, exercise/post-exercise hypoglycemia, bedtime glucose, and insulin-delivery modality as clinically relevant modifiers of risk [22].

Post-exercise management should therefore extend into recovery. CGM trend monitoring, appropriate carbohydrate replacement, and individualized adjustment of meal or basal insulin may be required. Fixed carbohydrate formulas and broad percentage reductions in insulin should not be interpreted as universal rules, because the appropriate intervention depends on exercise characteristics, insulin sensitivity, treatment modality, and the behavior of the AID system.

Quantitative strategies can nevertheless provide useful starting points when interpreted in context. Published guidance and controlled studies have evaluated carbohydrate replacement according to exercise duration and insulin exposure, as well as post-exercise reductions in prandial or basal insulin to reduce delayed hypoglycemia. These approaches are protocol-, treatment-, and timing-dependent and should be individualized rather than generalized across all people with T1D or all AID systems [12,14].

The above-mentioned considerations are clinically relevant, as nocturnal hypoglycemia is not only an acute safety outcome but also because fear of post-exercise/night-time hypoglycemia can influence future willingness to exercise. As a consequence of that, we could expect a vicious cycle to be triggered in ill-educated athletes with T1DM, including nocturnal post-exercise hypoglycemia experience/fear causing reduced self-confidence with avoidance of future exercise, eventually ending in loss of long-term benefit. What we need, instead, is to go in the other direction, with successful prevention building confidence, thus reinforcing adherence to regular exercise as a harbinger of rehabilitation benefits.

Accordingly, post-exercise decisions should combine current consensus recommendations with CGM trends and responses documented during prior comparable sessions [14,21].

8. Exercise as a Preventive and Rehabilitative Intervention

The clinical value of exercise in T1D extends beyond the prevention of an isolated episode of dysglycemia during a workout. Regular physical activity contributes to cardiorespiratory fitness, psychological well-being, and cardiovascular risk management. A systematic review and meta-analysis found exercise training to be associated with improved aerobic capacity, HbA1c, daily insulin requirements, and total cholesterol in people with T1D [6]. More recently, a nationwide Swedish longitudinal cohort of nearly 49,000 adults with T1D showed that persistently low physical activity was associated with higher all-cause mortality, whereas increasing or sustained higher activity trajectories were associated with substantially lower adjusted mortality risk [7]. These observations do not establish causality for every diabetes complication, but they provide contemporary support for sustained physical activity as a major component of long-term risk reduction and functional health in T1D.

Indeed, exercise-related outcomes should be distinguished across three levels: (1) acute safety, including avoidance of exercise-associated dysglycemia; (2) intermediate metabolic and functional adaptation, including improved insulin sensitivity,

cardiorespiratory fitness, strength, confidence, and participation; and (3) longer-term health and autonomy, including cardiovascular risk-factor improvement, preserved physical function, and potentially lower morbidity. Evidence is strongest for changes in fitness and selected risk markers; observational associations with mortality cannot establish causality, and direct evidence that training prevents specific T1D complications is less conclusive [6,7]. Neuromuscular outcomes deserve particular attention: diabetes-associated alterations in peripheral nerve, skeletal muscle, microvascular function, and physical performance may contribute to disability with increasing age and disease duration. Aerobic exercise promotes mitochondrial biogenesis and angiogenesis, supporting oxidative capacity and endurance and thus metabolic and cardiovascular health; resistance training primarily enhances neural plasticity, muscle strength and hypertrophy, which are crucial factors for mitigating sarcopenia and preserving functional reserve/independence [24]. The latter is discussed as a complementary rehabilitation modality, not as part of the aerobic-specific acute glycemic recommendations of this review.

From a rehabilitation perspective, the central objective is sustained participation. Fear of hypoglycemia, previous adverse experiences, and uncertainty regarding technology can lead individuals to reduce or abandon exercise even when they would otherwise benefit from it. A structured program that combines physiological education, individualized insulin and carbohydrate strategies, CGM interpretation, and appropriate use of AID can help remove these barriers.

Indeed, metabolic rehabilitation is not a short-term intervention after an acute event; it is a longitudinal process that supports functional autonomy and enables exercise to become a durable component of diabetes care.

The distinction between prevention and rehabilitation should nevertheless remain precise. Exercise does not provide primary prevention of T1D in people who already have the disease. Rather, it contributes to prevention of diabetes-related and cardiometabolic complications and may support primary prevention of additional chronic conditions. Prevention of the onset of complications in established T1D may be described as secondary prevention, whereas limiting progression, disability, or functional consequences of existing complications is more appropriately described as tertiary prevention. These categories should not be conflated.

9. From Guidelines to Personalized Exercise Management

A practical clinic learning loop may review representative exercise-day CGM traces (before, during, overnight), insulin delivery or injection records, carbohydrate intake, activity duration/intensity, symptoms, and device/app reports. A first review after several comparable sessions and periodic reassessment at routine diabetes visits can identify repeatable patterns; earlier review is appropriate after severe hypoglycemia, recurrent nocturnal events, or major treatment changes. Clinicians and individuals can agree on one or two measurable adjustments, document their rationale, and evaluate them against subsequent exercise sessions [13,14]. Indeed, people using the same AID system may respond differently to an apparently similar exercise session because of differences in insulin sensitivity, training status, recent food intake, stress, sleep, ambient conditions, and prior exercise. Even within the same individual, the response may vary from day to day.

The goal of education is to teach people how to apply AID technology-oriented guideline-based principles to their own recurring physiological patterns and reduce routine treatment burden but data in the context of exercise will help identify recurring patterns, and refine future decisions through an iterative learning process. This is particularly relevant for people who train regularly and for athletes, in whom small

differences in insulin availability or carbohydrate timing can influence both safety and performance.

10. The Role of the Multidisciplinary Diabetes–Exercise Team

Families and caregivers, school personnel, and coaches should be involved when relevant and with the individual's consent. Exercise should be deferred and ketones assessed in the setting of marked hyperglycemia or suspected insulin deficiency; blood ketones ≥1.5 mmol/L are a clear reason to avoid exercise until metabolic correction, while intermediate ketone elevations require caution and individualized clinical advice. Recent severe hypoglycemia or inability to recognize or treat hypoglycemia also warrants postponement and reassessment. Glucose thresholds depend on ketone status, exercise intensity, and treatment context; guidance should follow established consensus recommendations rather than a single universal cutoff [12,14].

Safe exercise participation requires more than device knowledge. The diabetes team should integrate expertise in insulin therapy, nutrition, exercise physiology, and interpretation of CGM/AID data, while the person with T1D contributes indispensable knowledge of previous individual responses. Where available, collaboration among different specialists can support shared decision-making and reduce avoidable barriers to physical activity [21,25].

An efficient model for rehabilitation-oriented care includes the persons with T1D a active members of the multidisciplinary team with—at least—the diabetes specialist for insulin/AID optimization, the dietitian for CHO availability and fueling, the exercise physiologist/sports physician for exercise characterization and training load a psychologist or mental health professional meant at addressing fear of hypoglycemia, distress, and behavioral barriers. Indeed, the main objective is to build confidence, autonomy, and reproducible strategies that allow physical activity to continue across the lifespan, even by postponing exercise when metabolic conditions are unsafe.

11. Limitations of the Present Review

As explained in Section 2, our paper was designed as a structured narrative synthesis and not as a systematic review. Accordingly, no formal risk-of-bias assessment, PRISMA flow diagram, or meta-analysis was undertaken because our aim was clinical interpretation rather than exhaustive evidence quantification.

12. Conclusions

Exercise should be regarded as an integral therapeutic component of T1D care and, when supported by a structured and individualized framework, as a meaningful component of metabolic and functional rehabilitation. Its long-term preventive potential depends on enabling people with T1D to participate safely, confidently, and consistently.

AID systems have substantially expanded the possibilities for exercise management, but technology does not eliminate the need for physiological understanding. Optimal use requires integration of device behavior with exercise type, insulin on board, carbohydrate availability, glucose trends, training status, and individual experience. Current consensus recommendations provide the essential framework; repeated observation during training allows that framework to be personalized.

The most productive relationship between technology and human expertise is therefore complementary rather than competitive. AID can reduce treatment burden and improve adaptability, while informed users and multidisciplinary teams provide the contextual interpretation that exercise demands. Integrating physiology, education, CGM/AID data, and individual experience may help transform physical activity from a

source of uncertainty into a sustainable therapeutic, preventive, and rehabilitative strategy throughout the life course of people with T1D.

Author Contributions: Conceptualization, F.S.; methodology, F.S. and M.C.B.; literature search, M.B. and N.V.; writing—original draft preparation, F.S.; writing—review and editing, F.S., M.C.B., M.B. and N.V.; supervision, F.S. and M.C.B. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: Not applicable.

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

Abbreviations

The following abbreviations are used in this manuscript:

CGM	Continuous Glucose Monitoring
AID	Automated insulin delivery

Appendix A

Reproducible PubMed/MEDLINE Search Framework

The following thematic search framework was used on 9 August 2026. Searches were restricted to English-language records and were screened for direct relevance to the clinical scope of this narrative review. Search strings may be adapted slightly by PubMed automatic term mapping.

Domain 1—Exercise physiology

("type 1 diabetes"[Title/Abstract]) AND (exercise[Title/Abstract] OR "physical activity"[Title/Abstract]) AND (physiology[Title/Abstract] OR aerobic[Title/Abstract] OR metabolic[Title/Abstract])

Domain 2—Insulin and carbohydrate adaptation

("type 1 diabetes"[Title/Abstract]) AND (exercise[Title/Abstract] OR "physical activity"[Title/Abstract]) AND (insulin[Title/Abstract] OR carbohydrate[Title/Abstract])

Domain 3—Exercise-associated and nocturnal hypoglycemia

("type 1 diabetes"[Title/Abstract]) AND (exercise[Title/Abstract] OR "physical activity"[Title/Abstract]) AND (hypoglycemia[Title/Abstract] OR hypoglycaemia[Title/Abstract] OR nocturnal[Title/Abstract] OR delayed[Title/Abstract])

Domain 4—CGM and automated insulin delivery

("type 1 diabetes"[Title/Abstract]) AND (exercise[Title/Abstract] OR "physical activity"[Title/Abstract]) AND ("automated insulin delivery"[Title/Abstract] OR "closed-

loop"[Title/Abstract] OR "continuous glucose monitoring"[Title/Abstract] OR CGM[Title/Abstract])

Domain 5—Prevention, cardiovascular risk, and rehabilitation

("type 1 diabetes"[Title/Abstract]) AND (exercise[Title/Abstract] OR "physical activity"[Title/Abstract]) AND (cardiovascular[Title/Abstract] OR complications[Title/Abstract] OR prevention[Title/Abstract] OR rehabilitation[Title/Abstract] OR mortality[Title/Abstract])

After this first screening, which turned out to retrieve too large an amount of records to allow efficient selection, we addressed the MESH search using to the following string (Diabetes Mellitus, Type 1[Mesh] OR "type 1 diabetes"[TiAb]) AND (Exercise[Mesh] OR "physical activity"[TiAb] OR rehabilitation[TiAb]) AND ("Insulin Infusion Systems"[Mesh] OR "automated insulin delivery"[TiAb] OR "continuous glucose monitoring"[TiAb] OR "personalized management"[TiAb]).

First, we screened the retrieved records to identify duplicate publications and assess their relevance to the review topic. Titles and abstracts were then examined to exclude studies that did not adequately address the principal research questions or fell outside the review's predefined scope. Publications considered potentially relevant after this preliminary screening underwent a more detailed assessment of their full texts. At this stage, particular attention was paid to the relevance of the study population, the correspondence between the investigated outcomes and the objectives of the review, the methodological characteristics of the studies, and the complementary contribution of the available evidence, to provide a coherent and balanced overview of the topic rather than an exhaustive quantitative synthesis.

Appendix B

The following members of the AMD Lazio Region Study Group on Exercise in Diabetes (Associazione Medici Diabetologi, the Italian scientific association of diabetes specialists) contributed to scientific discussions during sports meetings and educational sessions involving athletes with T1D: Sabrina Spera, Diabetes and Nutrition Unit, ASL Roma 1, Rome, Italy; Nicolina Di Biase, Diabetes Unit, San Pietro Hospital, Rome, Italy; Antonio Gianfelici, Institute of Sports Medicine and Science, CONI, Rome, Italy; and Alessandro Scotto di Palumbo, Department of Movement, Human and Health Sciences, University of Rome Foro Italico, Rome, Italy.

References

1. Joslin, E.P. Diabetes in the future. *Diabetes* **1961**, *10*, 148–151. https://doi.org/10.2337/diab.10.2.148.
2. Anderson, B.J.; Laffel, L.M.; Domenger, C.; Danne, T.; Phillip, M.; Mazza, C.; Hanas, R.; Waldron, S.; Beck, R.W.; Calvi-Gries, F.; et al. Factors associated with diabetes-specific health-related quality of life in youth with type 1 diabetes: The global TEENS study. *Diabetes Care* **2017**, *40*, 1002–1009. https://doi.org/10.2337/dc16-1990. Correction in *Diabetes Care* **2018**, *43*, 640.
3. Dimitri, P.; Joshi, K.; Jones, N.; Moving Medicine for Children Working Group. Moving more: Physical activity and its positive effects on long term conditions in children and young people. *Arch. Dis. Child.* **2020**, *105*, 1035–1040.
4. Wake, A.D. Protective effects of physical activity against health risks associated with type 1 diabetes: "Health benefits outweigh the risks". *World J. Diabetes* **2022**, *13*, 161–184. https://doi.org/10.4239/wjd.v13.i3.161.
5. Maqsood, S.; Chakole, V.; Dash, S. Navigating cardiovascular risk in type 1 diabetes: A comprehensive review of strategies for prevention and management. *Cureus* **2024**, *16*, e60426. https://doi.org/10.7759/cureus.60426.
6. Wu, N.; Bredin, S.S.D.; Guan, Y.; Dickinson, K.; Kim, D.D.; Chua, Z.; Kaufman, K.; Warburton, D.E.R. Cardiovascular health benefits of exercise training in persons living with type 1 diabetes: A systematic review and meta-analysis. *J. Clin. Med.* **2019**, *8*, 253. https://doi.org/10.3390/jcm8020253.

7. Mavridis, A.; Viktorisson, A.; Reinholdsson, M.; Eliasson, B.; Abzhandadze, T.; Sunnerhagen, K.S. Physical activity trajectories and all-cause mortality in type 1 diabetes: A nationwide longitudinal study. *Diabetes Res. Clin. Pract.* **2024**, *212*, 111702. https://doi.org/10.1016/j.diabres.2024.111702.
8. Ngamy, T.; Statham, L.; Smith, B.; Smith, J.R.; Lloyd, J.; Clarke, R.; Narendran, P.; Dias, R.P.; Andrews, R.C.; Cockcroft, E.J. A mixed methods exploration of the experiences of physical activity providers in supporting children and adolescents with type 1 diabetes in the UK. *Eur. J. Pediatr.* **2025**, *184*, 311. https://doi.org/10.1007/s00431-025-06139-z.
9. World Health Organization. International Classification of Functioning, Disability and Health: ICF. World Health Organization. 2001. Available online: https://iris.who.int/server/api/core/bitstreams/83e1c3e0-cf9e-4063-a424-71ccc9a84ded/content (accessed on 15 November 2026).
10. Galassetti, P.; Riddell, M.C. Exercise and type 1 diabetes (T1DM). *Compr. Physiol.* **2013**, *3*, 1309–1336. https://doi.org/10.1002/cphy.c110040.
11. Smee, S.N.; Spence, A.L.; Halse, R.; Ng, L.; Shetty, V.B.; Davis, E.A.; Davey, R.J. Physiological impacts of type 1 diabetes on exercise performance: A systematic review and narrative synthesis of the literature. *Can. J. Diabetes* **2026**, *online ahead of print*. https://doi.org/10.1016/j.jcjd.2026.06.007.
12. Riddell, M.C.; Gallen, I.W.; Smart, C.E.; Taplin, C.E.; Adolfsson, P.; Lumb, A.N.; Kowalski, A.; Rabasa-Lhoret, R.; McCrimmon, R.J.; Hume, C.; et al. Exercise management in type 1 diabetes: A consensus statement. *Lancet Diabetes Endocrinol*. **2017**, *5*, 377–390. https://doi.org/10.1016/S2213-8587(17)30014-1. Correction in *Lancet Diabetes Endocrinol*. **2017**, *5*, e3.
13. Moser, O.; Zaharieva, D.P.; Adolfsson, P.; Battelino, T.; Bracken, R.M.; Buckingham, B.A.; Danne, T.; Davis, E.A.; Dovč, K.; Forlenza, G.P.; et al. The use of automated insulin delivery around physical activity and exercise in type 1 diabetes: A position statement of the European Association for the Study of Diabetes (EASD) and the International Society for Pediatric and Adolescent Diabetes (ISPAD). *Diabetologia* **2025**, *68*, 255–280. https://doi.org/10.1007/s00125-024-06308-z.
14. Moser, O.; Riddell, M.C.; Eckstein, M.L.; Adolfsson, P.; Rabasa-Lhoret, R.; van den Boom, L.; Gillard, P.; Nørgaard, K.; Oliver, N.S.; Zaharieva, D.P.; et al. Glucose management for exercise using continuous glucose monitoring and intermittently scanned CGM systems in type 1 diabetes: Position statement of the EASD and ISPAD endorsed by JDRF and supported by the ADA. *Diabetologia* **2020**, *63*, 2501–2520. https://doi.org/10.1007/s00125-020-05263-9.
15. Riddell, M.C.; Milliken, J. Preventing exercise-induced hypoglycemia in type 1 diabetes using real-time continuous glucose monitoring and a new carbohydrate intake algorithm. *Diabetes Technol. Ther.* **2011**, *13*, 819–825. https://doi.org/10.1089/dia.2011.0052.
16. Helleputte, S.; Yardley, J.E.; Scott, S.N.; Stautemas, J.; Jansseune, L.; Marlier, J.; De Backer, T.; Lapauw, B.; Calders, P. Effects of postprandial exercise on blood glucose levels in adults with type 1 diabetes: A review. *Diabetologia* **2023**, *66*, 1179–1191. https://doi.org/10.1007/s00125-023-05910-x.
17. Jacobs, P.G.; Marak, M.C.; Calhoun, P.; Gal, R.L.; Castle, J.R.; Riddell, M.C. An evaluation of how exercise position statement guidelines are being used in the real world in type 1 diabetes: Findings from the Type 1 Diabetes Exercise Initiative (T1DEXI). *Diabetes Res. Clin. Pract.* **2024**, *217*, 111874. https://doi.org/10.1016/j.diabres.2024.111874.
18. Corrado, A.; Scidà, G.; Abuqwider, J.; Rainone, C.; Lupoli, R.; Masulli, M.; Bozzetto, L.; Annuzzi, G. Management of prolonged aerobic exercise in people with type 1 diabetes on automated insulin delivery systems: A randomized controlled study. *Diabetes Care* **2024**, *47*, e76–e77. https://doi.org/10.2337/dc24-0898.
19. Turner, L.V.; Sherr, J.L.; Zaharieva, D.P.; Baran, J.; Hirsch, I.B.; Bode, B.W.; Brown, S.A.; Bzdick, S.; Church, M.M.; Hansen, D.W.; et al. Use of the Omnipod 5 automated insulin delivery system Activity feature reduces insulin delivery and attenuates the drop in glycemia associated with exercise in a randomized controlled trial. *Diabetes Care* **2025**, *48*, 1598–1606. https://doi.org/10.2337/dc25-0141. Correction in *Diabetes Care* **2026**, *49*, 211.
20. McAuley, S.A.; Horsburgh, J.C.; Ward, G.M.; La Gerche, A.; Gooley, J.L.; Jenkins, A.J.; MacIsaac, R.J.; O'Neal, D.N. Insulin pump basal adjustment for exercise in type 1 diabetes: A randomised crossover study. *Diabetologia* **2016**, *59*, 1636–1644. https://doi.org/10.1007/s00125-016-3981-9.
21. Strollo, F.; Gentile, S.; Assaloni, R.; De Fazio, C.; Corigliano, G. Exercise related care pathways for people with diabetes: Literature review and expert consensus. *Diabetes Metab. Syndr.* **2019**, *13*, 2755–2762. Correction in *Diabetes Metab. Syndr.* **2019**, *13*, 2973–2974.
22. Bisno, D.I.; Turner, L.V.; Gallop, R.J.; Jo Kamimoto, J.L.; Reddy, S.; Gal, R.L.; Riddell, M.C.; Rickels, M.R. Factors associated with nocturnal hypoglycemia after exercise in the Type 1 Diabetes and Exercise Initiative (T1DEXI). *Diabetes Care* **2026**, *49*, 1404–1413. https://doi.org/10.2337/dc26-0381.

23. Campbell, M.D.; Walker, M.; Bracken, R.M.; Turner, D.; Stevenson, E.J.; Gonzalez, J.T.; Shaw, J.A.; West, D.J. Insulin therapy and dietary adjustments to normalize glycemia and prevent nocturnal hypoglycemia after evening exercise in type 1 diabetes: A randomized controlled trial. *BMJ Open Diabetes Res. Care* **2015**, *3*, e000085. https://doi.org/10.1136/bmjdrc-2015-000085.
24. Lecce, E.; Bellini, A.; Greco, G.; Martire, F.; Scotto di Palumbo, A.; Sacchetti, M.; Bazzucchi, I. Physiological mechanisms of neuromuscular impairment in diabetes-related complications: Can physical exercise help prevent it? *J. Physiol.* **2026**, *604*, 707–734. https://doi.org/10.1113/JP287589.
25. Katz, A.; Shulkin, A.; Fortier, M.A.; Yardley, J.E.; Kichler, J.; Housni, A.; Talbo, M.K.; Rabasa-Lhoret, R.; Brazeau, A.-S. Strategies to reduce hyperglycemia-related anxiety in elite athletes with type 1 diabetes: A qualitative analysis. *PLoS ONE* **2025**, *20*, e0313051. https://doi.org/10.1371/journal.pone.0313051.

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