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The Effect of Physical Exercises on Glucose Control in Patients with Type 1 Diabetes Mellitus. Literature Review.

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Integrated studies

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Abbreviations and Definitions

ADA	American Diabetes Association
AHA	American Heart Association
AID	Automated insulin delivery
BGC	Blood glucose concentration
CL	Closed loop
CONT	Continuous moderate-intensity aerobic exercise
CSII	Continuous subcutaneous insulin infusion
DSS	Decision Support Systems
EB-HIIE	Elastic Bans- High Intensity Interval Training
GI	Glycemic Index
HIIT	high-intensity interval training
MARD	Mean absolute relative deviation
MDI	Multiple daily injections
OP	Open loop
SMBG	Self-Monitoring of Blood Glucose
T1DM	Type 1 Diabetes Mellitus

T2DM	Type 2 Diabetes Mellitus
TAR	Time above range, percentage of time blood glucose levels are above target range
TBR	Time blow range, percentage of time blood glucose levels are below target range
TIR	Time in range, percentage of time blood glucose levels are in target range
WHO	World Health Organization

Summary

Type 1 diabetes mellitus (T1DM) is a growing global health concern, particularly among younger populations, due to its autoimmune destruction of pancreatic ß-cells, leading to insulin deficiency and serious complications if not properly managed. This review explores how regular physical exercise can positively impact glucose control in T1DM patients, despite the challenges they face, and aims to identify strategies to optimize exercise benefits through tailored insulin management, diet, and modern technology.

The literature review followed a systematic search strategy using PubMed, focusing on studies published between 2015 and 2025 that examined the relationship between T1DM, exercise, glucose control, and technology. After applying specific inclusion and exclusion criteria, and screening of 372 initial records, 92 relevant sources were selected for the final review.

Exercise in individuals with T1DM showed to improve short-term glycemic control by increasing time in target glucose range, while evidence on its long-term effect on HbA1c remains mixed. Different training modalities, particularly high-intensity interval training (HIIT) and continuous exercise, have been shown to impact glucose balance in individuals with type 1 diabetes, with HIIT offering more stable glucose levels and reduced hypoglycemia risk, while continuous exercise tends to lower glucose more significantly during and after activity. Despite the clear benefits of physical activity, many adolescents with type 1 diabetes remain inactive due to psychological barriers—particularly fear of hypoglycemia—as well as logistical, physiological, and technological challenges, all of which contribute to poorer glycemic control and reduced overall well-being. To manage exercise-induced glycemic fluctuations in type 1 diabetes, it is crucial to adjust carbohydrate intake based on pre- and post-exercise blood glucose levels, consume carbohydrate-rich foods with a high glycemic index for immediate glycogen replenishment, reduce insulin doses before and after prolonged exercise, monitor glucose frequently, and consume a balanced pre-bedtime snack to prevent nocturnal hypoglycemia, while considering insulin sensitivity, exercise type, and the timing of meals. In recent years, there has been a significant advancement in the field of technology. These advancements have been particularly impactful in the realm of diabetes treatment. Continuous glucose monitoring systems (CGMs), artificial intelligence systems, insulin pumps and supportive applications have been shown to enhance glycemic control, particularly during physical activity.

Keywords

Type 1 diabetes mellitus, physical activity, glucose, hypoglycemia, hyperglycemia, insulin, nutrition, technology, challenges

1. Introduction

Type 1 diabetes mellitus (T1DM) is one of the most prevalent endocrine diseases on a global scale and the prevalence of T1DM is rising, especially in younger populations (1). While an estimated 8.4 million people worldwide were living with type 1 diabetes in 2021, it is predicted that this figure will rise to between 13.5 and 17.4 million by 2040 (2), thereby increasing the importance of understanding and treating the disease. T1DM is characterized by the autoimmune destruction of the endocrine ß-cells of the pancreas (3). The resulting deficiency in insulin production and the consequent hyperglycemia can lead to microvascular damage, including retinopathy, neuropathy and nephropathy. In addition, macrovascular damage can result in the development of coronary heart disease and heart failure, as well as cerebrovascular events such as stroke. When treating T1DM patients, the main objective is to maintain optimal glucose control (4,5). Poorly monitored blood glucose levels and inadequate insulin therapy are known to increase the risk of developing those serious complications (3). Numerous studies have demonstrated that regular exercise can enhance both physical and mental well-being, thereby reducing the risk of various complications (6). Nevertheless, individuals diagnosed with MM face several challenges when it comes to implementing regular physical activity and are found to engage in less physical activity compared to healthy individuals (7). This review examines the physiological impact of exercise on patients with T1DM, the risk management of hypo- and hyperglycemia, and the possibilities and limitations of integrating modern technology. It will emphasize the importance of a precise and informed approach to exercise behavior in the management of T1DM, highlight the challenges faced by patients and the need for individualized education to facilitate a deeper understanding of personal glucose trends.

AIM: to provide an overview of studies published in recent years on the effect of physical activity on glycemic control in patients with type 1 diabetes. Special emphasis will be placed on approaches to improve glycemic control through dietary modification, insulin dose management and the use of modern technology.

2. Methods

This review was written following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) scoping review guidelines.

2.1 Information Sources and Searching Strategy

The search was performed systematically by the author of this review. The main database used was PubMed. The search was restricted to studies published between 2015 and 2025. The search terms, using the Boolean operator AND included: T1DM AND Exercise AND Glucose control, T1DM AND Exercise AND Technology T1DM AND sensor AND activity and T1DM AND Anaerobic AND Aerobic.

2.2 Inclusion criteria

- All publications that were published between 2015 and 2025 that were including the keywords and evaluated at least one main point of interest: T1DM, exercise, technology, glucose control
- All types of studies were included: meta-analyses, systematic and narrative reviews, case reports, prospective and retrospective studies as well as cohort studies

2.3 Exclusion criteria

- Literature published before 2015
- Sources only referring to Type 2 diabetes Mellitus (T2DM) or not strictly differentiating from T1DM
- Data associated with the COVID-19 pandemic
- Data associated with pancreatic implantation

2.4 Study selection and characteristics of the final included studies

All search records were downloaded from the database until the 9th of April 2025. A total of 372 records from PubMed were identified. All records were uploaded to Zotero, an open-source reference management tool used to store, manage and cite bibliographic references such as books and articles. From the initial search, 56 duplicates were removed, leaving 316 articles. All the titles and abstracts were reviewed according to inclusion and exclusion criteria. Following the initial screening, 155 sources were excluded due to their irrelevance to the subject matter, 15 - because they focused on T2DM or did not differentiate between T2DM and T1DM, 11 - due to their relation to the COVID19 pandemic, 14 - because they were published before 2015 and 3 - due to their relation to pancreas transplants. Consequently, the complete text of 124 articles was assessed for eligibility. 32 of these were then excluded after reading through the full text due to their irrelevant results. Consequently, the final review incorporated a total of 92 sources. Figure 1 shows the PRISMA flow diagram for the screening process.

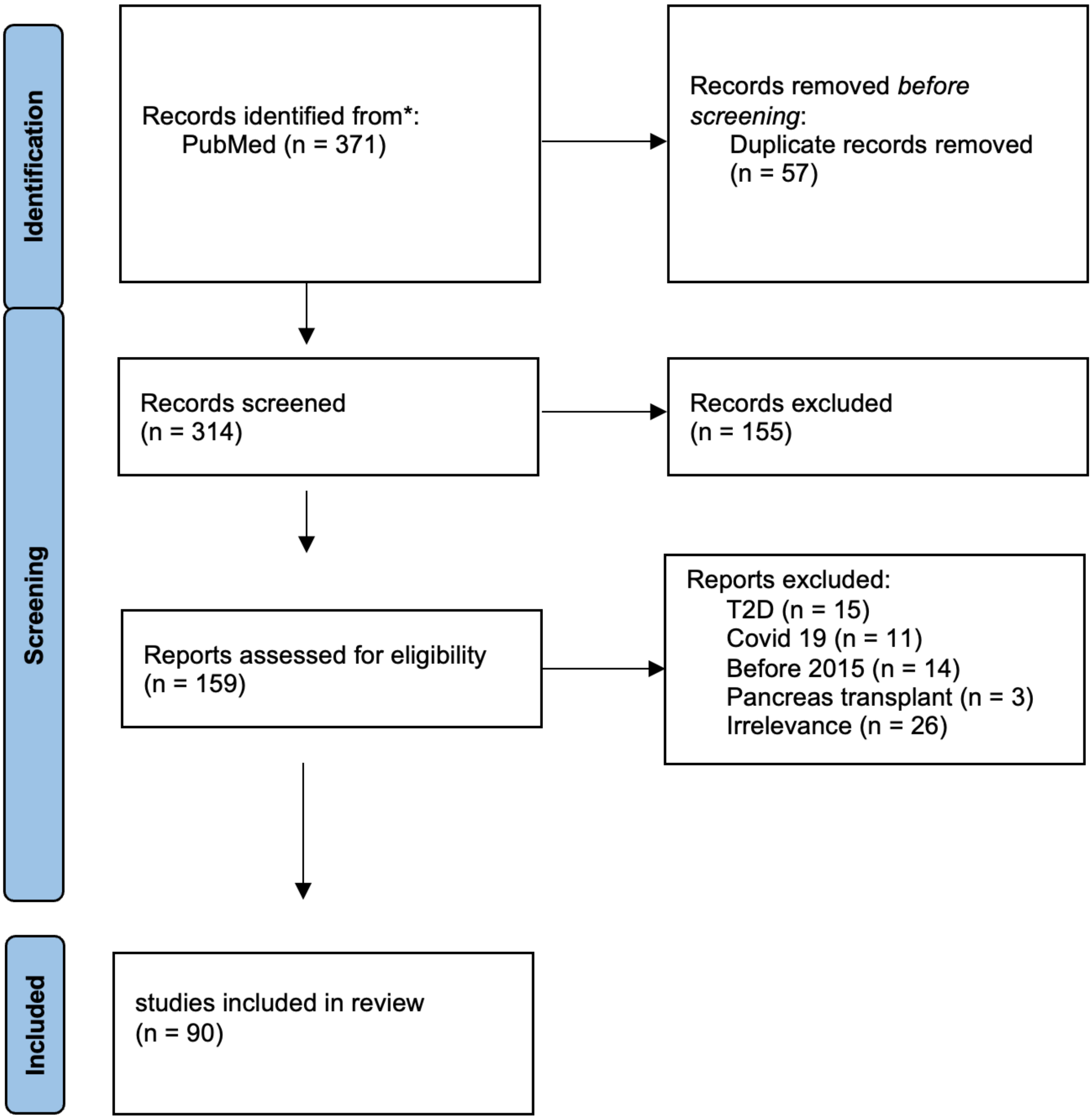

Figure 1: PRISMA flow diagram for the screening process.

2.5 Software used to aid the review

AI and other software were used to facilitate the review process. Zotero was chosen for reference management, Grammarly Premium for plagiarism check and both Grammarly Premium and DeepL were used as writing assistance.

3. Research Results and Discussion

3.1 Glycemic response to Regular Exercise in Patients with T1DM

3.1.1 Changes in blood glucose levels

In recent years, the positive effects of different types of training on physical and mental health have been the focus of intensive study for both people living with T1DM and healthy people. For individuals with diabetes, the emphasis has been particularly placed on the regulation of blood glucose levels. Numerous positive effects on the glucose balance during and after exercise in patients with type 1 diabetes have been demonstrated (8).

Riddell et al. (9) conducted a study to examine the 24-hour effect of exercise on glycemic control. Over a period of four weeks, patients with T1DM participated in various training programs, and a comparison was made between their blood glucose values on training days and those on days when no training was undertaken. The mean glucose levels on days of exercise were 8.66 ± 2.50 mmol/l (156 ± 45 mg/dl), compared to 9.21 ± 2.72 mmol/l (166 ± 49 mg/dl) on sedentary days. The time spent in the target range 3.89–7.77 mmol/l (70-140 mg/dl) was 6% higher on exercise days, Time below range (TBR) was 2,9% higher and Time above range (TAR) was 14% lower. Figure 2 from this study provides an overview of the blood glucose values comparing exercise days and sedentary days.

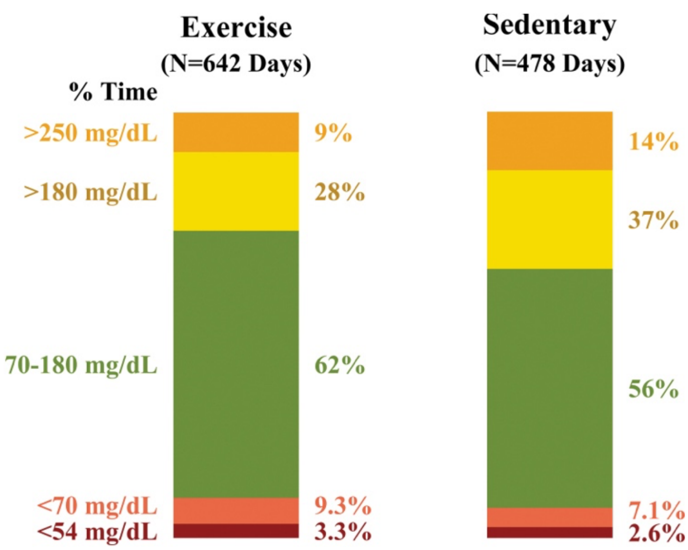

Figure 2: Stacked bar plot of average % time <54, <70, 70 to 180, >180, and >250 mg/dl on exercise versus sedentary days. Percent time <54 mg/dl is a subset of % time <70 mg/dl, while % time >250 mg/dl is a subset of % time >180 mg/dl. Due to skewed distribution, % time <70, <54, >180, and >250 mg/dl values were each censored at the 5th and 95th percentile (9).

These observations have been reported in other studies and meta-analyses as well (10,11).

3.1.2 Changes in HbA1c

Conversely, the findings concerning the impact of regular exercise on HbA1c are not consistent (12).

A meta-analysis performed by Chang et al (13) included 9 studies to analyze the effect of physical activity/exercise on cardiorespiratory fitness in children and adolescents with T1DM. Eight of the nine studies have analyzed the effect of exercise on HbA1c and only five of them showed a significant decrease in HbA1c after a long training period. The other studies reported no significant differences.

King et al (14) investigated the effects of physical activity in childhood and adolescence on HbA1s levels. They found that children who were active for 60 minutes on at least 3 days a week had significantly lower HbA1c levels compared to those who exercised for less than 3 days. An overview of the results of the study is shown in Figure 3. Bohn et al (15) also observed an inverse association between physical activity and HbA1c.

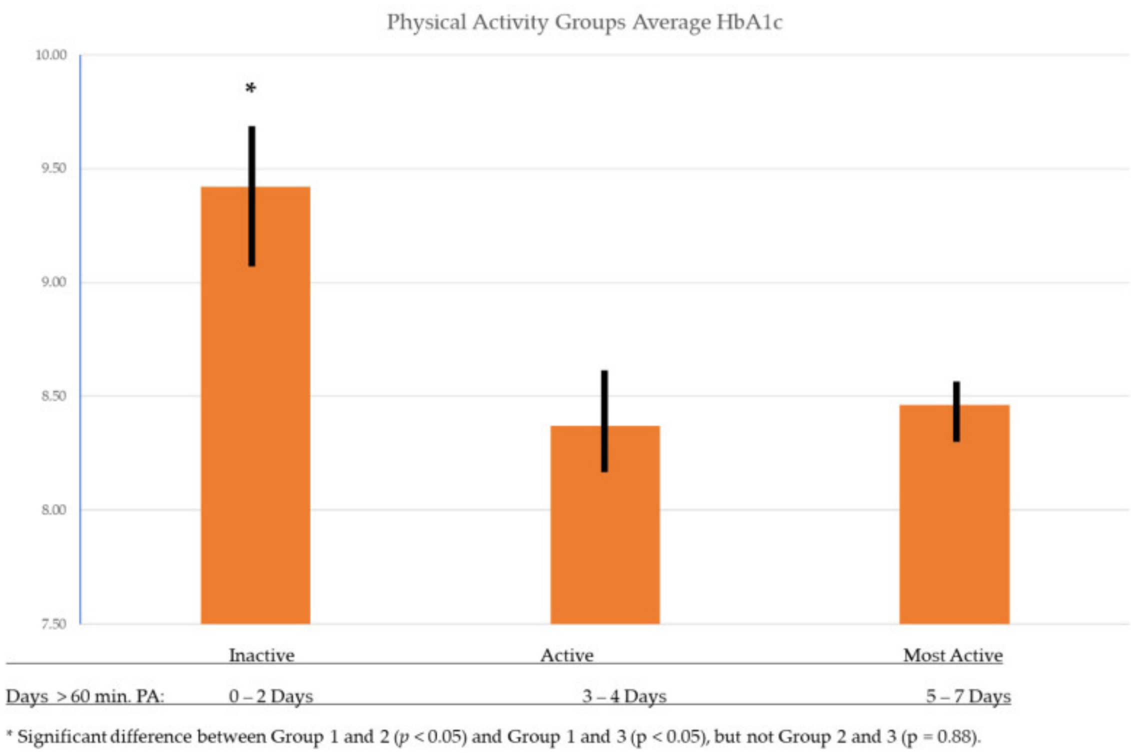

Figure 3: Differences in HbA1c Across Physical Activity Groups (14)

3.1.3 Other benefits

In addition to the positive effects on the glucose balance, other studies have described further health-promoting effects such as improvements in levels of triglycerides, cholesterol, LDL cholesterol and HDL cholesterol (13). Furthermore, it has been demonstrated that patients who engage in regular physical activity exhibit enhancements in cardiovascular and cardiorespiratory fitness, increased muscle mass, and improved endothelial function (15,16). Subsequent studies examined the impact of consistent training on mental health. The results of these studies indicated that regular training had a positive effect on sleep quality, motivation, pain, emotional well-being and quality of life (17).

As the type of training has been shown to have a significant impact on metabolic effects in several studies, a discussion of the different types of training is included below.

3.2 Exercise types

3.2.1 Aerobic training

Aerobic training refers to sports in which energy is mainly generated by burning energy sources such as carbohydrates or lipids while consuming oxygen. Examples of aerobic training include running, cycling and swimming. It should be done with light or moderate intensity over a long time (>20-30 minutes). According to the American Heart Association (AHA), aerobic exercises should be carried out at an intensity where only 70-85% of the maximum heart rate is used.

The benefits of aerobic exercise are numerous and include improved cardiovascular fitness, increased myocardial oxygen capacity, reduced cardiovascular disease and lower arterial blood pressure (18). The World Health Organization (WHO) and AHA have set a recommendation of 150 minutes of aerobic exercise per week (19).

A meta-analysis performed by Garcia-Hermoso et al (20) showed that regular aerobic exercise has a moderate positive effect resulting in a greater TIR, reduction in HbA1c as well as improvement of cardiorespiratory fitness in children and adolescents with T1DM.

Other studies have shown a positive effect on HDL and LDL levels, as well as a reduction in arterial blood pressure and improved insulin sensitivity (21) .

3.2.2 Anaerobic training

Anaerobic training, in contrast to aerobic training, does not rely on the use of oxygen for energy production. During high-intensity resistance training, the oxygen dissolved in the blood and available for energy production is often insufficient to meet the energy demands of the muscles. In the long term, anaerobic metabolism cannot provide as much energy as aerobic metabolism, but energy reserves can be released much more quickly. Anaerobic metabolism is primarily utilized at heart rates that exceed 85% of the maximum heart rate. Examples of anaerobic training include sprinting, strength training, and high-performance sports. Specifically, resistance training and high-intensity interval training as types of anaerobic exercise have been studied in recent years for their effects on patients with type 1 diabetes.

3.2.2.1 Resistance training

During resistance training, specific muscle groups are purposefully tensed and engaged in exercise. The utilization of tools such as weights, bands, or body weight can increase the intensity of the workout. Examples of resistance training include weightlifting, push-ups, squats, and pull-ups.

The benefits of this type of training include increased muscle strength, improved bone density, and, as a result, a reduced risk of injury (18). As people with T1DM are more susceptible to sarcopenia and loss of muscle mass, this form of exercise has a special role as it can be used for muscle mass building and maintenance (22,23). In addition, patients with type 1 diabetes are more susceptible to bone mineral density loss and developing osteoporosis due to more frequent hyperglycemic episodes than healthy individuals (24).

In addition to improvements in bone density and muscle mass, other effects such as improved lipid balance, improved vascular function, improved insulin sensitivity (25) and decrease in inflammatory markers (26) have also been demonstrated. Therefore, resistance training can help in the management of obesity, improve daily functionality, contribute to injury prevention, and help prevent cardiovascular disease (27).

3.2.2.2 High Intensity Interval Training

High-intensity interval training (HIIT) is a training method that involves alternating units of high-intensity and maximum strength with brief recovery periods. HIIT can be performed in a variety of ways. There are different recommendations regarding the number of sets, the duration of each set, and the number of intervals between sets. The effort phases of HIIT typically last from 10 seconds to several minutes, while the recovery phases mostly last for 30 up to 60 seconds. The exercises to be performed during the effort phase can vary, but it is essential that they are executed with maximal intensity. Activities such as light running or passive rest are recommended during recovery phase (28). The popularity of HIIT training has grown in recent years due to its demonstrated superiority in enhancing health and metabolic outcomes in a shorter timeframe when compared to traditional endurance or strength training modalities (29). In a systemic review on the effects of HIIT interventions on cardiorespiratory fitness and glycemic parameters in adults with type 1 diabetes, Lazic et al. (10) summarized the results of 10 studies. The findings indicated that regular HIIT resulted in enhancements in cardiorespiratory fitness and a substantial reduction in 24-hour average glucose values. However, no reduction in HbA1c or fasting glucose levels was observed. Furthermore, the study revealed that the efficacy of HIIT in enhancing fitness and regulating glycemic parameters remained consistent across various parameters, including the duration of training, the duration of exercise, the peak intensity, and the time spent at the maximum intensity level. Other reported positive effects of HIIT training include improved VO2 max and cardiorespiratory health (30).

3.2.3 Advantages and disadvantages of each type

Of course, personal preferences play the most important role in the choice of training, but recent studies show a tendency towards better tolerability of interval training among patients with T1DM.

During aerobic exercise, energy production primarily relies on aerobic glycolysis within skeletal muscle, leading to a substantial increase in glucose demand. In individuals without T1DM, this elevated demand triggers a coordinated physiological response, including enhanced insulin sensitivity, upregulation of glucose transporter type 4 (GLUT4) translocation to the muscle cell membrane, and increased hepatic glucose output. These mechanisms collectively support efficient glucose uptake and utilization while simultaneously reducing the requirement for circulating insulin. To further safeguard against hypoglycemia, counter-regulatory hormones such as glucagon, epinephrine, cortisol, and growth hormone are mobilized to stimulate hepatic gluconeogenesis and glycogenolysis, ensuring adequate blood glucose levels during and after exercise.

Those mechanisms do not work quite as well individuals with T1DM, due to their dependence on exogenous insulin. The externally administered insulin- both basal and bolus- cannot be downregulated in real time, leading to persistently elevated circulating insulin levels during exercise. This condition suppresses hepatic glucose production and promotes excessive glucose uptake by muscle cells, markedly increasing the risk of hypoglycemia. Additionally, the impaired counter-regulatory hormone response in people with T1DM further compromises their ability to maintain euglycemia during prolonged or intense aerobic activity (31,32) Figure 4 from: Exercise-induced hypoglycaemia in type 1 diabetes. Experimental Physiology (Exercise-induced hypoglycaemia in type 1 diabetes. Experimental Physiology), provides a good overview on the physiological changes in healthy people and people with T1DM.

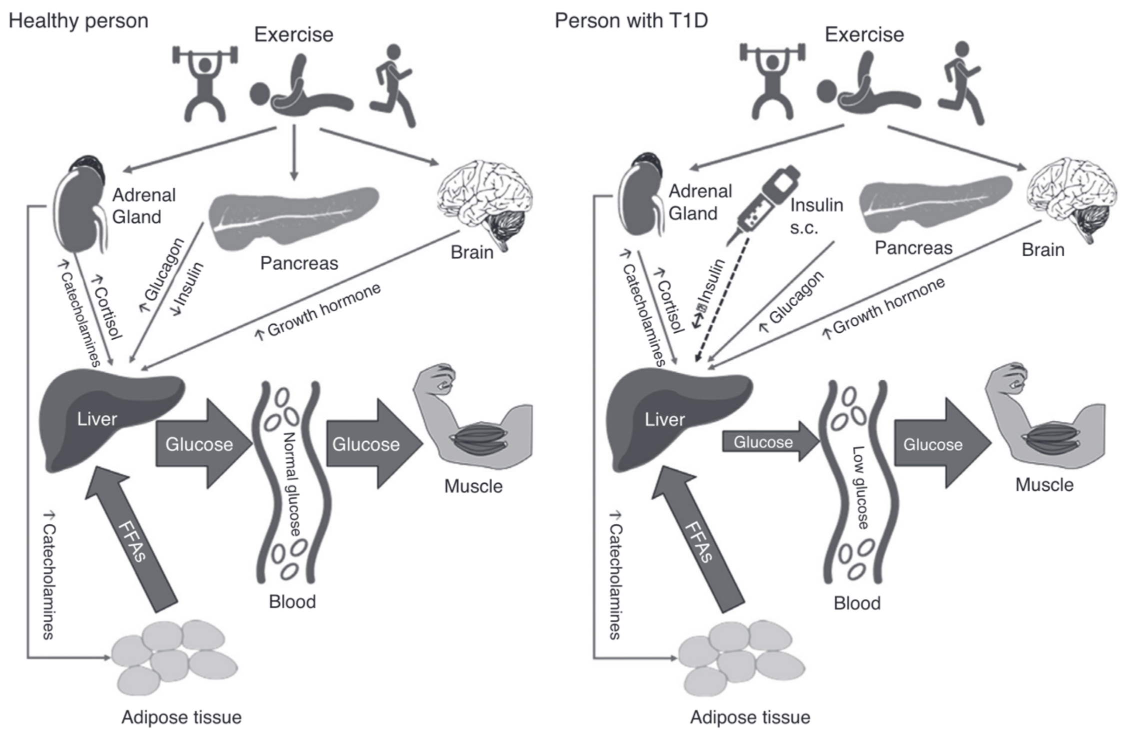

Figure 4: Physiological changes during exercise in healthy people and people with T1DM (33)

Conversely, HIIT stimulates catecholamine secretion (34), which in turn inhibits insulin-mediated glucose uptake and promotes glucose production through gluconeogenesis. Consequently, this results in anaerobic glycolysis, elevated blood lactate levels, and a greater reliance on glucose without oxygen. These mechanisms help regulate blood sugar more effectively in individuals with T1DM, reducing the risk of hypoglycemia compared to moderate-intensity aerobic exercise (32).

The impact of distinct training modalities on glucose balance has been evidenced in numerous studies (35–37). Da Prato et al (38) investigated the plasma glucose levels of type 1 diabetics during continuous exercise in comparison to interval exercise. The study's findings revealed that plasma glucose levels remained comparable between the two groups during the exercise periods. However, post-exercise plasma glucose levels were found to be significantly lower in the Continuous exercise group compared to the Interval exercise group (−2.51 ± 2.36 mmol/l or −45.3 ± 42.5 mg/dl vs −1.38 ± 2.2 mmol/l or −24.9 ± 39.7 mg/dl).

A study performed by Martin San Augustin et al (39) compared the effects of two exercise protocols- elastic band high-intensity interval exercise (EB-HIIE) and continuous exercise (CONT)- on blood glucose levels in 39 men with T1DM. Each participant completed both sessions in a randomized order, separated by at least 72 hours. CONT led to significantly lower blood glucose levels than EB-HIIE, with notable differences during exercise (-1.95 mmol/l or -35.1 mg/dl), at the end (-2.75 mmol/l or -49.5 mg/dl), and at 10- and 20-minutes post-exercise (-2.85 mmol/l or -51.2 mg/dl and –2.55mmol/l or -45.9 mg/dl). EB-HIIE resulted in more stable glucose levels during and after exercise, with a TIR of 68.6% and minimal level 1 hypoglycemia (<1%). In contrast, CONT had a greater glucose-lowering effect, with a TIR of 62.8% and a 16.9% incidence of level 1 hypoglycemia. Figure 5 from this study was included in this review to visualize the results.

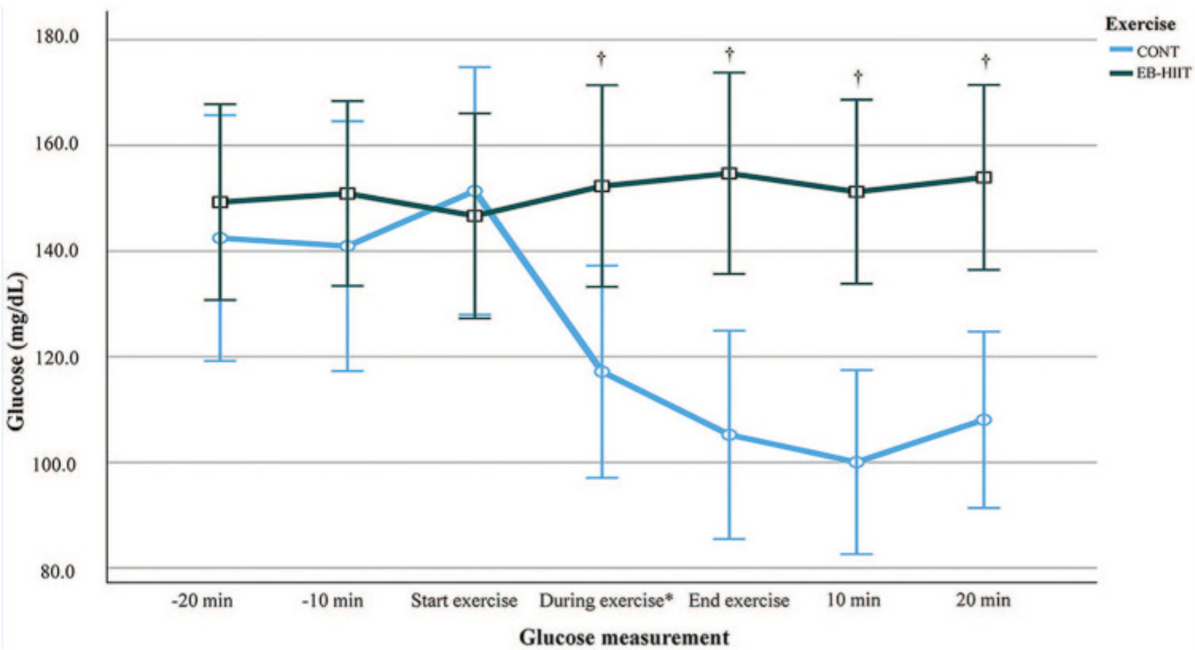

*Figure 5: Glucose measurements during and immediately after exercise by CONT and EB-HIIT sessions. *Measured at 4 minutes of EB-HIIT (i.e., at the end of the first series) and at 20 minutes of CONT. †Significant differences (P < .05) between CONT and EB-HIIT. CONT, continuous moderate intensity aerobic exercise; EB-HIIT, elastic band high intensity interval training(39)*

These findings support the conclusion that HIIT is an effective strategy for reducing (nocturnal) hypoglycemia. This phenomenon may also have influenced the quality of sleep in patients with T1DM (17).

The results of other studies demonstrated that high-intensity interval training (HIIT) exhibited a more favorable effect in reducing hemoglobin A1c (HbA1c) levels, enhancing cardiovascular fitness, and decreasing the daily dose of insulin required under HIIT (20).

Another study investigated the effect of HIIT versus moderate intensity continuous training on endothelial function, oxidative stress, and fitness in patients with T1DM. While no significant differences were observed between the groups in terms of glycemic control, patients in the HIIT group demonstrated significantly improved endothelial function and higher levels of fitness compared to those in the moderate intensity continuous training group at the conclusion of the 8-week study period (16).

In a position statement by the Association for the Study of Diabetes and the International Society for Pediatric and Adolescent Diabetes (40), the following figure 6 can be found summarizing their findings on glucose response and recommendations for different types of exercises.

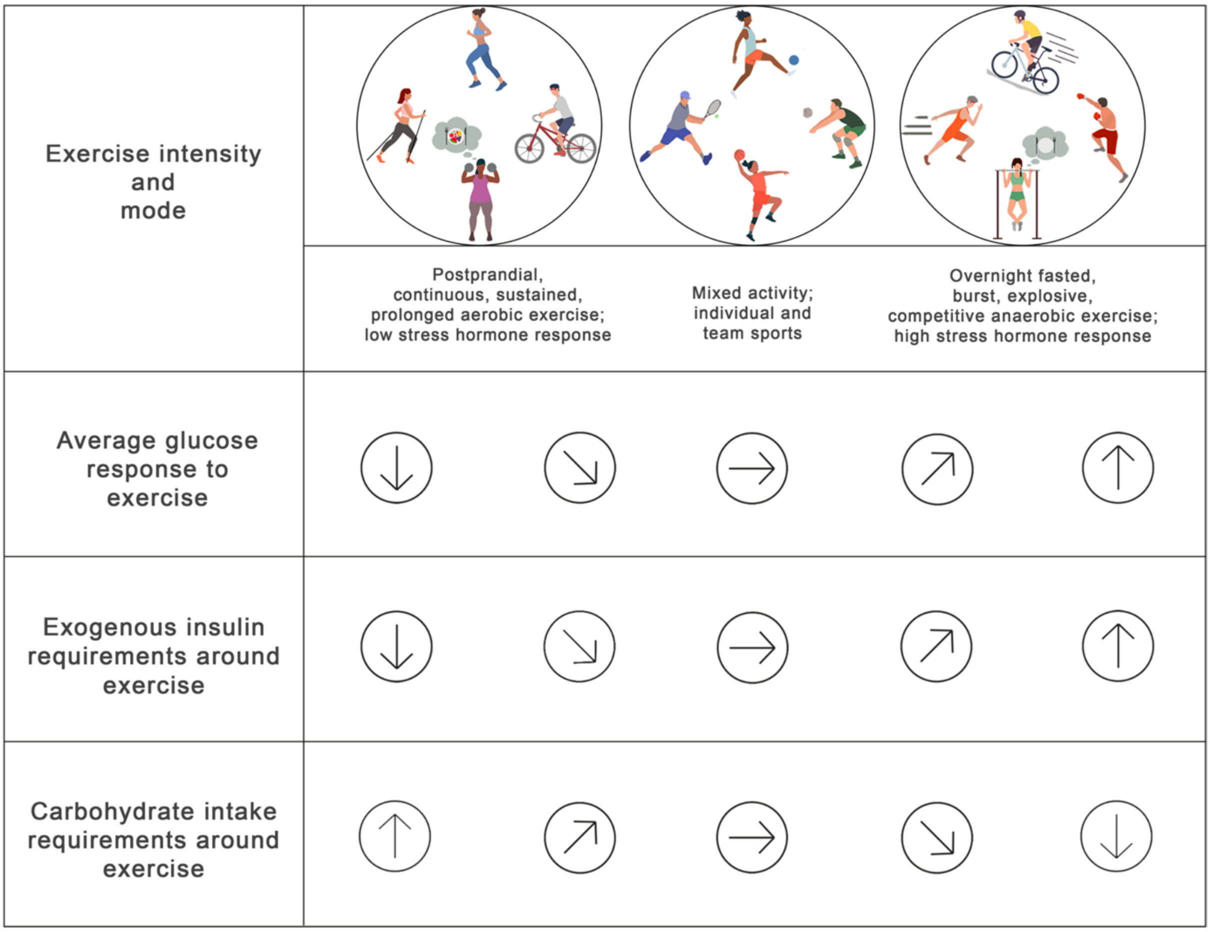

Figure 6: Graphical Summary from Moser et al., The use of automated insulin delivery around physical activity and exercise in type 1 diabetes: a position statement of the European Association for the Study of Diabetes (EASD) and the International Society for Pediatric and Adolescent Diabetes (ISPAD) (40)

A summary of studies analyzing glycemic response to exercise is presented in the Supplementary Table 1.

Despite these findings, interval training does not appear to have been incorporated into the recommendations of the American Diabetes Association (ADA).

3.2.3 Recommendations of the American Diabetes Association

The following is a summary of the ADA's recommendations for physical activity in people with type 1 diabetes (41). Prolonged seated activities should be interspersed with at least one 30-minute interval for brief physical activity breaks.

For adolescents with T1DM, the recommendation is to engage in a minimum of 60 minutes of moderate-to-vigorous intensity physical activity, three days per week. This activity should be focused on enhancing muscle and bone strength and should be at least moderate or vigorous in nature.

For adults with T1DM, the recommended weekly volume of aerobic exercise is 150 minutes of moderate or vigorous intensity. This activity should be distributed across at least three days, with no more than two consecutive rest days. Alternatively, 75 minutes of interval training is sufficient for healthy and fit young adults. 2-3 sessions of resistance training per week on non-consecutive days are also recommended.

For patients who are older or more fragile, it is recommended that they engage in flexibility and balance training two to three times per week. Integrating yoga and Tai Chi into the training regimen is also beneficial.

3.3 Challenges T1DM patients are facing

As demonstrated in the earlier chapter, regular physical activity has a positive effect on glycemic control, fitness and health in people with T1DM. However, studies have repeatedly demonstrated that teenagers with T1DM move significantly less and sit more than their peers without diabetes (7). No difference could be found between overweight and normal-weight type 1 diabetics, both failing to meet the recommendations (42). Such lack of exercise leads to increased HbA1c and an increased incidence of comorbidities (14,43). As many adolescents with T1DM do not meet the recommendations for daily exercise, their increased sitting time correlates with poorer glycemic status. That does not only lead to a decreased physical well-being but has also a significant impact on their psychological health (44). Inactive adolescents report more symptoms of anxiety, stress, and depression (43).

The following discussion outlines the potentially underlying factors that may have contributed to these observations and potentially explain the noticed behavior.

3.3.1 Fear of Hypoglycemia and Hypoglycemia

One of the possible reasons could be the fear of hypoglycemia (FoH). It is often the leading psychological barrier that limits regular physical activity among people with type 1 diabetes (45). Exercise-related hypoglycemia is one of the most common complications in T1DM patient physical activity and often occurs even in well-controlled patients (33). It was mentioned that aerobic exercise can increase glucose uptake in working muscles up to fivefold and additionally increase insulin sensitivity, which potentially causes hypoglycemia both during and after exercise (5,46).

In the T1DEXIP study (47), 251 adolescents were observed over 10 days under real world conditions. Patients with lower HbA1c values showed lower glucose values after exercise. The further the glucose levels fell during exercise, the lower they were post-exercise. This effect was observed for 12 to 16 hours after the end of exercise until the glucose levels slowly increased again. Another study shows similar results (48). Lower baseline glucose values represent a risk for hypoglycemia after exercise (49). Therefore, in the case of severe hypoglycemia, exercise should not be started in the last 24 hours in order to avoid subsequent hypoglycemia (33).

On the other hand, the occurrence of nocturnal hypoglycemia after an exercise day is described in various studies as higher than on sedentary days: 14% on exercise days vs 12% on sedentary days (47), 20% on exercise days vs. 12% on sedentary days (50). McCarthy et al (49) observed only 6% of time spend in hypoglycemia after 9 consecutive days of cycling. In addition, the occurrence of nocturnal hypoglycemia is associated with an increased risk of hypoglycemia on the following day (49).

Next to that, there were greater glycemic variations observed overnight after an exercise day compared to sedentary days. Type 1 diabetics are therefore more vulnerable to hypoglycemia and changes in glucose levels, which requires increased monitoring of glucose levels after exercise (51).

The length of exercise also appears to have an important influence, as hypoglycemic episodes were observed more frequently when exercise was performed for more than 60 minutes or longer than individual sessions (47).

McCarthy et al (52) investigated further metabolic changes in 13 type 1 diabetics who completed 45 minutes of exercise. Metabolic data of patients who had hypoglycemia after exercise were compared with those of patients in euglycemia. It was found that hypoglycemia also triggers other stress mechanisms that could mask possible hypoglycemia symptoms.

The anxiety to experience hypoglycemic symptoms generates a permanent mental load that makes it challenging to integrate spontaneous or regular exercise into everyday life. In a study of Vlcek et al. (53), using semi-structured interviews, all 15 adult participants described FoH as a constant mental load during exercise planning, influencing spontaneity and willingness to be active. Because people avoid physical activity, therapy decisions are often shaped by safety considerations, such as excessive insulin protection or the deliberate avoidance of exercise (43,54,55).

3.3.2 Hyperglycemia

In addition to hypoglycemic states, hyperglycemic episodes can also be observed on repeated occasions (31,56). To meet glucose needs during exercise, counterregulatory hormones such as the catecholamines adrenaline and noradrenaline and glucagon are released. These hormones lead to increased glucose production in the liver through gluconeogenesis and glycogenolysis. This effect occurs especially during intense and prolonged exercise (57). Normally, the increased release of insulin during exercise would lead to increased glucose uptake in muscle cells. However, in type 1 diabetics, insulin secretion and sensitivity are reduced, which can lead to hyperglycemia (58).

This effect may be intensified if exercise is performed in the fasting state or if high carbohydrate or low insulin are consumed prior to exercise to avoid hypoglycemia (59).

In contrast to the existing body of literature addressing hypoglycemia during physical activity, there is a lack of studies addressing hyperglycemia during exercise sessions, and therefore few recommendations for the prevention and management of hyperglycemia (60).

However, it has been shown that short-term hyperglycemic episodes have fewer effects on health than hypoglycemia. In a meta-analysis conducted by McGuire et al.(59), the effect of hyperglycemia on sports performance was investigated. The analysis encompassed a total of seven studies, which collectively included 119 patients. The findings of this meta-analysis indicated that mild to moderate hyperglycemia during exercise can be considered safe, which was confirmed by another study as well (61). Furthermore, the analysis revealed that blood glucose levels ranging from 7.1 to 13.9 mmol/l (128–250 mg/dl) exhibited no significant impact on performance outcomes.

3.3.3 Other challenges

A qualitative study published in 2023 utilized structured interviews to inquire about the exercise routines of patients with type 1 diabetes (53). This study offers insights into the various challenges patients are facing.

Many participants emphasized the additional time required to prepare for training. It is always necessary to ensure that the blood glucose level is sufficiently high to avoid hypoglycemia, and that sufficient insulin or carbohydrates are available to counteract blood sugar fluctuations. The study noted that spontaneous activities were either not feasible or required significant effort.

The need to develop individual solutions was also identified, as existing guidelines do not meet the patients' requirements. However, these solutions were only effective for a limited time and required constant modifications.

Following the release of continuous glucose monitors, the implementation of regular training became more feasible for many individuals. However, this transition was concomitant with increased financial expenditures and concerns regarding theft. Furthermore, not all devices and pumps can be discreetly worn under light sportswear, which can be embarrassing for many diabetics.

Even in high-performance sport, athletes are repeatedly confronted with the challenges of type 1 diabetes (55).

However, the psychological stress and the fear of (nocturnal) hypoglycemic episodes, which prevent many patients from exercising on a regular basis, should be emphasized again (62).

The following sections provide a summary of recommendations from the literature to counteract these hypoglycemic episodes.

3.4 Recommendations for T1 diabetics to avoid hypo-/hyperglycemia

3.4.1 Nutrition and carbohydrate intake

In order to reduce the risk of hypoglycemia and hyperglycemia, it is important to consider carbohydrate intake before and after exercise. The type, length and intensity of training should be taken into account. For exercise of greater intensity and duration, elevated glucose intake is necessary for energy production. The prevailing glucose levels and the most recent insulin administration must also be considered, as circulating insulin causes greater amounts of glucose to be absorbed by the muscles, which can increase the risk of hypoglycemia (63).

A comprehensive literature review was conducted by Moser et al. (64) to determine the optimal glucose levels at which carbohydrate intake should be initiated, depending on pre-exercise glucose levels and the type of exercise: <7.0 mmol/l (<126 mg/dl) for adults with type 1 diabetes, intensively exercising and/or with low risk of hypoglycemia; <8.0 mmol/l (<145 mg/dl) for adults with type 1 diabetes, moderately exercising and/or with moderate risk of hypoglycemia, or for older adults with coexisting chronic illnesses and intact cognitive and functional status; <9.0 mmol/l (<161 mg/dl) for adults with type 1 diabetes, minimally exercising and/or with high risk of hypoglycemia.

The most common recommendation is to consume carbohydrates to provide extra energy. Carbohydrate-rich foods can raise blood glucose levels at different rates after ingestion. Glucose, for instance, has been demonstrated to be utilized more efficiently and rapidly than fructose and lactose, and is therefore most likely to be recommended during acute hypoglycemic episodes (56). The glycemic index (GI) is a measure of how quickly and strongly a carbohydrate-containing food causes blood sugar levels to rise, with glucose set as a reference value of 100. Carbohydrates with a GI <100 result in a more gradual increase in blood glucose levels, while those with a GI >100 led to a rapid rise. As previously mentioned, carbohydrates with a high GI are suitable in acute hypoglycemic phases, while carbohydrates with a low GI are more suitable during prolonged training or after training to avoid post-exercise hyperglycemia(65).

In 2022, the Brazilian Diabetes Society issued a recommendation on carbohydrate intake depending on the baseline blood glucose value. Figure 7, which contains these recommendations from this work (67), is shown below.

Glycemia (mg/dL)	Recommendation
< 90	Intake 15-30g of carbohydrate before exercise, especially when performing longer exercises (>30-45min).
90 - 150	Consume carbohydrate from the beginning of exercise (0.5-1.0g/kg/hour). Depending on the type of exercise and the amount of circulating insulin.
151 - 250	Start exercising and delay carbohydrate intake until blood glucose levels are lower than 150 mg/dL.
251 - 350	Test for ketones if available, and do not exercise if moderate to large amounts are present. Mild to moderate intensity exercise may be performed.
> 350	Test for ketones, if available, and do not exercise if moderate to large amounts are present. If ketones are negative (or only trace levels), consider correcting blood glucose levels with lower doses of insulin (50% of the dose). Avoid exercise until blood glucose levels are lowered.

Figure 7: Conduct recommendation based on pre-exercise glucose levels on T1DM (67)

In a study by Patton et al. (68) on 208 adolescents with type 1 diabetes (mean age 14 years, mean HbA1c 7.1%), glycemic variability in the three hours following meals was measured using standard deviation (SD) and coefficient of variation (CV). The findings of this study indicated that carbohydrate-rich meals were associated with increased postprandial variability, while fat- and protein-rich meals, after adjustment for carbohydrate content, were associated with reduced variability (particularly for fat, both standard deviation [SD] and coefficient of variation [CV], and for protein, only SD).

According to different studies (67), it is generally recommended to check blood glucose levels more frequently before, during, and after training. This practice allows for the detection of trends at an early stage and facilitates timely reactions. This is of particular importance given that insulin sensitivity can remain elevated for up to 48 hours following exercise (31,69).

The replenishment of depleted glycogen stores after training is similarly relevant (56). It has been shown that consuming larger amounts of carbohydrates after exercise can be beneficial but is dependent on insulin availability (70). Foods with a high glycemic index, such as bananas, are particularly suitable for replenishing glycogen stores directly after training (64). To avoid nocturnal hypoglycemia, it is also advisable to eat a snack consisting of protein, fat and carbohydrates before going to bed.

In the Position of Brazilian Diabetes Society on exercise recommendations (49), a recommendation for carbohydrate intake based on post-exercise sensor glucose measurements can be found as well.

A summary of studies analyzing *the recommendations on carbohydrate intake and nutrition during physical exercise* is presented in Supplementary Table 2.

3.4.2 Insulin dose adjustment

As with carbohydrate intake, recommendations for insulin dose adjustments vary depending on several factors. These include the spontaneous or planned nature of the training, the type, duration, and intensity of the exercise, and the device used for glucose measurements. Elevated insulin levels during physical activity led to increased glucose uptake by muscle cells, resulting in hypoglycemia. It is therefore recommended that the basal insulin rate be reduced and/or the bolus insulin rate be adjusted prior to periods of prolonged exercise (71).

Romeres et al (61) investigated the impact of varying glucose and insulin levels on blood glucose levels during moderate endurance training. Participants with T1DM were divided into three groups: Normoglycemia + low insulin levels, Moderate increased glucose + low insulin levels, Moderate increased glucose + increased insulin levels. This study aimed to assess the body's response to the training, with a particular focus on its endogenous glucose production (EGP). The results indicated that hyperinsulinemia, hinders the natural release of glucose from the liver (EGP) during training, even when insulin levels are only moderately elevated. Moderately elevated glucose alone was unproblematic as long as insulin levels were low. Consequently, it can be concluded that the increased amount of insulin is a risk factor for hypoglycemia. It is, therefore, safer to exercise with slightly elevated blood sugar and low insulin than with normal blood sugar and high insulin levels.

McCarthy et al. (72) investigated how bolus insulin adjustments before activity can reduce post-exercise and night-time hypoglycemia. 16 participants with type 1 diabetes were divided into 2 groups. One group received a regular insulin dose (100%) and the other group a reduced insulin dose (50%) with insulin apart one hour before and one hour after 45 minutes of moderate exercise. Reducing the insulin dose by 50% before exercise reduced the risk of hypoglycemia during exercise, while a corresponding adjustment after exercise reduced the risk of nocturnal hypoglycemia. The combination of both strategies led to increased glucose levels after exercise and at night, but without severe hyperglycemia. These results suggest that targeted bolus insulin adjustments around physical activity may be a safe measure to prevent hypoglycemia.

A number of studies have also investigated the effects of bolus reduction of the meal for exercise (71,73,74). Depending on the study, the temporary bolus rate can be reduced by up to 80% (75).
It is important, however, that a meal should be taken before exercise and that there should be no long intervals >90 minutes between meal and exercise to avoid hypoglycemia (11). In the absence of a meal prior to exercise, a 50% to 80% reduction in basal insulin rate can be considered (65,76). However, this adjustment is recommended 90 minutes prior to training (64). Furthermore, in instances where individuals engage in prolonged training sessions or multiple training sessions over the course of a day, a reduction in basal insulin rate of 20 to 80% can be effective (67,77,78).

The type of training is a contributing factor in this regard as glucose levels can also rise during anaerobic training. For this reason, a reduction in insulin doses should only be undertaken with caution (65).

Moser et al (64) developed diabetes specific recommendations for each of the most relevant pumps and different exercise types. In figure 8 of “2022: Position of Brazilian Diabetes Society on exercise recommendations for people with type 1 and type 2 diabetes” (67), a recommendation is made how to reduce bolus insulin doses for meals administered 90 minutes before nutrition intake.

Recommendation to decrease insulin bolus on meals that precede exercise by up to 90 min for T1DM

Physical Exercise Intensity	30 min duration	60 min duration
Light Aerobic (~ 25% VO2 max)	− 25%	− 50%
Moderate Aerobic (~ 50% VO2 max)	− 50%	− 75%
Intense Aerobic (70–75% VO2 máx)	− 75%	NA
Intense Aerobic/Anaerobic (> 80% VO2 máx)	No reduction	NA

NA Not available

Source: Adapted of Colberg [5] and Yardley [15]

Figure 8: from 2022: Position of Brazilian Diabetes Society on exercise recommendations for people with type 1 and type 2 diabetes(67). The table provides information on insulin bolus reduction depending on duration and intensity of the physical training. (67)

A summary of stydies analyzing the recommendations for insulin dose adjustment during physical exercise is presented in Supplementary Table 3.

3.5 Technology used to improve diabetes patients' glucose control

Technological progress has become increasingly significant in recent years, especially with recent advances in the field of artificial intelligence. This modernization is also evident in the field of diabetology.

3.5.1 Continuous glucose monitoring CGM

CGM technologies are typically categorized into real-time CGM (rtCGM), intermittently scanned CGM (isCGM), and implantable systems. Nearly all CGM systems measure glucose levels in real-time and provide sensor glucose data, while isCGM systems measure at the time of scanning with the reading device. It is important to understand that interstitial glucose sensing has a physiological lag and damping compared to blood glucose (64). This difference must be considered as it influences sensor glucose measurement accuracy against blood glucose values. This observation is nicely illustrated in Figure 9 by Da Prato et al. (2022) (38). In their study, all participants with T1DM used pumps integrated with CGM systems during aerobic continuous and anaerobic interval exercises. The results revealed that during the continuous workout the CGM sensors significantly overestimated plasma glucose levels (with a Sensor Bias of 38.5 ± 27.1 mg/dl or 2.14 MMOL/L ± 1.51mmol/l)

and a MARD of 31.1%, indicating reduced accuracy.) Such discrepancy can mislead the pumps algorithms or the patient into under-correcting high glucose levels, increasing the risk of exercise-induced hyperglycemia. These results demonstrate how sensor inaccuracies during continuous exercise can unintentionally contribute to poor glycemic outcomes.

The most frequently described devices are the Dexcom G4, G5, G6 and G7 version, Medtronic Guardian 3 sensor, Medtronic Enlite / Enlite 2 and the Freestyle Navigator II .

In the study by Moser et al (2020) (64), most of the devices were tested using the mean absolute relative deviation (MARD) metric. The findings of this study indicated a trend towards increasing quality due to the higher measurement accuracy and lower MARD of the newer devices.

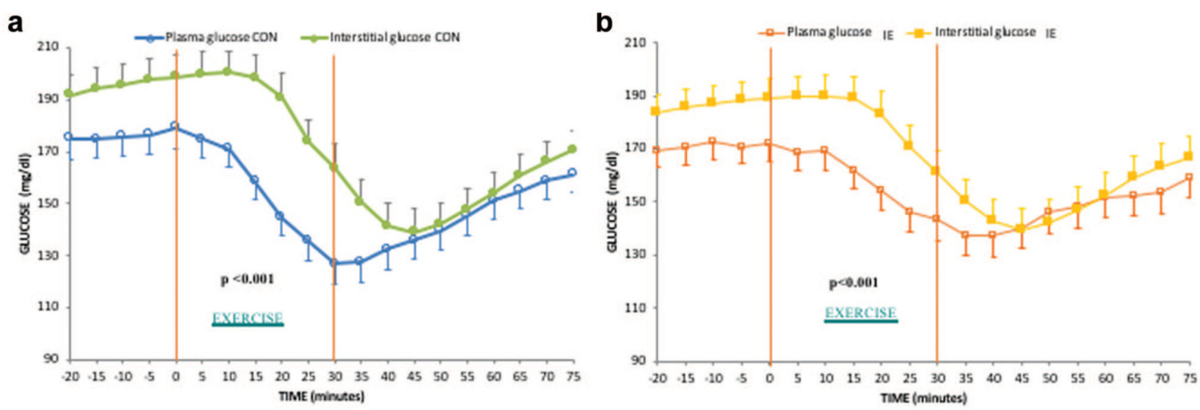

Figure 9. Plasma and interstitial glucose changes in the exercise sessions. During moderate continuous (CON) (a) and interval exercise (IE) (a) (38)

3.5.2 Automated Insulin Delivery (AID)

Automated insulin delivery systems (AIDs) are a significant advancement in the management of T1DM. These systems consist of three essential components: a continuous glucose monitor (CGM), an insulin pump, and a control algorithm. Combined, they form an integrated feedback loop and collaborate to autonomously calibrate insulin delivery in accordance with real-time glucose measurements, ensuring blood glucose levels remain within safe parameters with minimal user intervention. Bombaci et al. (79) state that “Automated insulin delivery (AID) systems are therapeutic tools that get closer to the idea of the artificial pancreas." More recently, systems such as the MiniMed 780G not only automatically deliver basal insulin but can also automatically deliver correction boluses and enable individual glucose targets. As indicated by the authors, this increased flexibility supports stricter glucose control while reducing the user's workload. AID systems assist users in maintaining stability, particularly in their active daily lives. However, meals and correction boluses still require user input, highlighting that while automation is advanced, it is not yet fully autonomous.

3.5.3 Loop Systems – Open vs. Closed

Understanding AID also requires distinguishing between different types of loop systems it may operate on. These include Open Loop Systems (OLS) and Closed Loop Systems (CLS). Using OLS the user maintains complete control over insulin delivery by receiving glucose data from the CGM and deciding manually on insulin dosing. The system does not automatically adjust insulin, what makes them less dynamic than hybrid or closed-loop approaches, particularly in physically active individuals (64).

In CLS insulin adjustments are executed autonomously based on CGM data. The evolution from OLS to CLS is what makes AID so promising, moving from manual decision-making to intelligent, adaptive insulin management. Closed-loop insulin therapy improves glycemic control in adolescents and young adults while reducing hypoglycemia during and after physical activities as the meta-analysis of Jabari shows (79,80).

3.5.4 Insulin pump systems

Insulin pumps are small portable devices that deliver a continuous subcutaneous insulin infusion (CSII) through a small catheter and allow for personalized basal and bolus insulin dosing.

The basal rate can be individually adjusted to the sleep schedule, meals and physical activity, while bolus doses can be administered in real time to correct hyperglycemia or cover carbohydrate intake. This constant infusion of insulin throughout the day is accompanied by one-time doses called boluses.

A lot of the newer pumps come with special features like a temporary basal rate, bolus calculators or extended bolus options that are supposed to help the patient increasing their TIR throughout the day. Some of them also come with specialized modes, for example the exercise mode of the t:slim X2 which increases their flexibility and is supposed to help reducing the risk of hypoglycemia during and after aerobic exercise (40)

These possibilities reduce the patients fear of hypoglycemia and support them into safer engagement to do sports with ultimately improves the patient's glucose stability. Unfortunately, if not timed well, such settings can also create challenges like the increased risk of hyperglycemia. The disadvantage of these devices is that they must be carried around by and attached to the patient, which can cause uncomfort, a concern about their body image or adverse skin reactions to infusion set adhesives. Furthermore, achieving long TIR demands active participation in the process by the patient. They must respond to system alerts, refill the insulin reservoir, charge the pumps battery monitor glucose consistently and manage technical issues like infusion set malfunctions (66).

Despite all those challenges, new pumps- especially those integrated in a hybrid closed loop system- will further help improving glycemic control through automatic meal bolus when integrated carefully into lifestyle and exercise routines (6).

The pump systems can be divided into the categories tubed or tubeless.
Some devices like the Tandem t: slim X2 or the MiniMed 780G function tubed as they have an external injection sight patched to them that is connected to their pump via tubing.
Other devices like the Omnipod DASH, Omnipod 5, Wellion Micro Pump or the Medisafe WITH attach their cannula right under the so called "patch pump" itself.
Due to their tubeless design no extra infusion set is necessary. This is not only great for the environment but also allows more freedom of movement during exercises. They were tested to have significant advantages over the tubed kind like significant reduced time of initiation which increases efficiencies and reduces workloads (81).
Such systems are not only a tubeless but also waterproof patch pump, praised for its discreet design which makes them even more convenient when showering, swimming, or during exercise or sex, as the risk of tangling, catching, or pulling the tube when moving is reduced (82).
They also help with other challenges some patients are facing, like insecurities regarding self-awareness about insulin delivery in public due to their discreetness (83).

3.5.5 Pump adjustments

To achieve a sufficient glycemic control and an accomplish a long TIR the patient must actively participate in the adjustment of the pump setting while exercising. Exercise type, duration, and timing affect sensor reliability and insulin strategy, which requires patient input and pre-planning to achieve a sufficient glycemic control. Such efforts can be very challenging for patients. For this reason, Moser et al. (40) have conducted a positions statement in which they have given recommendations for glucose management around physical activity and exercise with the currently most relevant pumps (iLet Bionic Pancreas system; mylife CamAPS FX system; DBLG1 system; Omnipod 5 system; MiniMed 780G system; t:slim X2 Control-IQ system). For each of them they illustrated how to exactly set the pumps mode designed for while exercising. Additionally, they show what settings to put for either planned or unplanned training.

3.5.6 Use of wearables and advanced algorithms for optimization of glycemic control

The use of wearables in T1DM care is becoming more interesting particularly as more variables that reflect metabolic states during exercise or stress become measurable by these portable non-invasive devices. Daskalaki (84) conducted an extensive review of noninvasive wearable sensor technologies and their application to T1DM management. They explained that variables like heart rate, respiratory rate, oxygen saturation, skin temperature, electrochemical skin conductance, and galvanic skin response can be used for further optimization of T1DM treatment. Additionally, body motion can be assessed with the use of an Accelerometer or Gyroscope. Most recent devices are even able to provide an ECG cardiac state, such as heart rate variability and QT interval. Even though we can still see some challenges in the use of wearables like due to motion artifacts, signal noise or complex glucose-physiology interactions, adding such additional markers to CMGs could help detecting and predicting glucose changes earlier.

Being able to predict physiological delays in the production of insulin after increasing blood glucose and in the effect of insulin on inhibition of blood glucose is key as Vosoughi et al. (85) show in their analytical study. Mathematical modeling of all the variables, modern wearables can detect nowadays, is necessary for the integration into current systems that are only detecting insulin-glucose dynamics.

A great example of how this could be achieved is the mvAID system developed by Askari et al. (86). It uses multivariable model artificial intelligence algorithms that incorporates inputs such as heart rate, energy expenditure, skin temperature, and electrodermal activity from a wrist-worn wearable. These should automatically detect physical activity and adapt the patient's insulin delivery accordingly. Their in-silico study had great results and significantly increase the safety and efficacy of insulin delivery in the presence of unannounced physical activities and meals.

3.5.7 Supportive applications

Besides hardware devices like sensors, pumps or wearables improving the diabetic patient's everyday life, also software like machine learning algorithms or apps might revolutionize the treatment approach as well.
For example, McGaugh et al. (87) developed an Exercise Advisor App, an app, based on the consensus guidelines that helps T1DM patients by managing their glucose levels peri-exercise. The patients needed to input their key data, like what kind of delivery was used and the glucose levels and the app was able to provide personalized guidance on insulin dosing, a post-exercise guidance, and a learned patterns log for reviewing previous workouts for them.
This app was one of the first of its kind and started out with a whole new approach to overcome challenges that patients with T1DM might experience. These are as we have discussed earlier already especially important for children and adolescents with T1DM as they are known to be less active, more sedentary, and therefore less fit than healthy people of the same age. As already discussed before research has revealed that children and adolescents living with T1DM do not typically meet the time of exercise recommended guidelines of physical activity (88).
It is therefore vital that barriers are overcome in the patients' early years to ensure long-term health. For this reason, for the following apps were encompassed in which the youth was focused to help them with their exercise regime.

In Diactive-1 study by Hormazábal-Aguayo et al., the effectiveness of the Diactive 1 application for a 24-week exercise intervention in children and adolescents with T1DM was evaluated. Participants were randomly assigned to either the app or the control group. The app group received a training program tailored to the participants, while the control group received standard care. The app provided individual resistance training plans with integrate educational support for insulin and carbohydrate management based on each participant's fitness level, glucose values and trend data. Integrated education tools provided guidance on when to train safely, while gamification elements such as promotions and rankings promoted consistent use. They tried to figure out if the use of the app is significantly reducing the daily insulin requirement per kilogram of body weight. Unfortunately, results are not published yet (89).

Another study by Shetty et al. describes a similar application called the acT1ve app, which was developed by a user-centered co-design in an 18-month process with more than 60 Adolescents and young adults with T1DM between the age of 13 and 25 and their parents to support the safety in young patients' physical activity. Focus groups were formed, design workshops held, and lots of feedback provided by the patient, their parents and physicians to ensure that the app addresses the real-world exercise challenges faced by young people with T1DM. The resulting app contains personalized training instructions based on user input such as activity type, glucose levels, insulin timing, and carbohydrate intake. A Key element of acT1ve is the Training Advisor algorithm, which generates individualized insulin and carbohydrate recommendations. A pilot experiment involving 10 participants, who had not attended any of the participatory design workshops, demonstrated a high level of satisfaction, user-friendliness, and confidence in secure training management with the app (90).

Such mHealth applications are a great example of the possibilities and the potential of optimization in diabetes treatment are for the future. They might not only help the patients providing a safe educated way of exercise.

Also, they show that communication between patients, their parents and their physicians and lead to great achievements.

Another good example how important communication is for T1DM patients is the study by Morrow et al. (88) in which 29 participants with T1DM used the Application Photovoice over 6 months to gain a better understanding of their and others experiences of technology and physical activity. The authors noted that overcoming barriers during the early years is critical for long-term health. Therefore, it is important to understand how such technology fits into young people's daily routine to design effective tools. So, they used Photovoice to explore how adolescents with T1DM and their parents experience the role of technology in engaging with physical activity and exercise. The participants were sharing photos and reflections in form of texts about experiences.

After analysis of the co-researchers using the 'PHOTO' mnemonic, these posts were categorized in benefits of technology, complexity and difficulty, emotional impact, reliance and risk.

In benefits the patients especially appreciated the passive features like AI controlled dose adjustments as well as the technology itself like CGM, insulin pumps that help them to be more free and less fearful during physical activity and exercise.

One difficulty was adolescents trying to be independent from their parents during such activities and the tension created due to the gatekeeping effect of them by acting protective and reminding to check for their glucose level.
Also, in the section of emotional impact, despite technological assistance, parents were observed with significant emotional distress, as they were concerned regarding hypoglycemia or technical malfunctions. Such malfunctions were finally pointed out together with deliberate alarms in reliance and risk again. These were leading to ignoring or even silencing their alarm and great frustration.

4. Conclusion and Recommendations

Regular exercise demonstrated to enhance glycemic control in individuals with type 1 diabetes, to extend the time in range, to reduce the risk of comorbidities, and to have a positive effect on mental health. However, the impact of exercise on blood glucose levels can be influenced by various factors, including the type of exercise, duration, intensity, and personal metabolic status. Despite the documented benefits for health, studies have shown that type 1 diabetics engage in less exercise than their healthy peers. The most common reason given is the fear of hypoglycemic episodes that may occur during or after exercise. To reduce the risk of hypoglycemia, people with type 1 diabetes must consider many factors, including their physical condition, current blood glucose levels, previous insulin doses, and diet. Several recommendations exist for carbohydrate intake and insulin dose adjustment before and after exercise. However, studies have demonstrated that patients must develop customized routines to ensure optimal outcomes. The recently developed technologies have been well-received by patients and have made a substantial contribution to glucose control in type 1 diabetes. However, there is a limited body of research examining how well these devices perform during exercise. The existing studies have identified discrepancies between interstitially measured glucose and plasma glucose values. The use of newer technologies, smart devices and AI may help to predict individual metabolic situations and implement individualized therapies in the future.

It is not possible to formulate a universally applicable recommendation for glucose control during exercise for individuals with type 1 diabetes. The determination of the appropriate exercise type and duration is dependent upon a comprehensive evaluation that encompasses the glycemic response, the physical condition of the patient.

Individualized education is imperative for patients with T1DM, as their glycemic responses to exercise and insulin needs can vary significantly. Consequently, patients should be counseled by their physician to ensure optimal health management. It is essential to adjust both insulin therapy and carbohydrate intake according to the type, intensity, and duration of physical activity and to learn how to adjust and utilize the used technology accordingly.

Patients are strongly advised to plan ahead and prepare for exercise by monitoring glucose levels, adjusting insulin dosages, and preparing or ingesting appropriate carbohydrate sources. Ideally, planning should begin approximately two hours prior to the initiation of the workout, including the evaluation of active insulin and glucose trends.

In instances where blood glucose levels fall below 5 mmol/L or exceed 13.9 mmol/L, exercise should be avoided for the time being and counter measurements initiated.

The emphasis is on the implementation of more frequent blood glucose testing, at shorter intervals before, during, and after exercise. Therefore, the utilization of continuous glucose monitoring (CGM) is strongly recommended to enhance safety and to more effectively track glucose dynamics. CGMs have the capacity to facilitate real-time data analysis, thereby reducing the psychological distress associated with hypoglycemic anxiety, particularly in the context of unscheduled activities.

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Supplementary

Supplementary Table 1: Overview of key findings concerning glycemic response to exercise				
Ref. no.	Author(s)	Year	Type of Exercise	Outcome
8	Khalafi et al.	2025	Physical activity, undefined	- Regular exercise led to reduction in fasting glucose [weighted mean difference = -14.97 mg/dl (-0.83 mmol/l)] - And HbA1c [weighted mean difference= -0.49%]
9	Riddell et al.	2021	Physical activity, undefined	- mean glucose levels on days of exercise: 8.66 ± 2.50 mmol/l compared to 9.21 ± 2.72 mmol/l on sedentary days - TIR was 6% higher, TBR was 2,9% higher and TAR was 14% lower on exercise days
10	Lazić et al.	2024	HIIT vs. Control group, HIIT vs. moderate-intensity continuous training	- HIIT was associated with significant improvements in 24-h mean glucose control - HIIT showed positive effects on reduction of HbA1c compared to control group (standardized mean difference= -0.74)
11	Helleputte et al.	2023	Continuous moderate intensity training, continuous high intensity training, HIIT, interval training, walking exercise	- All exercise types caused consistent acute glycemic declines - Largest effect could be observed in the continuous high intensity training group - Effects on glycemic parameters were pending on duration and intensity of exercise
13	Chang et al.	2023	Physical activity, undefined	- 5 of the 9 analyzed studies showed a significant decrease in HbA1c after a long training period - 3 described no significant difference in HbA1c after physical activity
14	King et al.	2021	Physical activity, undefined	- Physical activity of 60 minutes at least 3 times per week led to a significant reduction in HbA1c levels in children and adolescents
15	Bohn et al.	2015	Physical activity, undefined; patients were stratified into 3 groups according to the	- Physical activity led to a reduction in HbA1c levels - Physical inactive patients: mean HbA1c= 8.20% (n=10978) - Physical activity performed 1 to 2 times per week: HbA1c= 7.92% (n=3396) - Physical activity performed more than 2 times per week: HbA1c= 7.84% (n=3168)

			frequency of physical activity	
20	García-Hermoso et al.	2023	Different exercise types compared to control groups	- HbA1c levels were overall reduced in exercise groups compared to control groups - Reductions in HbA1c were stronger in high intensity and concurrent training groups compared to other exercise modalities - Interventions lasting longer than 24 weeks, with more than 3 sessions per week and a duration over 60 minutes per session showed lower HbA1c levels compared to other exercise modalities
25	Lima et al.	2022	Resistance training	- A significant reduction in HbA1c levels was observed in patients undergoing resistance training compared to a control group
26	Minnock et al.	2022	12 weeks of combined resistance and aerobic training	- Better glucose control, reduced glycaemic fluctuations and fewer hypoglycaemic events were recorded at post- compared to pre-intervention in type 1 diabetes - Interstitial glucose variance was higher in Type 1 diabetics compared to healthy control
29	Farinha et al.	2019	HIIT vs. strength training vs. strength and HIIT training (10-week training protocol with intervention 3 times per week)	- HIIT sessions led to lower rate of change in glycemia in most weeks than other training protocols - All 10-week training protocols decreased similarly HbA1 levels
32	Mallad et al.	2015	75 min of moderate-intensity exercise	- Glucose levels gradually fell during exercise - Baseline glucose levels were reached at the end of exercise
34	Lee et al.	2020	45 min of HIIT vs. moderate-intensity exercise in random order	- Glucose TIR measured with a CGM device was similar for both exercise types (79.5% vs. 76.1%; $p=0.37$)
36	Martins et al.	2024	Interval aerobic exercise vs. continuous aerobic exercise	- Men showed reduced blood glucose values after both training types (-3.7mmol/l and -1.6 mmol/l) - Women showed reduced blood glucose levels only after continuous aerobic exercise (-1.4 mmol/l)

				- The decrease in BG was higher for men after continuous aerobic exercise compared to interval aerobic exercise
37	García-García et al.	2015	Continuous moderate exercise vs. HIIT vs. resistance training	- Rate of change in glucose concentrations (RoCE): -4.43 mmol/l·h for continuous training vs. resistance training - RoCE: -5.25 mmol/l·h for HIIT vs. resistance training
38	Da Prato et al.	2022	Moderate continuous (CON) vs. interval exercise (IE)	- Both average plasma and interstitial glucose concentrations did not significantly differ during CON and IE - plasma glucose change at the end of exercise was greater during CON than during IE (−2.51 ± 2.36 mmol/l vs −1.38 ± 2.2 mmol/l) - interstitial glucose change showed a trend to be greater during CON than during IE although the difference did not reach statistical significance (−1.93 ± 1.94 mmol/l vs −1.19 ± 1.52 mmol/l, p = 0.060)
39	Martín-San Agustín et al.	2025	HIIT with elastic bands (EB-HIIE) vs. moderate-intensity exercise (CONT)	- CONT led to significantly lower blood glucose levels than EB-HIIE, with notable differences during exercise (-1.95 mmol/l), at the end (-2.75 mmol/l), and at 10- and 20-minutes post-exercise (-2.85 mmol/l and –2.55mmol/l). - EB-HIIE: TIR of 68.6% and minimal incidence of level 1 hypoglycemia (<1%) - CONT: TIR of 62.8% and a 16.9% incidence of level 1 hypoglycemia - EB-HIIE resulted in more stable glucose levels during and post-exercise
40	Moser et al.	2025	Continuous aerobic exercise vs. mixed mixed vs. anaerobic exercise	- Outcome summarized in Figure 6

Abbreviations: HIIT = High-Intensity Interval Training; TIR = Time in Range, TBR = Time Below Range; TAR = Time Above Range; EB-HIIE = Elastic Band High-Intensity Interval Exercise; CON = Continuous Exercise; IE = Interval Exercise; RoCE = Rate of Change in Glucose

Supplementary Table 2: Overview of recommendations on carbohydrate intake and nutrition during physical exercise				
Ref. no.	Author(s)	Year	Type of Exercise	Recommendations on carbohydrate intake
31	Molveau et al.	2021	Physical exercise, undefined	- consuming a postexercise snack as well as a bedtime snack - recommended amount of carbohydrate intake for activities lasting from 30 to 60 minutes range widely from 10 to 15 g/h of activity for athletes to 15 to 30 g/0.5h for recreational activities -with a glucose threshold of 7.0 mmol/l associated with a horizontal trend arrow, 10 to 15 g of carbohydrates should be consumed
56	Riddell et al.	2017	Aerobic exercise and HIIT	- starting range for most patients doing aerobic exercise lasting up to an hour is 7–10 mmol/l - Concentrations higher than 7–10 mmol/l might be acceptable in some situations where added protection against hypoglycaemia is needed - Anaerobic exercise and a high intensity interval training session can be initiated with a lower starting glucose concentration (~5–7 mmol/l) - Before exercise: A minimum of 1 g carbohydrate per kg bodyweight according to exercise intensity and type - If blood glucose concentration is less than 5 mmol/l before exercise ingest 10–20 g carbohydrate under low insulin conditions - If blood glucose concentration is less than 5 mmol/l before exercise ingest 20–30 g carbohydrate under high insulin conditions - If starting glucose values are at target levels or slightly above target levels, exercise can be started immediately - Carbohydrate intake depends on intensity and duration of exercise
63	Colberg SR.	2020	Aerobic and anaerobic exercise	- For most regularly training individuals, daily protein requirements are roughly 1.1 to 1.5 g of protein per kilogram of weight - optimal starting blood glucose: 3.9 to 10.0 mmol/l for most activities - <5.0 mmol/l: Ingest 15–30 g of fast-acting carbohydrate before start of exercise - 5.0-8.3 mmol/l: Start consuming carbohydrate at the onset of most exercise (~0.5–1.0 g/kg body mass per hour of exercise) - 8.3-13.9 mmol/l: Initiate exercise

				- >13.9 mmol/l: Test for ketones and do not start exercise
64	Moser et al.	2020	Physical activity, undefined	- during exercise sensor glucose ranges should be between 7.0-10.0 mmol/l (higher for increased risk of hypoglycemia) - 7.0 mmol/l during exercise: accompanied by horizontal trend arrow → 10-15g of carbohydrates should be consumed; downward trend arrow → 15-35g should be consumed - >15.0mmol/l during exercise: test for ketones, insulin correction might be needed - if blood glucose <4.4mmol/l after exercise, consume 10-15 g of carbohydrates
65	Gitsi et al.	2023	Physical activity, undefined	-Incorporate additional glucose supplementation and/or insulin reduction for longer-duration, moderate-intensity exercise compared to short, high-intensity training - For hypoglycemia prevention or treatment, consider a pre-exercise carbohydrate dose adjustment of 15 g/h for optimal results - in case of low glucose levels or a downward trend, consider consuming high glucose index carbohydrates (sugar, honey, corn syrup)
66	Pereira et al.	2023	-	Outcome shown in Figure 7
69	Margolis et al.	2021	Physical exercise, undefined	- Glycogen synthesis rates are enhanced when carbohydrates and proteins are co-ingested after exercise compared with carbohydrates only when the added energy of protein is consumed in addition to, not in place of, carbohydrate
76	Franc et al.	2015	Two moderate and two intense 30 minutes sessions of aerobic exercise	- 3 hours post lunch exercise is considered safe

Abbreviation: HIIT = High-Intensity Interval Training

Supplementary Table 3: Summary of recommendations for adjusting insulin during physical exercise

Ref. no.	Authors	Year	Type of Exercise	Recommendations on insulin dose adjustments

31	Molveau et. al	2021	Physixal exercise undefined	- Pending on intensity and duration of physical activity recommended bolus insulin dose reduction: 25%-75% - reducing insulin basal rate by 20% in the early evening (e.g. up to 3:00 AM) for approximately 6 hours and/or consuming a postexercise snack as well as a bedtime snack
64	Moser et al.	2020	Physical exercise, undefined	- Mealtime insulin dose reduction from 25% to 75% before exercise - Bolus insulin dose reduction based on individual glucose response
65	Gitsi et al.	2023	Aerobic exercise	- Basal insulin dose reduction of 50%-80% - Bolus insulin dose reduction of 30%-50%
66	Pereira et al.	2023	Physical exercise, undefined	- Outcome shown in Figure 8
70	McCarthy et al.	2020	45 minutes of moderate intensity continuous exercise	- Significant reduction in basal and basal insulin dose requirements from pre-to-post-study involvement
71	McCarthy et al.	2021	45 minutes aerobic exercise	- Pre exercise and post exercise bolus dose reduction of 50% led to a decreased risk of hypoglycemia both during exercise and at night
72	Myette-Côté et al.	2023	60 min or 120 min of moderate intensity aerobic exercise	- Bolus insulin dose reduction of 33% before exercise was considered safe in both groups
73	Moser et al.	2020	Road cycling race over a 5-day period	- Bolus insulin dose reductions were considered safe - Basal insulin dose was not adjusted over the course of 5 days
74	Shahar & Hamdy	2015	Physical activity, undefined	- Bolus insulin dose reduction of 25 to 75% one to two hours before planned exercise pending on intensity and duration of exercise
75	Roy-Fleming et al.	2019	45 min aerobic exercise, comparison of basal insulin dose reduction of 80% 40,20 and 0 minutes before exercise	- Basal insulin dose reduction of 80% up to 40 min before exercise onset is insufficient to reduce exercise-induced hypoglycemia

76	Franc et al.	2015	Two moderate and two intense 30 minutes sessions of aerobic exercise	- Bolus insulin dose reduction of 30%-50% for exercise lasting over 30 min within 60-90 min after a meal - Basal insulin dose reduction of 50%-80% - Less hypoglycemic events with 80% Basal insulin dose reduction compared to 50%
77	Campbell et al.	2015	45 min of treadmill running 60 minutes after carbohydrate intake	- Basal insulin dose reduction of 20% prevented from nocturnal hypoglycemia - Bolus insulin dose reduction of 75% before exercise and 50% after exercise were considered safe