Post-exercise recovery for the endurance athlete with type 1 diabetes: a consensus statement

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There has been substantial progress in the knowledge of exercise and type 1 diabetes, with the development of guidelines for optimal glucose management. In addition, an increasing number of people living with type 1 diabetes are pushing their physical limits to compete at the highest level of sport. However, the post-exercise recovery routine, particularly with a focus on sporting performance, has received little attention within the scientific literature, with most of the focus being placed on insulin or nutritional adaptations to manage glycaemia before and during the exercise bout. The post-exercise recovery period presents an opportunity for maximising training adaption and recovery, and the clinical management of glycaemia through the rest of the day and overnight. The absence of clear guidance for the post-exercise period means that people with type 1 diabetes should either develop their own recovery strategies on the basis of individual trial and error, or adhere to guidelines that have been developed for people without diabetes. This Review provides an up-to-date consensus on post-exercise recovery and glucose management for individuals living with type 1 diabetes. We aim to: (1) outline the principles and time course of post-exercise recovery, highlighting the implications and challenges for endurance athletes living with type 1 diabetes; (2) provide an overview of potential strategies for post-exercise recovery that could be used by athletes with type 1 diabetes to optimise recovery and adaptation, alongside improved glycaemic monitoring and management; and (3) highlight the potential for technology to ease the burden of managing glycaemia in the post-exercise recovery period.

Introduction

Over the past decade or so, there has been substantial progress in the knowledge of managing glycaemia in the context of exercise and type 1 diabetes, with the development of exercise-specific guidelines.[1] Many people with type 1 diabetes now live an active lifestyle, and there are many examples of people achieving incredible feats of physical endurance while living with the condition,[2,3] even reaching the highest level of competition in their sport. However, in contrast to athletes without diabetes, research specifically examining a post-exercise recovery routine is scarce, with most of the focus being placed on insulin or nutritional strategies to manage glycaemia before or during the exercise bout, or both. Although previous guidelines[1] have contained some brief advice regarding the post-exercise period, the focus was on glycaemia rather than optimising recovery. The absence of information is unfortunate, because irrespective of an individual's training or competition goals, the post-exercise recovery period provides an opportunity for maximising training adaption and recovery.[4]

The aim of this Review is to provide an up-to-date consensus on post-exercise recovery and glucose management for endurance athletes living with type 1 diabetes. First, we will outline the principles and time course of post-exercise recovery, highlighting the additional implications and challenges for athletes living with type 1 diabetes. Second, we will provide an overview of potential post-exercise recovery strategies that could be used by endurance athletes with type 1 diabetes to optimise recovery and adaptation, alongside improved glycaemic monitoring and management. Third, we will outline the ways in which rapid developments in technology can be used to ease the burden of managing glycaemia in the post-exercise period.

Principles and time course of exercise recovery

An increasing number of individuals living with type 1 diabetes are now aiming to compete at the top level of their chosen sport.[5] This aim requires developing behaviours to optimise nutrition and insulin doses during the periods before, during, and after exercise. The importance of post-exercise recovery practices have been well described for athletes without diabetes, with hundreds of studies investigating various ways to optimise training adaptations and rates of glycogen resynthesis, leading to multiple guideline papers and the incorporation of these strategies as an integral part of evidence-based training regimens.[6,7] For athletes with type 1 diabetes, the challenge of managing glycaemia makes post-exercise recovery more difficult, because they should also consider the effects of altered insulin sensitivity, post-exercise hyperglycaemia, depleted glycogen stores, dehydration, impaired glucose counter-regulatory responses, insulin doses, abrupt changes in the rate of muscle glucose uptake because of a halt in muscle contraction, and the effect of nutritional selection (for energy or macronutrient intake) on blood glucose concentration. The absence of clear guidance for athletes living with type 1 diabetes means that they often either develop their own recovery strategies on the basis of individual trial and error, or follow guidelines that have been developed for athletes without diabetes.

Defining the post-exercise period

The post-exercise period can be simply defined as the period of time after exercise until a new bout is initiated. A bout of exercise influences glycaemia both during and after, and this effect can persist for 48 h or more because of changes in insulin sensitivity and muscle glucose

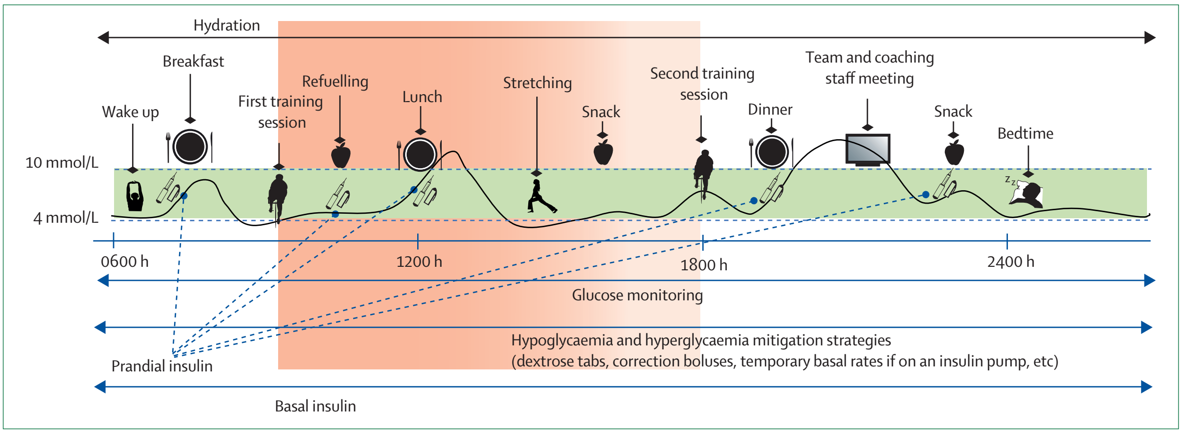

Figure 1: **Timeline of one day of training for athletes living with type 1 diabetes**
Unlike athletes without diabetes, for those with type 1 diabetes, the tasks of monitoring glucose concentrations, insulin doses, and carbohydrate intake for optimal glycaemia should always take priority. Athletes with type 1 diabetes need to individually balance the regular recovery requirements (replenishment of energy substrates, promotion of muscle remodelling, and recovery of skeletal muscle damage), while preventing potentially life-threatening severe hypoglycaemia or ketoacidosis[9] that might also prolong recovery. This figure shows an example of the tasks and challenges that an athlete with type 1 diabetes needs to manage when training more than once per day. Note that the task of managing glycaemia is in addition to the other logistical and personal challenges such as travel, media demands, work, and family commitments. In the image, the red box represents the recovery period between the first and second training sessions, during which the athlete needs to make sure they are prepared for the next exercise session. In this example, recovery time will be restricted to just a couple of hours between sessions, meaning athletes with type 1 diabetes should have a sound strategy in place to ensure recovery and nutrition for the next training session, while simultaneously managing glycaemia. Please note that the hours are approximate.

uptake.[8] Therefore, technically speaking, the post-exercise period includes everything from immediately after exercise to the subsequent 48 h (and potentially longer, if the athlete underwent exhaustive endurance exercise or if there is severe muscle damage). In reality, athletes compete or train much more regularly than every 48 h, sometimes multiple times per day (figure 1). Rest and recovery are important aspects of an athlete's training regimen for optimal performance and training adaptation.[10] During situations of suboptimal recovery time, the athlete or sports coach, or both, should have a good understanding of which aspects of recovery to prioritise. The aim will be to ensure that glycaemia is stable within optimal ranges and energy substrates have recovered to as great a degree as possible to facilitate performance, while avoiding potentially dangerous glucose excursions and the risk of complications.

For athletes with type 1 diabetes, it would seem that managing post-exercise glycaemia and achieving adequate recovery (eg, replenishing glycogen stores, ensuring adequate sleep, etc) should go hand in hand with each other. Late-onset hypoglycaemia after exercise is a common occurrence for people with type 1 diabetes,[11] suggesting that improving the post-exercise recovery routine could reduce this risk. On the other hand, high-intensity efforts (exceeding lactate threshold) might be related to immediate post-exercise hyperglycaemia, which appears to be more common with fasted morning exercise compared with exercise at other times of the day.[12] Post-exercise hyperglycaemia might also occur after aerobic exercise of moderate intensity[13] because of many factors such as insulin pump suspension or removal over a long period of time,[14] loss of insulin delivery (pump site failure), reduced basal insulin delivery before or during exercise, and insulin administration poorly matched with high rates of carbohydrate feeding. Post-exercise hyperglycaemia that is long lasting, with or without hypoinsulinaemia, might affect optimal glycogen recovery and should be managed with insulin dose adjustments in the immediate post-exercise period to promote the complete restoration of liver and muscle glycogen stores. Excessive insulin administration in early recovery might, however, increase the risk of late-onset hypoglycaemia.[15] An understanding of the metabolic changes that occur during and after exercise, as well as the individual glycaemic responses with different types or intensities of exercise, might facilitate the development of nutrition and insulin dose regimens to optimise the rate of recovery.

Changes in post-exercise metabolism

At rest, energy consumption is low, with a carbohydrate oxidation rate of approximately 0·1 g per min^{-1} depending on the diet and exercise before the measurements for athletes without diabetes.[16] During exercise, there are considerable changes in fuel use that are established primarily by the intensity and duration of exercise.[16] When exercising at intensities of more than 70% of the maximum rate of oxygen consumption measured during incremental exercise (VO_{2max}), carbohydrate will be the main fuel source.[16] These changes in metabolism also occur in people living with type 1 diabetes, in whom there is greater carbohydrate oxidation with higher exercise intensities.[17]

A handful of studies have investigated exercise-associated fuel metabolism in people with type 1 diabetes and the effect of differing plasma glucose and insulin concentrations.[18–22] Chokkalingham and colleagues[20] compared the effects of differing insulin concentrations on whole-body and muscle metabolism in people with type 1 diabetes during moderate-intensity exercise. Hyperinsulinemia caused an increase in blood glucose use during exercise but with no sparing of intramyocellular glycogen. Subsequently, Chokkalingham and colleagues[21] compared hepatic glycogen use during exercise in people with type 1 diabetes and those without. Despite the substantially higher systemic insulin and glucose concentrations in those with type 1 diabetes, there were no major differences in substrate oxidation nor hepatic glycogen breakdown between the two groups. Jenni and colleagues[18] investigated the effect of different glucose concentrations at identical amounts of low insulinaemia on fuel metabolism during moderate-intensity exercise in people with type 1 diabetes. They found a higher rate of carbohydrate oxidation during exercise in hyperglycaemia than during euglycaemia, with inverse findings for lipid oxidation. Although these studies provide important insight into the potential effects of pharmacological insulin amounts and varying glucose concentrations on fuel metabolism, the effects after exercise are yet to be established. Therefore, the data below are drawn primarily from research done in individuals without diabetes.

Carbohydrate oxidation is predominant during a bout of moderate-intensity to high-intensity exercise,[16] but lipid oxidation becomes the main fuel source after exercise,[23] resulting in a decrease in the respiratory exchange ratio, even under conditions of high carbohydrate feeding.[23] The decrease in the respiratory exchange ratio following long periods of aerobic exercise has been shown to persist to the following morning in adults without diabetes.[24] This shift in substrate metabolism shows a high metabolic priority for muscle glycogen resynthesis, whereby lipid oxidation from intramuscular and extramuscular sources is elevated to meet fuel requirements.[25] The importance of this elevation is evidenced by the fact that there is a strong relationship between the replenishment of liver and skeletal muscle glycogen stores after exercise, and an individual's subsequent exercise performance.[26,27] Commencing a bout of exercise with reduced muscle glycogen content impairs exercise capabilities,[28] meaning that the restoration of muscle glycogen is necessary if an optimal performance is desired.

Muscle glycogen resynthesis: insulin independent and dependent phases

The process of muscle glycogen resynthesis begins immediately after exercise and is the most rapid during the first 5–6 h of recovery.[29] Glycogen resynthesis after exercise occurs in a biphasic pattern, whereby there is an initial rapid phase, lasting minutes to hours, that does not require the presence of insulin, and subsequently a more long-lasting insulin-dependent phase lasting up to 72 h.[30,31] Following an exercise bout, muscle glycogen is typically restored to pre-exercise concentrations within 24–36 h, provided sufficient carbohydrate is ingested.[32,33] For athletes involved in multiple training sessions or competitions on the same day or successive days, muscle glycogen stores need to be replenished more rapidly, which can be facilitated with some carbohydrate feeding strategies.[4,34,35] When rapid recovery from long-term exercise is the key objective, and peak performance is required within 24 h, people without diabetes are advised to consume 1·0–1·3 g carbohydrates per kg per h for the first 4 h of recovery, starting as soon as possible after exercise with frequent feeding intervals thereafter (ie, every 30 min).[6,36,37] These carbohydrate requirements are likely to be similar for an endurance athlete living with type 1 diabetes. For athletes with type 1 diabetes, who manage their insulin via exogenous administration, a greater understanding of the physiology of glycogen resynthesis might help to reduce the risk of hypoglycaemia and hyperglycaemia, with the appropriate adjustments in insulin delivery to facilitate a safe and effective recovery.

Insulin-independent phase of muscle glycogen resynthesis

After exercise of sufficient intensity and duration to largely deplete muscle glycogen stores, glycogen synthase activity[30,38] and the permeability of the muscle cell membrane to glucose increases.[39,40] These changes result in an initial rapid phase of glycogen resynthesis, which is independent of insulin signalling that typically lasts 30–60 min according to studies done in people without diabetes.[31,38,41] Glucose is the primary substrate for muscle glycogen resynthesis; however, after predominantly anaerobic exercise, lactate also becomes a substantial contributor, accounting for approximately 20% of total muscle glycogen resynthesis.[42] The initial rapid phase of glycogen resynthesis in the muscle appears to be because of contraction-induced GLUT4 translocation to the cell membrane and augmented glycogen synthase activity.[38,43] The rate of resynthesis during this initial phase can rapidly decline in the absence of exogenous carbohydrate.[30,41] There is little research done in people with type 1 diabetes in this area, with the exception of a few studies in the 1970s.[30,44,45] However, it can be assumed that, provided adequate carbohydrates are consumed, this initial phase of glycogen resynthesis would be normal in athletes with type 1 diabetes (figure 2).

Insulin-dependent phase of muscle glycogen resynthesis

The second phase of glycogen resynthesis has been defined as the insulin-dependent phase,[30,31,46] which potentially requires additional considerations in athletes with type 1 diabetes because insulin is administered exogenously. In individuals without diabetes, insulin release because of carbohydrate intake increases blood flow to the muscle, GLUT4 translocation to plasma membrane, and hexokinase II and glycogen synthase activity,[47–49] all of which contribute to increased glucose uptake by the muscle and glycogen synthesis. In the absence of carbohydrate intake, this second phase occurs at a rate 7–10 times slower than the initial rapid phase.[46] Carbohydrate feeding immediately after exercise, along with the natural rise in insulin concentrations, has an important effect on the rate of glycogen synthesis during the slow phase. The effectiveness of the carbohydrate intake to speed muscle glycogen recovery during the second phase is directly related to the plasma insulin response.[50]

During the mid to late post-exercise period (3–12 h after exercise), the magnitude of increased insulin sensitivity can be high, substantially increasing the risk of post-exercise hypoglycaemia. Therefore, individuals with type 1 diabetes should take this factor into account and typically reduce their bolus or basal insulin dose, or both, accordingly after exercise,[51] on the basis of frequent glucose monitoring and some trial and error, to help prevent hypoglycaemia. Because of the absence of studies quantifying insulin adaptations in the post-exercise period, we usually recommend that the bolus insulin dose can be reduced by 20–50% at the first recovery meal, along with a similar reduction in the insulin basal delivery rate (for those using a pump) for 6–12 h or a reduction in the first basal insulin dose (multiple daily insulin injections) in the recovery period, although the precise amount will depend on the type, intensity, and timing of the exercise done. Other athletes with type 1 diabetes might choose not to adjust their insulin delivery but simply consume carbohydrates at an elevated rate that preserves blood glucose concentrations.

A handful of pioneering studies done in the 1970s used muscle biopsies to investigate muscle glycogen synthesis after exercise in people with type 1 diabetes.[44,45,52,53] Maehlum and colleagues[52] compared glycogen resynthesis rates in six participants with type 1 diabetes and six without ingesting a carbohydrate-rich diet during the 12 h of recovery after exhaustive cycling exercise. The group with type 1 diabetes took a fixed insulin dose after the exercise, although not enough to maintain blood glucose concentration within the target range because of the additional carbohydrates consumed. During exercise, muscle glycogen use was similar in the two groups. Following exercise, the glycogen synthesis rate was most rapid in the first 4 h of recovery in both groups (with type 1 diabetes, 6·4±0·6 mmol glucosyl units per kg of wet weight per h *vs* without type 1 diabetes, 7·2±0·7 mmol glucosyl units per kg per wet weight per h). In a subsequent experiment, the same authors[45] investigated the effect of insulin deprivation on muscle glycogen resynthesis during the 12 h of recovery after exhaustive exercise. With the use of a similar protocol to the previous study, five participants with type 1 diabetes were given a carbohydrate rich diet, but this time insulin was withheld during recovery. In the first 4 h, the participants reported high rates of glycogen synthesis, similar to the earlier mentioned study in which they were given insulin.[30] In the subsequent 8 h, there was no further increase in glycogen synthesis in the insulin deprivation condition, despite the fact that the plasma glucose concentration was 20–30 mmol/L and that glycogen synthase was activated.[45] These observations provide clear support for the importance of insulin signalling in the second phase of glycogen resynthesis. However, it is important to note that these studies were not done under physiological conditions given the probability of ketoacidosis with insulin deprivation, and the authors did not control factors including the duration of the exhaustive exercise bout, the amount of food consumption, and blood glucose concentration. Since the completion of these studies[30,44,45] more than 40 years ago, there have been substantial improvements in insulin formulations and delivery methods and knowledge of the effects of exercise on glucose concentrations in type 1 diabetes. Therefore, the post-exercise period in athletes with type 1 diabetes should be the focus of renewed interest, particularly with the use of rapid-acting insulin analogues with much shorter half-lives.

These studies illustrate the importance of post-exercise insulin adjustments for optimal glycogen resynthesis and individual basal insulin adjustments because of increased insulin sensitivity. For athletes with type 1 diabetes, the

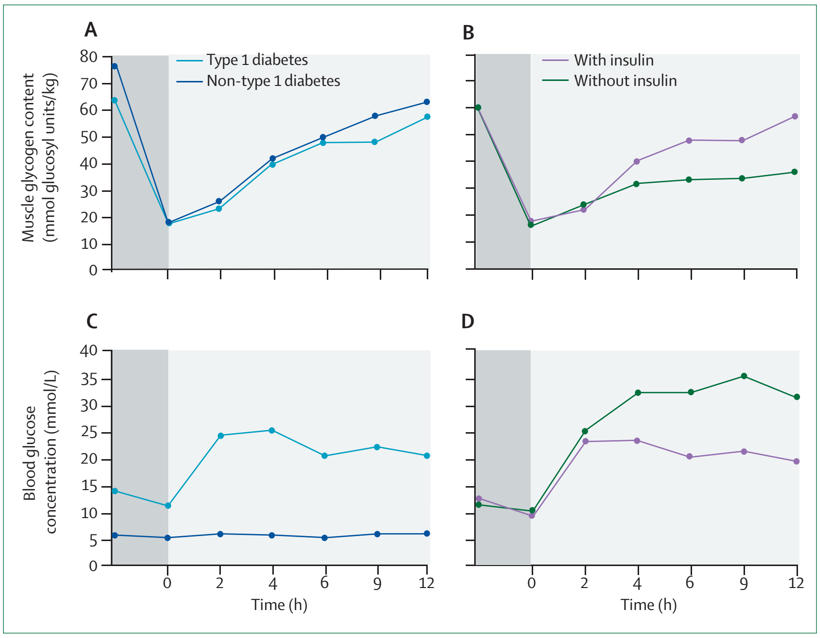

Figure 2: **Muscle glycogen recovery and blood glucose concentrations after long periods of exercise**
Adapted from Maehlum and colleagues.[30,45] The dark grey shading illustrates the exercise period and light grey is the recovery period up to 12 h after exercise. (A) The glycogen content in individuals with type 1 diabetes with insulin administration and individuals without type 1 diabetes. (B) The effects of insulin deprivation in individuals with type 1 diabetes, where the changes are apparent in the insulin-dependent phase. (C,D) The corresponding blood glucose profiles to (A) and (B) above, showing the importance of prioritising blood glucose concentration during recovery.

best strategies for insulin administration after exercise are likely to be highly individual and depend on particular circumstances. The priority after finishing a bout of exercise should be to first get the blood glucose concentration of the individual stable and within the target range (4–10 mmol/L). This might be done by taking an insulin correction if required[13] and then adding additional bolus insulin to cover the carbohydrate and protein intake consumed in early recovery to stimulate glycogen resynthesis and muscle protein synthesis. As always, it is important to re-emphasise that, although the rate of glycogen resynthesis is important, the athlete with type 1 diabetes needs to balance this with the risk of hyperglycaemia and hypoglycaemia. Athletes with type 1 diabetes should also be made aware that the greater muscle insulin sensitivity after exercise can persist for up to 48 h (or even longer after extreme exercise bouts), which means they should be aware of a delayed onset of hypoglycaemia. In addition, they should adapt their insulin doses on the basis of individual increases in insulin sensitivity during periods of increased training or competition.[2] Athletes and their coach, trainer, or nutritionist should work on developing a regular routine of post-exercise nutrition and insulin administration based on individually defined variables and requirements. The section on strategies to maximise and facilitate post-exercise glycogen synthesis in athletes with type 1 diabetes in this Review will outline potential strategies to help facilitate the development of such a routine.

Liver glycogen metabolism during and after exercise

Skeletal muscle glycogen metabolism has received much attention over the last six decades since the development of the muscle biopsy technique.[35,54] However, the role of hepatic glycogen during and after exercise has been less well studied, primarily because of the difficulty of accessing tissues samples compared with muscle biopsy samples. The development of ^{13}C-magnetic resonance spectroscopy (C-MRS) as a non-invasive measurement of human liver glycogen[55] has enabled repeated measurements of liver glycogen content to be made without inducing the catecholamine response that sometimes is induced by biopsy procedures. A handful of studies have used ^{13}C-MRS to measure the effect of carbohydrate ingestion on the rate of post-exercise hepatic glycogen resynthesis in athletes without diabetes[26,56,57] (see the section on effects of the type and form of carbohydrates on post-exercise recovery and glycaemia). Although there are no data on hepatic glycogen metabolism during the post-exercise period in athletes with type 1 diabetes, Bally and colleagues[58] found similar hepatic and intramyocellular glycogen stores between adults with well-controlled type 1 diabetes and a group of matched individuals without type 1 diabetes under standard resting conditions. Future research should aim to use these techniques to investigate optimal strategies to maximise hepatic glycogen resynthesis after long periods of endurance exercise in athletes with type 1 diabetes.

Influence of sex hormones and menstrual cycle phase on fuel metabolism and glycogen resynthesis

Within the type 1 diabetes and exercise literature, most published work has only included young healthy male individuals, and those that have included female individuals tend not to recognise the potential sex-related effect on their outcomes. As was highlighted in previous publications,[5,59,60] this effect is an important issue, because there are likely to be important sex-related differences in metabolic and neuroendocrine responses during and after exercise that will influence glycaemia, carbohydrate requirements, and glycogen resynthesis. Female athletes with type 1 diabetes might have important changes in glycaemia that are linked to the menstrual cycle phase. These changes are likely to influence insulin and carbohydrate needs before, during, and after an exercise bout.

Strategies to maximise and facilitate post-exercise glycogen synthesis in athletes with type 1 diabetes

Athletes without diabetes do not need to consider their blood glucose concentration in the same way as those with type 1 diabetes, since their β cell response is intact and insulin is produced endogenously. For those without type 1 diabetes, after a bout of exhaustive exercise, the replenishment of glycogen stores is the primary aim, with the rate of carbohydrate absorption in the gut and glucose uptake in the muscle being the main limiting factors, with little concern of hyperglycaemia or hypoglycaemia.[38] For the athlete with type 1 diabetes, maintaining blood glucose concentration within target range (4–10 mmol/L) adds an additional complexity that requires vigilance, frequent glucose monitoring, preferably by continuous glucose monitoring (CGM), and often insulin dose titration. Nutritional strategies to maximise the rates of glycogen resynthesis and muscle protein synthesis after exercise have been well studied in athletic populations without diabetes.[4,26,32–38] Muscle damage repair and skeletal muscle reconditioning are also important determinants of recovery.[7] A positive muscle protein balance is needed to facilitate the repair of exercise-induced muscle damage[61] and, in the long term, for muscle hypertrophy for improved athletic performance, depending on the event. In this section, we outline the potential effects of timing, quantity, and type of nutrition, as well as post-exercise recovery practices (cool down, ice baths, and sleep) and how they could be used to simultaneously manage glycaemia and the rate of recovery (figure 3).

Post-exercise carbohydrate intake

The quantity of post-exercise carbohydrate intake will depend on the type, duration, and intensity of the exercise done, as well as blood glucose concentration and the circulating amount of insulin. If maximising the rate of muscle glycogen resynthesis is the primary aim (which is common for endurance or ultra-endurance athletes that compete multiple times within a short timespan), post-exercise carbohydrate ingestion is the most important

GLUCOSE CHECK*[1,62]
- Check immediately after exercise because of increased risk of hypoglycaemia or hyperglycaemia[1,14,63]
- Continue to check at regular intervals (15 min) or use CGM or flash glucose monitoring because of an increased risk of dysglycaemia after exercise*[5,62]
- Consider setting alarms to guide the timings of your checking routine*
- Because of the potentially elevated risk of hypoglycaemia overnight, CGM alarm should be set at 4·4 mmol/L (80 mg/dL) and those using flash glucose monitoring should do at least one scan during the night[62]

INSULIN ADJUSTMENTS (including pre-exercise and post-exercise)
- These are likely to be highly individual and depend on the circumstances, including but not limited to, the type, intensity, and timing of the exercise done[1,5,11–14,63,51]
- After exercise, the magnitude of increased insulin sensitivity can be high, substantially increasing the risk of post-exercise hypoglycaemia

If using multiple daily injections
- Consider reducing insulin dose pre-exercise*[51]
- Reduce the first basal insulin dose in the recovery period, particularly if the exercise session was >30–60 min*[1]
- Reduce bolus insulin dose with recovery meal[14,64]

If using subcutaneous insulin infusion
- Basal rate reduction 60–90 min before the start of exercise*[5]
- When suspending the pump at the start of the exercise, limit the suspension to a maximum of 45–60 min. Consider a hybrid regimen[13]
- The bolus insulin dose can be reduced by 20–50% at the first recovery meal, along with a similar reduction in the insulin basal delivery rate for 6–12 h*[5]

CARBOHYDRATE INTAKE
- Initiate carbohydrate feeding when the glucose concentration is less than 8·0 mmol/L (144 mg/dL), particularly if glucose is decreasing*[5]
- When rapid recovery from a long period of exercise is the key objective, and peak performance is required within 24 h, aim to consume 1·0–1·3 g carbohydrates per kg-1 per h-1 for the first 4 h of recovery, starting as soon as possible after exercise, with frequent feeding intervals thereafter (ie, every 30 min)[6,36,37,65]
- In some scenarios (eg, focus is on enhancing the training stimulus or adaptive response), low carbohydrate availability might be deliberately done by reducing the total carbohydrate intake, or by manipulating carbohydrate intake related to training sessions (eg, training in a fasted state or undertaking a second exercise session with a low carbohydrate intake).[66] However, there is little information on athletes with type 1 diabetes and we do not generally recommend a low carbohydrate diet for exercise performance*[66]
- The use of multiple transportable carbohydrates (eg, fructose) in combination with glucose after exercise will promote a faster liver glycogen repletion rate than glucose alone[26,56,57]
- Fructose alone cannot be used to immediately treat low blood glucose[67]
- Fructose and glucose co-ingestion will require a lower insulin dose compared with glucose alone[68,69]
- A previous study by Thomas and colleagues[6] has more detailed information on fuel and recovery

PROTEIN INTAKE
- Daily protein recommendations are 1·6–1·8 g per kg-1 per d-1 for endurance athletes[6,7]
- Protein added to carbohydrate immediately after exercise might speed up recovery[4,6,7,32,36,70–74]

HYDRATION
- Be aware of the effects of drinks containing high amounts of carbohydrate on blood glucose concentration*
- Hydrate with carbohydrate-free drinks if blood glucose concentration >10·0 mmol/L*
- Effective rehydration requires the intake of a greater volume of fluid (eg, 125–150%) than the final fluid deficit (eg, 1·25–1·50 L fluid for every 1 kg of bodyweight lost)[6]
- Dietary sodium and sodium chloride (from foods or fluids) helps to retain ingested fluids
- Be aware of environmental conditions (hot or humid conditions)[75,76]
- Excessive alcohol intake in the recovery period is discouraged because of the diuretic effect and increased risk of hypoglycaemia[77–79]

CAFFEINE
- Caffeine in a dose of 3 mg per kg (200–300 mg) might reduce the risk for hypoglycaemia during and after exercise.*[80,81] This amount can be consumed alongside glucose*
- Avoid high amounts of caffeine consumption late in the day, because this can negatively affect sleep[82]

COOL DOWN
- If during the last 10 min of exercise the blood glucose concentration is >10·0 mmol/L, consider a more prolonged low-intensity cool down*
- If during the last 10 min of exercise the blood glucose concentration is 5–10 mmol/L, reduce the length of the cool down*

Figure 3: **Summary of considerations to maximise and facilitate post-exercise glycogen synthesis in endurance athletes with type 1 diabetes**
The rates of carbohydrate, protein, and fluid intake suggested here are based on research done on individuals without type 1 diabetes. CGM=continuous glucose monitoring. *Where there was an absence of published evidence because of too few studies in the post-exercise period in individuals with type 1 diabetes, statements are based on the authors' opinion and experience. For each of these considerations, glycaemia, insulin dose (type and whether on multiple daily injections or a pump) will have to be taken into account and monitored.

factor establishing the rate of muscle glycogen synthesis.[33,38] During situations in which a speedy recovery of glycogen is required (<8 h recovery between two fuel demanding sessions), athletes without type 1 diabetes are recommended to consume 1·0–1·3 g carbohydrates per kg per h for the first 4 h, and then to resume regular meal patterns to meet daily fuel needs.[6] During such situations, athletes might choose carbohydrate-rich foods that are low in fibre and are easily consumed (eg, white rice or pasta). For athletes with type 1 diabetes, there is little research in this area. However, it is probable that the requirements are similar, provided insulin is taken in the correct amount to manage glycaemia. Low carbohydrate or carbohydrate-restricted diets have received much attention because of the suggested benefits for health, glycaemic management, and sports performance. Because these diets are a topic of debate beyond the scope of this Review, interested readers are referred to another review by Scott and colleagues.[66]

Athletes with type 1 diabetes should also be aware that the addition of fat, protein, or fibre, or a combination, will alter the glycaemic profile of a meal.[83,84] The use of a hybrid closed-loop insulin delivery system that automatically changes basal insulin delivery on the basis of unique settings customised to the individual's insulin sensitivity, real-time glucose measurements, and other variables might facilitate glycaemic management during the recovery period, particularly when sleeping.[85]

Effects of the type and form of carbohydrates on post-exercise recovery and glycaemia

The form in which carbohydrates are ingested (ie, solid *vs* liquid) does not appear to make a difference to the rate of glycogen resynthesis.[86] However, the type of carbohydrate is important, because of differing rates of digestion, intestinal absorption, and hepatic metabolism, which are key determinants of their glycaemic effect and rate of delivery to skeletal muscle.[38,57,67] A handful of studies have directly compared the ingestion of glucose–fructose mixtures versus glucose alone on the post-exercise muscle glycogen repletion in individuals without diabetes.[26,56,87,65] Based on the evidence from these studies, the post-exercise ingestion of glucose–fructose mixtures does not appear to accelerate muscle glycogen repletion compared with glucose alone. A few studies have used ^{13}C-MRS to non-invasively compare the effects of glucose and fructose co-ingestion with glucose alone on post-exercise liver glycogen resynthesis in people without diabetes.[26,56,57] When fructose is co-ingested with glucose (either as free glucose and free fructose or sucrose), the rate of liver glycogen repletion is approximately double the rate of when ingesting glucose alone and this effect is clearest when the carbohydrate ingestion rate exceeds 0·9 g carbohydrates per kg per h. The greater liver glycogen repletion seen with glucose and fructose is probably because of the preferential hepatic metabolism of fructose or faster digestion and independent absorption kinetics, or both. Other reviews have covered this topic in detail.[88,89]

Focusing on athletes with type 1 diabetes, these alternative, multiple transportable carbohydrates, such as fructose, isomaltulose, and galactose (although there is only data on fructose), might also be beneficial for reducing the risk of exercise-associated hypoglycaemia because of the lower amount of insulin required to cover their intake.[68,69] Unfortunately, no studies have yet investigated the glycaemic effects of fructose ingestion after exercise in people with type 1 diabetes or the possible effect on glycogen resynthesis (liver or muscle).

Fluid management

To preserve homoeostasis, optimal body function, and wellbeing, athletes should aim to have fluid management strategies for before, during, and after exercise to maintain euhydration, depending on the type and duration of exercise, as well as the environment. Athletes with type 1 diabetes will have to consider what they drink (ie, if it contains carbohydrates), in addition to how much they consume, to manage glycaemia and hydration. Most athletes finish a bout of exercise with a fluid deficit and so will need to restore euhydration during recovery.[90] In addition to water, sweat contains substantial but variable amounts of sodium, potassium, calcium, and magnesium. Therefore, athletes should not be advised to restrict sodium after exercise, particularly when large sodium losses have occurred.[6]

Concerns that thermoregulation might be impaired in people living with type 1 diabetes during exercise, particularly under hot and humid conditions, have previously been raised.[75] Data in this area are scarce, but studies have shown that young individuals with type 1 diabetes without diabetes-related complications have no differences in sweat rates during low-intensity to moderate-intensity exercise compared with individuals without diabetes matched for age, sex, body surface area, body composition, and physical fitness.[76,91] However, Carter and colleagues[76] found that when exercising at higher workloads (≥250 watts per metre squared of body surface area) in the heat (35°C at 20% humidity), the local sweating response in individuals with type 1 diabetes was lower and their core body temperature was higher compared with participants without type 1 diabetes. These findings suggest that the reduced sweat rate might lead to a reduced ability to dissipate heat at higher workloads.

Whether those with type 1 diabetes have differences in thirst perception versus those without diabetes (ie, thirst depending on changes in blood osmolality) has not been fully established, although high blood glucose concentrations increasing blood osmolality are likely to signal for an increased thirst sensation.[92] This is supported by Buoite Stella and colleagues,[93] who found, via a questionnaire, that self-reported fluid intake during exercise was higher in a group of individuals with type 1 diabetes compared with a group of age-matched and sport-matched individuals without type 1 diabetes. Hyperglycaemia influences the hydration status in individuals with diabetes because it alters the fluid resorption in the kidneys and causes a shift in free water from cells into the circulation. When blood glucose concentration is less than 9–10 mmol/L, almost all glucose in filtrate is reabsorbed in the proximal tubule and the amount of glucose in the urine is negligible. When the blood glucose concentration is more than 9–10 mmol/L, glucose in the filtrate can escape and glucose can be found in the urine (glucosuria).[94] The amount of glucose reabsorbed increases linearly with rising plasma glucose concentration until a maximum value is reached. Any further increase in the filtered glucose load is excreted in urine.[94] Because glucose needs to be dissolved in water, whenever glucose is lost in urine, water will follow. This osmotic drive increases the risk of dehydration if fluid losses are not compensated.

Co-ingestion of additional nutrients: protein, caffeine, alcohol

Rates of glycogen resynthesis and blood glucose concentration can be affected (both positively and negatively) by the co-ingestion of other nutrients with carbohydrate.[4,70] Such information is useful when glycogen resynthesis is required in a short time frame.

Protein

In addition to carbohydrates, insulin secretion is induced through intravenous infusion or oral ingestion of some amino acids in individuals without diabetes.[95,96] Studies have also shown that there is a synergistic effect of combined amino acids or protein and carbohydrate ingestion, or both, on insulin secretion.[96,97] This evidence led to the commonly used strategy in athletes without diabetes of co-ingesting carbohydrates and protein with the aim of accelerating post-exercise muscle glycogen resynthesis and taking advantage of the anabolic effects of insulin.[4,6,7] There is evidence that when protein is co-ingested with carbohydrate, postprandial insulin concentrations are augmented, leading to an increase in glycogen synthase activity when carbohydrate intake is less than the threshold for glycogen storage (ie, 0·5–0·8 g carbohydrates per kg per h).[70–72,98] However, when carbohydrate intake is adequate (eg, >1 g carbohydrates per kg per h), the co-ingestion of protein has no additional effect on glycogen synthesis,[36,99] although protein will still affect anabolism.

The beneficial effects of protein intake in the recovery period are well described for athletes who do not have type 1 diabetes. Studies have shown that exercise performance was better in a second exercise bout 18 h after exhaustive exercise with an intake of 0·8 g of carbohydrates per kg per h in combination with 0·4 g protein per kg per h, compared with 1·2 g carbohydrates per kg per h alone during the first 2 h of recovery.[73,74] Although muscle glycogen was not measured in these studies, metabolic data suggested that the glycogen stores did not limit performance after carbohydrate-only intake during the first 2 h of recovery.[73,74] Importantly, muscle glycogen synthesis was similar during the 5 h recovery period with an intake of 0·8 g carbohydrates per kg per h in combination with 0·4 g protein per kg per h compared with 1·2 g carbohydrates per kg per h alone during the first 2 h after exhaustive exercise,[36] but the exercise performance was better when protein was added to the recovery drink. Clearly, protein intake will not influence endogenous insulin production in athletes with type 1 diabetes, but it might increase insulin dose requirements. The addition of protein after exercise is recommended, provided insulin is taken, because the protein is likely to contribute to glycogen resynthesis and increase net muscle protein balance.

Caffeine

Caffeine is naturally found in many foods and is frequently added to sports supplements because of its ergogenic effects in a range of sporting events. Caffeine has many physiological effects, including increased lipolysis in adipose tissues and hepatic glucose production, alongside a decrease in glucose uptake in skeletal muscle.[80,100] In people without diabetes, caffeine intake before exercise increases plasma glucose concentration (0·5 mmol/L) during moderate-intensity endurance exercise,[101,102] and slightly more (1·0–1·5 mmol/L) after maximal effort time-trials.[95,96] These responses have led to the suggestion that acute caffeine intake might attenuate exercise-associated hypoglycaemia in people with type 1 diabetes.[104] The ingestion of modest amounts of caffeine (200–250 mg, equivalent to three or four cups of coffee) has been shown to augment the symptomatic (ie, increased hypoglycaemia awareness) and hormonal responses (eg, greater catecholamine release) to hypoglycaemia in participants with[105,106] and without[107] type 1 diabetes. Regular caffeine ingestion has also been shown to reduce the frequency of moderate episodes of hypoglycaemia occurring overnight in individuals with long-standing type 1 diabetes.[108]

Just one study has investigated the effects of caffeine on exercise-associated hypoglycaemia in individuals with type 1 diabetes.[81] However, there are no data to support the use of caffeine during the recovery period in athletes living with type 1 diabetes. If caffeine is useful for post-exercise recovery, future research should aim to define the lowest caffeine intake required to reduce the risk of hypoglycaemia because of the need to consider the possible disadvantages, such as impaired sleep quality. The paucity of data on caffeine and exercise in individuals with type 1 diabetes in conjunction with caffeine's popularity, both socially and as a sports supplement, suggest that this factor deserves further attention.

Alcohol

Alcohol is an important factor to consider because anecdotal evidence suggests that some athletes regularly consume large amounts in the post-exercise period, particularly in team sports after a competition. Alcohol intake has substantial effects on carbohydrate metabolism in the liver and muscle, as well as negative effects on fluid balance[77] with important implications for post-exercise recovery.[109] Alcohol has been shown to inhibit glucose uptake into skeletal muscle,[110] decrease the stimulating effect of exercise on muscle glucose uptake[111] and impair glucose use.[112] There is an increased risk of hypoglycaemia when consuming alcohol [78,79] because of the inhibition of hepatic gluconeogenesis,[113] which is aggravated by blunted symptoms of hypoglycaemia[114] and the impairment of cognitive function.[115] Therefore, athletes with type 1 diabetes need to be particularly careful when consuming alcohol in the context of an exercise bout because of the potentially additive risk of severe hypoglycaemia.[116]

Non-nutritional recovery methods

Aside from the nutritional and insulin adjustment strategies, the most common recovery strategies are an active cool down (usually consisting of light aerobic activity),[117] cold water immersion,[118] and massage. In this section, we provide a brief overview of the potential role of these strategies (excluding massage) in the post-exercise routine of an athlete with type 1 diabetes.

Active cool down

Many people regularly have an active cool down, consisting of 5–15 min of low-intensity to moderate-intensity exercise after training or a competition, with the aim of facilitating recovery.[117] Although there are many proposed benefits, such as a faster recovery of heart rate, reduced muscle soreness, and a more rapid reduction of metabolic byproducts,[119,120] only a few benefits are actually supported by research (reviewed by Van Hooren and Peake).[117] Despite uncertainty surrounding the potential benefits of cool down in terms of recovery for those without diabetes, for those living with type 1 diabetes, an active cool down should be considered because this short active phase has the potential to influence blood glucose concentration and therefore might be used to help manage post-exercise glycaemia. For example, if blood glucose concentrations are only slightly elevated (ie, 8–12 mmol/L) at the end of an exercise bout (eg, after high-intensity exercise, or after the ingestion of carbohydrates during exercise), it might be appropriate to do a low-intensity aerobic cool down with the aim of gradually reducing glucose concentration without the need to apply insulin (which might otherwise result in hypoglycaemia). On the other hand, if blood glucose is on the low side or trending down, or both, the cool down can be reduced or eliminated and additional carbohydrates need to be consumed.

Ice baths

Cold water immersion in an ice water bath (also known as cryotherapy) is a common recovery practice.[121] This strategy is used by athletes involved in various sports, with the aim of reducing muscle fatigue and potentially accelerating recovery between exercise sessions. However, there is still much debate on the potential beneficial effects of cold water immersion, with contradicting evidence regarding the effects, with some studies even indicating potentially deleterious effects.[122,123] Although research has shown that cold water immersion does not impair glycogen resynthesis rates after exercise,[124] the potential effect on glycaemia during post-exercise recovery in athletes with type 1 diabetes has not been investigated. Therefore, there is no evidence to support the routine recommendation of cold water immersion in endurance athletes with type 1 diabetes.

Optimising sleep and avoiding nocturnal hypoglycaemia

People with type 1 diabetes tend to have higher rates of sleep disturbances than those without diabetes.[125] Poor sleep has particular negative implications for those with type 1 diabetes, because it has been linked with reduced insulin sensitivity[126] and is associated with poorer glycaemic management.[127,128] Sleep is also crucial for optimal athletic performance and for the regenerative processes and adaptations that take place during training and competition.[129]

In people living with type 1 diabetes, physical activity, especially aerobic exercise, has been shown to increase the risk of nocturnal hypoglycaemia because of an increase in insulin sensitivity.[130–132] Nocturnal hypoglycaemia is often particularly challenging for people with type 1 diabetes, and is associated with a significant risk, with more than 50% of severe hypoglycaemia episodes occurring overnight.[79,133] In a 3-week crossover trial by Reddy and colleagues,[134] actigraphy was used to assess sleep in individuals with type 1 diabetes during periods in which they undertook no exercise, resistance training, or aerobic exercise. Participants slept less on nights after aerobic exercise and there was a trend towards decreased sleep in the resistance training condition compared with a control week with no exercise.

General information relating to napping, sleep extension, and sleep hygiene practices, have been detailed in a review by Fullagar and colleagues.[82] Specifically for athletes with type 1 diabetes, it seems that increasing the time in target glycaemic range is a key component of getting a good night's sleep. There are studies that have investigated the effects of a pre-bedtime snack on reducing the risk of nocturnal hypoglycaemia,[135–136] but with mixed results as to the effectiveness. More recently, technology for diabetes management, including advances in closed loop systems, have shown improvements in glycaemic variability and time in range overnight.[85,137,138]

The potential for technology to aid post-exercise recovery

A wide variation in training and nutrition plans, insulin requirements, and experience an individual has with managing their glycaemia in different situations, strongly suggest that there will never be a one size fits all set of guidelines that can be applied to every athlete with type 1 diabetes. What is consistent between individuals, however, is the large number of decisions that can influence glucose management and general health. Following the diagnosis of type 1 diabetes, an individual is launched into a process of decision making that becomes part of their daily life. It has been estimated that people with type 1 diabetes make as many as 600 decisions per day to manage their diabetes.[139] Self-adjusted insulin dosing is complex because it involves recalling the time and amount of a dose while the insulin is still active, as per the pharmacokinetics of insulin and the temporal relationship of these doses to any recently ingested food. Physical activity presents additional challenges, with most decision making based on personal trial and error rather than input from medical professionals.[140] Therefore, developing decision support tools that are adaptable and easy to follow, that can be adjusted according to each individual's needs, are likely to be useful for improving not only performance but also blood glucose management and exercise participation.

Rapid developments in technologies such as CGM sensors, smart devices or wearables, and closed-loop systems, all contribute to the possibility of an increased time in range around exercise with less input by the user (figure 4). The use of increasingly accurate and reliable CGM technology has greatly improved knowledge of the glycaemic responses to exercise, even during the nocturnal period,[62,141,142,144] thereby positively affecting post-exercise recovery. CGM technology has also been essential in the ongoing development of artificial pancreas systems with the use of closed-loop automated insulin delivery.[142] These systems combine sensor glucose measurement with insulin pumps with the use of an algorithm to direct insulin delivery.[85,145–147] Next-generation closed-loop systems that are under investigation integrate other signals such as heart rate, skin conductance, ventilation rate, and body temperature, and add other hormones such as glucagon, to help increase time in the target glycaemic range during and after exercise.[145–148] Hybrid closed-loop systems offer benefits for improved time in the glycaemic target range overnight, even under demanding environmental and unplanned conditions.[85,146,147,149] In the future, innovative algorithmic and machine learning (artificial intelligence) approaches are likely to further facilitate decision support.[145] Such technology might also help to reduce some of the psychological toll and cognitive burden that type 1 diabetes can have on the individual because of constantly having to calculate meal or correction boluses and account for differences in insulin sensitivity during or after exercise.[150] Therefore, appropriate guidance and support should be given to individuals interested in using these technologies, so that they are used to their maximum potential.

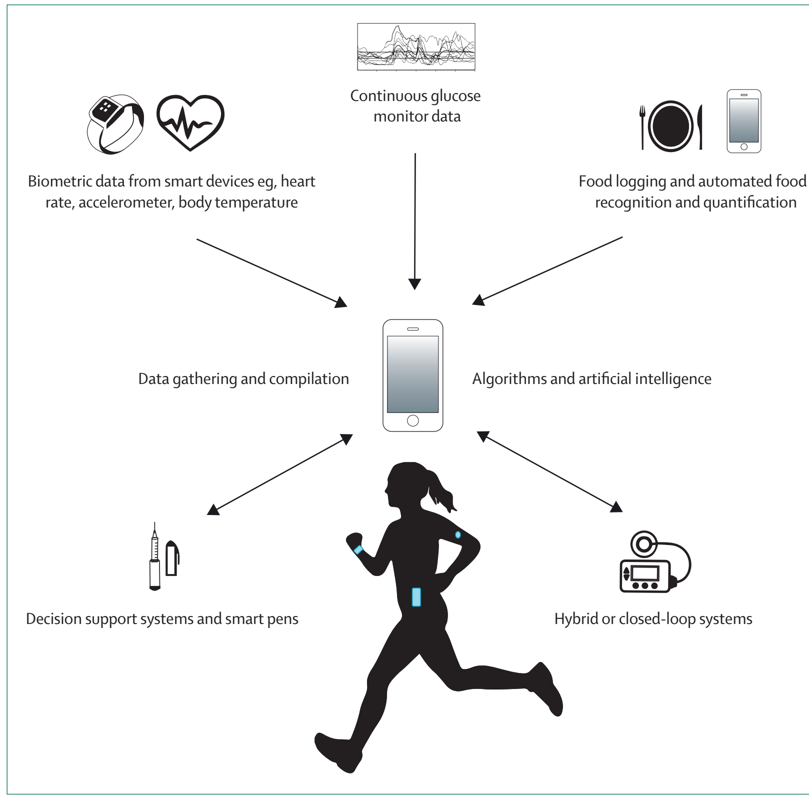

Figure 4: **Example of a connected virtual ecosystem to aid the decision making processes for optimised post-exercise glycaemia and recovery in people with type 1 diabetes**
Researchers, clinicians, sports coaches, and athletes with type 1 diabetes are increasingly integrating different data sources to facilitate the decision making behaviours related to glycaemia, training, and nutrition to meet energy requirements. The rapid development of hybrid closed-loop systems is also helping to make insulin delivery more automated.[141,142,143] It is important to note that athletes without diabetes are also using similar data tools (eg, glucose monitoring, food logging apps, wearables) to make decisions about their training and nutrition practices.

Limitations

Limitations of this Review include the paucity of published research done over the post-exercise period in people living with type 1 diabetes, meaning that many of the statements are based on our opinion and experience. We also acknowledge that there is little research that has been done in female athletes living with type 1 diabetes, and that this should be a key focus area in the future. We acknowledge the inadequate number of women among the authorship and are aware that including a more diverse group of researchers would be beneficial. The working group for the study of Integrative Biology of Exercise in diabetes is fully open to inviting additional people to join this new working group and are in the process of asking female scientists to join, who would then have the opportunity to contribute to future works generated by this working group.

Conclusions

The post-exercise recovery phase is an important, and yet somewhat unexplored, topic for athletes with type 1 diabetes. Regardless of the athlete's sport or competition level, it is clear that many different behaviours will have an

Search strategy and selection criteria

We identified references for this Review through searches of PubMed, Google Scholar, and Web of Science for articles containing the terms "type 1 diabetes" or "insulin-dependent diabetes" and "exercise", "post-exercise", or "physical activity", published from Feb 7, 1967 to Dec 23, 2020, and restricted to publications in the English language. Additional searches were done with the following terms for various subtopics within this Review: "nutrition", "carbohydrate", "protein", "fructose", "caffeine", "glycogen", "active cool down", "alcohol", "cold water immersion", "ice baths", "dietary protein", "glycaemic index", "energy expenditure", "glycaemic control", "management", "hypoglycaemia", "hyperglycaemia", "hydration" "sleep", "technology", "decision", "decision-making", or "prevention and control".

effect on short-term and long-term recovery, and thus affect the subsequent performance, training adaptation, and time in the target glycaemic range. Athletes with type 1 diabetes should always prioritise blood glucose management, which is essential for overall health and to optimise aspects of recovery. However, the unique ability of people living with type 1 diabetes to influence their insulin concentration through exogenous administration suggests that greater planning and attention is needed to optimise nutrition and insulin strategies for glycogen resynthesis.

Contributors

SNS did the literature search. All authors (SNS, FYF, MC, JPM, RD, JFPW, JJ, RC, MCR, AJ, and CS) contributed to the original draft of the manuscript. SNS, FYF, MC, MRC, and CS edited the revised manuscript. All authors approved the final submission.

Declaration of interests

JPM reports personal fees from Science in Sport, outside the submitted work. AJ is involved with and receives a consulting fee from Neverseond (which makes sports nutrition products for athletes). JFPW has research collaborations with Pfizer and Novo Nordisk, outside the submitted work. MCR reports personal fees from Zucara Theraputics, Zealand, Lilly Diabetes, Novo Nordisk, and Sanofi; and grants from Insulet, outside the submitted work. All other authors declare no competing interests.

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