

**DETERMINATION OF A LOW GLYCAEMIC
INDEX PRE-EXERCISE RICE-BASED MIXED
MEAL AND ITS EFFECT ON ENDURANCE
EXERCISE PERFORMANCE IN A HEAT STRESS
ENVIRONMENT**

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EXERCISE PERFORMANCE IN A HEAT STRESS
ENVIRONMENT**

by

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LIST OF SYMBOLS

%	percent
~	approximate
+	plus
<	less than
=	equal to
>	greater than
±	plus minus
°C	degree Celsius
b.min ⁻¹	beat per min
cm	centimetre
g.kg ⁻¹	gram per kilogram
kcal	kilocalorie
kg	kilogram
km	kilometre
km.h ⁻¹	kilometre per hour
km.week ⁻¹	kilometre per week
L.hr ⁻¹	litre per hour
m	metre
mL	millilitre
mL.hr ⁻¹	millilitre per hour
mL.kg ⁻¹ .min ⁻¹	millilitre per kilogram per min
mm	millimetre

LIST OF ABBREVIATIONS

ACSM	American College of Sports Medicine
ANOVA	analysis of variance
ATP	adenosine triphosphate
AU	arbitrary unit
BIA	bioelectric impedance analysis
BMI	body mass index
BMR	basal metabolic rate
CHO	carbohydrate
CV	coefficient of variation
<i>d</i>	absolute error of precision
df	degree of freedom
et al.	and others
EI	energy intake
GI	glycaemic index
HGI	high glycaemic index
HH	hot-humid
HIIT	high intensity intermittent exercise
HR	heart rate
hr	hour
iAUC	incremental area under the curve
ISO	International Standards Organization
LGI	low glycaemic index
min	minute
PPGR	postprandial glucose responses
RDS	rapidly digestible starch
RER	respiratory exchange ratio
RH	relative humidity
RNI	recommended nutrient intakes
RPE	rating of perceived exertion
RS	resistant starch
rpm	revolution per min

s	second
SD	standard deviation
SDS	slowly digestible starch
SEM	standard error of mean
SS	steady-state
SPSS	statistical package for social science
T_{re}	rectal temperature
T_{sk}	skin temperature
TDEI	total daily energy intake
TN	thermoneutral
TT	time-trial
TT _{10km}	10 km time-trial
TTE	time to exhaustion
USG	urine specific gravity
$\dot{V}CO_2$	volume of carbon dioxide
$\dot{V}O_2$	volume of oxygen
$\dot{V}O_{2max}$	maximum oxygen consumption
$\dot{V}O_{2peak}$	peak oxygen consumption
% $\dot{V}O_{2max}$	percentage of maximum oxygen consumption

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**PENENTUAN MAKANAN CAMPURAN PRA-SENAMAN BERASASKAN
NASI DENGAN INDEKS GLISEMIK RENDAH DAN KESAN TERHADAP
PRESTASI SENAMAN KETAHANAN DALAM PERSEKITARAN
TEKANAN HABA**

ABSTRAK

Makanan pra-senaman dengan indeks glisemik rendah telah dibuktikan boleh meningkatkan prestasi senaman ketahanan dalam persekitaran termoneutral. Pada masa ini, maklumat sedia ada tentang makanan indeks glisemik rendah secara hidangan campuran berasaskan diet Asia adalah terhad. Di samping itu, sumbangan makanan indeks glisemik rendah secara hidangan campuran berasaskan diet Asia untuk meningkatkan prestasi senaman ketahanan dalam persekitaran tekanan haba masih belum dikaji secara meluas. Berdasarkan kekurangan maklumat berkaitan dengan hidangan campuran berasaskan diet Asia terhadap prestasi senaman ketahanan dalam persekitaran tekanan haba, satu siri kajian telah dijalankan. Kajian pertama dijalankan untuk mengenal pasti pengambilan pemakanan atlet ketahanan Malaysia ($n = 85$) dan pemilihan makanan yang selalu diambil oleh atlet. Kajian kedua dijalankan untuk menentukan nilai indeks glisemik makanan campuran berasaskan nasi, yang mana menu hidangan adalah berdasarkan makanan yang selalu diambil oleh atlet. Kajian ketiga dijalankan untuk menentukan kesan hidangan campuran indeks glisemik rendah berasaskan nasi yang diambil ketika pra-senaman terhadap prestasi senaman ketahanan dalam persekitaran tekanan haba di kalangan pelari ketahanan terlatih ($n = 12$). Kajian pertama menunjukkan bahawa 51% daripada peserta memenuhi had minimum untuk pengambilan karbohidrat ($6 \text{ g.kg}^{-1}.\text{hari}^{-1}$). Untuk pengambilan protein, 88% peserta telah melepasi had minimum $1.2 \text{ g.kg}^{-1}.\text{hari}^{-1}$. Had minimum

pengambilan lemak (20% daripada jumlah pengambilan tenaga harian) dipenuhi oleh 99% peserta. Makanan tempatan yang biasa dimakan adalah makanan hidangan campuran yang terdiri daripada nasi, ayam, dan sayur-sayuran berdaun hijau. Kajian kedua menunjukkan hidangan campuran berasaskan nasi yang terdiri daripada beras Basmati, ayam goreng, dan sayur tumis berdaun hijau boleh diformulasi menjadi hidangan indeks glisemik rendah (nilai indeks glisemik = 47). Dalam kajian ketiga, para peserta berlari lebih pantas semasa ujian masa 10 km (TT_{10km}) dalam persekitaran panas lembap selepas mengambil hidangan campuran indeks glisemik rendah berasaskan nasi berbanding hidangan campuran indeks glisemik tinggi berasaskan nasi (LGI: 55.18 ± 1.22 vs. HGI: 57.03 ± 2.25 min, $p = 0.010$). Kesimpulannya, pengambilan makanan berasaskan makanan tempatan adalah mencukupi untuk membekalkan tenaga, protein dan lemak kepada atlet ketahanan Malaysia. Ia memberikan bukti yang meyakinkan bahawa atlet ketahanan tempatan boleh memperoleh nutrien yang mencukupi daripada makanan tempatan apabila berlatih dalam persekitaran panas lembap (32°C , 65% relatif kelembapan). Penemuan baharu ini menekankan bahawa hidangan campuran indeks glisemik rendah berasaskan nasi yang diambil ketika pra-senaman boleh mengurangkan kesan yang melemahkan latihan ketahanan yang berpanjangan dalam persekitaran tekanan haba.

**DETERMINATION OF A LOW GLYCAEMIC INDEX PRE-EXERCISE
RICE-BASED MIXED MEAL AND ITS EFFECT ON ENDURANCE
EXERCISE PERFORMANCE IN A HEAT STRESS ENVIRONMENT**

ABSTRACT

The pre-exercise low glycaemic index (LGI) meal has been shown to enhance endurance exercise performance in a thermoneutral environment. Limited information is currently available on the LGI mixed meal based on the Asian-based diet. Furthermore, the contribution of this Asian-based LGI mixed meal in enhancing endurance exercise performance in a heat stress environment has yet to be widely examined. Based on this lack of information relating to the Asian-based mixed meal on endurance exercise performance in a heat stress environment, a series of studies were conducted. The first study was conducted to identify the dietary intakes of Malaysian endurance athletes ($n = 85$) and the selection of foods that the athletes commonly consumed. The second study was carried out to determine the glycaemic index (GI) value of rice-based mixed meals, whereas the menu was based on the foods the athletes commonly consumed. The third study was conducted to determine the effect of pre-exercise LGI rice-based mixed meals on endurance exercise performance in a heat stress environment among trained endurance runners ($n = 12$). The first study indicated that 51% of the participants met the minimum recommendations for carbohydrate intake ($6 \text{ g.kg}^{-1}.\text{day}^{-1}$). For protein intake, 88% of participants had surpassed the lower limit of $1.2 \text{ g.kg}^{-1}.\text{day}^{-1}$. The lower limit of fat intake (20% of total daily energy intake) was met by 99% of the participants. The commonly consumed local foods were mixed meals consisting of rice, chicken, and green leafy vegetables. The second study showed that the rice-based mixed meal consisting of Basmati rice,

fried chicken, and stir-fried green leafy vegetables can be formulated into an LGI meal (GI value = 47). In the third study, the participants ran faster during a 10-km time trial (TT_{10km}) in hot-humid conditions after consuming the LGI rice-based mixed meal compared to the high glycaemic index (HGI) rice-based mixed meal (LGI: 55.18 ± 1.22 vs. HGI: 57.03 ± 2.25 min, $p = 0.010$). In conclusion, the dietary intake based on local foods was sufficient to provide the energy, protein, and fat intake of Malaysian endurance athletes. It provided convincing evidence that local endurance athletes can obtain sufficient nutrients from local foods when training in hot-humid conditions (32°C , 65% relative humidity). This novel finding highlighted that the pre-exercise LGI rice-based mixed meal can reduce the debilitating effects of prolonged endurance training in a heat stress environment.

CHAPTER 1

INTRODUCTION

1.1 Background and scope of the research

Nutrition is one of the most important factors in sustaining prolonged endurance performance (Martinez-Sanz et al., 2020; Ravindra et al., 2022) and is closely linked to the dietary intake patterns of endurance athletes (Naderi et al., 2023). The published guidelines by the Academy of Nutrition and Dietetics, Dietitians of Canada, and the American College of Sports Medicine (Thomas et al., 2016) and the International Society of Sports Nutrition (Kerksick et al., 2018) have highlighted the importance of fulfilling the energy, macronutrients, and micronutrients requirements for achieving optimum athletic performance. However, there have been numerous studies indicating that endurance athletes often lack the necessary nutrients, which has been observed across different populations (Beermann et al., 2020; Mielgo-Ayuso et al., 2020; Moss et al., 2023; Noh et al., 2020; Wardenaar et al., 2017). The evidence for this inadequacy is supported by the insufficient serving sizes of food from various food groups (Nunes et al., 2018; Pelly & Thurecht, 2019). The understanding of a selection of foods commonly practised by endurance athletes is a crucial factor in achieving optimal nutrient intake to enhance endurance performance.

A study conducted among highly trained distance runners at a National Collegiate Athletic Association in the United States demonstrated that their carbohydrate (CHO) intake was lower than the recommended minimum of $6 \text{ g.kg}^{-1} \text{.day}^{-1}$ (Beermann et al., 2020). Moss et al. (2023) showed that 95.8% of trained endurance athletes in the United States did not meet the CHO recommendation, and the majority of them had inadequacy of several micronutrients, namely, vitamin D, E,

magnesium, and potassium. Likewise, a study by Noh et al. (2020) in Malaysia among university endurance athletes showed the inadequacy of CHO intake, evidenced by the intake of $6.06 \pm 2.07 \text{ g.kg}^{-1}.\text{day}^{-1}$ and $5.73 \pm 1.99 \text{ g.kg}^{-1}.\text{day}^{-1}$ for male and female athletes, respectively.

CHO is the primary source of energy during prolonged endurance exercise (Burke, 2010; Ravindra et al., 2022). Several stages of CHO intake prior to exercise have been outlined (Burke et al., 2019), emphasising the crucial role of CHO in providing a constant supply of glucose during prolonged high-intensity endurance exercise. It supplied up to 90% of the energy expenditure for elite marathon runners who were running at a speed corresponding to 80-90% of maximum oxygen consumption ($\dot{V}O_{2\text{max}}$) (Stellingwerff, 2013). There are various dietary sources of CHO, such as rice, pasta, potatoes, oats, lentils, bananas, raisins, and oats, whereas each of them has distinct impacts on postprandial glucose response. Some CHO sources caused an elevation of insulin levels and reduced fat oxidation, potentially leading to a fast depletion of glycogen storage, resulting in early fatigue (Moitzi & König, 2023). This was attributed to the distinct nutrient composition of the respective food items (Naderi et al., 2023). Thus, the quality of pre-exercise CHO, which refers to the glycaemic index (GI) of CHO, is crucial in order to achieve favourable metabolic responses (Augustin et al., 2015; Ormsbee et al., 2014).

The GI is a property of the CHO-containing foods, which is attributed to the blood glucose-raising ability of the digestible CHO. It compares the glycaemic response after ingesting CHO in the food items to that of the similar quantity of CHO from a reference food, which is glucose or bread. The GI of foods is categorised into three categories, namely low (GI value ≤ 55), medium (GI value = 56 – 69), and high

(GI value \geq 70) (Brouns et al., 2005; Wolever et al., 2003). Low GI (LGI) foods are those containing CHO that are digested and absorbed at a slower rate as compared to high GI (HGI) foods, resulting in a gradual rise in blood glucose and insulin concentration. In contrast, HGI foods resulted in postprandial hyperglycaemia, which led to elevated insulin levels in the blood (Brouns et al., 2005; Wolever, 2013). The metabolic response facilitated by LGI through the sustaining of plasma glucose and CHO availability would be advantageous for prolonged endurance exercise. While hyperinsulinaemia as demonstrated after consuming HGI reduced the fat oxidation rate, leading to rapid glycogen depletion, thus negatively impacting endurance exercise performance (Burdon et al., 2017; Heung-Sang Wong et al., 2017; Moitzi & König, 2023; Shin et al., 2013).

The GI concept and its relation to endurance exercise performance have been investigated by many researchers (Burdon et al., 2017; Heung-Sang Wong et al., 2017) over the last three decades. The first study conducted in 1991 among trained cyclists revealed that the consumption of 1 g of available CHO per kilogram of body mass of lentils (GI value = 29) 60 min before exercise at 65 – 70% $\dot{V}O_{2\max}$ significantly prolonged the time to exhaustion (TTE) compared to consuming potatoes (GI=98) (Thomas et al., 1991). The improvement in endurance exercise performance was attributed to the ability of LGI as a fuel source as reflected in elevated plasma glucose and fat oxidation rate during prolonged exercise.

The systematic reviews on the effects of pre-exercise GI meals on endurance exercise performance revealed that many studies utilised individual food items, pre-packaged meals, and snacks (Burdon et al., 2017; Heung-Sang Wong et al., 2017). Many of these foods were based on the Western diet and were investigated among the

Western athletes population (Bennett et al., 2012; Moore et al., 2013). It was shown that very few studies employed the Asian diet as a dietary intervention, specifically rice-based mixed meals (Hulton et al., 2012). Studies conducted among Japanese athletes (Fujita et al., 2020) and Malaysian athletes (Noh et al., 2020) found that the primary sources of CHO intakes were white rice and noodles, commonly consumed together with sources of protein and vegetables, in the form of mixed meals. The mixed meal concept offers the consumption of various sources of foods in a set of meals, which cannot be obtained from a single food item. This will enable the fulfilment of various nutrients for optimum athletic performance as advocated in the published guidelines (Kerksick et al., 2018; Thomas et al., 2016), and promote favourable metabolic responses specifically related to postprandial glycaemic response (Alsalim et al., 2016).

Furthermore, data are scarce regarding the GI of Asian mixed meals, particularly rice-based mixed meals, as evidenced in a few review studies (Henry et al., 2021; Kaur et al., 2016; Osman et al., 2021). The lack of this evidence restricts the applicability of the Asian diets with respective GI values to endurance exercise performance. Therefore, it warrants determining the GI values of rice-based mixed meals, and further investigating their effects on endurance exercise performance.

The improvement in endurance exercise performance following pre-exercise LGI consumption was based on studies carried out in a thermoneutral environment (TN) (temperature between 20°C – 23°C and relative humidity (RH) between 48% - 64%) (Burdon et al., 2017). The LGI has the capacity to enhance fat oxidation and preserve CHO for the later stage of exercise, hence enhancing endurance performance (Heung-Sang Wong et al., 2017; Moitzi & König, 2023). Limited data is currently

available to provide insight into whether similar benefits are recorded during exercise in a heat stress environment (Otsuka et al., 2021; Takada et al., 2022). In a heat-stress condition, the rate of CHO metabolism is increased (López-Torres et al., 2023), leading to a more rapid depletion of glycogen storage. This can result in the early onset of muscular fatigue during prolonged endurance performance (Peel et al., 2021). In an attempt to enhance endurance exercise performance in heat, it has been recommended that athletes consume sufficient pre-exercise foods that can supply continuous sources of CHO throughout the prolonged endurance exercise (Naderi et al., 2023). With the ability of the LGI food to gradually release and maintain glucose concentration levels during prolonged endurance exercise (Moitzi & König, 2023), the potential benefits of pre-exercise LGI in enhancing endurance exercise performance in a heat stress condition warrant further investigation.

Based on the lack of research relating to the consumption of LGI Asian-based food in a mixed meal approach, it is necessary to carry out systematic evaluation on the matter. In addition, it is necessary to examine the effect of this LGI Asian-based mixed meal consumption towards enhancing endurance exercise performance in a heat stress environment. Hence, a series of research studies were designed to determine a pre-exercise LGI rice-based mixed meal based on the selection of foods commonly consumed by the endurance athletes and investigate its effect during prolonged endurance exercise performance in a heat stress environment.

1.2 Statement of problem

Literature showed limited studies investigating the dietary intakes of Asian endurance athletes, particularly in terms of the adequacy and selection of foods that endurance athletes commonly consume (Capling et al., 2017; Heydenreich et al., 2017;

McGuire et al., 2020). Studies have demonstrated that pre-exercise LGI meals can enhance endurance performance in a TN condition (Heung-Sang Wong et al., 2017; Moitzi & König, 2023). However, the utilisation of Asian based diet in the form of mixed meals was scarce (Burdon et al., 2017; Heung-Sang Wong et al., 2017). Nevertheless, limited evidence demonstrates the ergogenic benefits of a LGI pre-exercise meal on endurance exercise performance in a challenging environment of a hot and humid condition. In order to mitigate the impact of heat stress, it is necessary to ensure that the pre-exercise meal is capable of providing a consistent supply of fuel, mainly CHO throughout prolonged periods of endurance exercise. Thus, the ability of pre-exercise LGI local mixed meal to sustain CHO during prolonged endurance exercise performance warrants further investigation in a heat stress condition. Hence, a systematic study to identify the foods that endurance athletes commonly consume, followed by the determination of a pre-exercise LGI rice-based mixed meal and its effect on endurance exercise performance in a heat stress environment was carried out in this research project.

1.3 Research aims

The primary objectives of this research project are:

- i. To identify the trained endurance athletes' dietary intakes and the selection of local Malaysian foods that the participants commonly consumed.
- ii. To determine the GI value of rice-based mixed meals based on the foods that the trained endurance athletes commonly consumed.

- iii. To determine the effect of pre-exercise LGI rice-based mixed meals on endurance exercise performance in a heat stress environment among trained endurance runners.

1.4 Significance of the research

This research demonstrated the dietary intakes and selection of foods by endurance athletes who were practicing an Asian-based diet. The determination of GI value of rice-based mixed meals that were based on the commonly consumed foods added data to the international GI databases, specifically focusing on Asian-based diets and mixed meal foods. The utilisation of pre-exercise LGI and HGI rice-based mixed meals prior to prolonged endurance exercise in a heat stress environment provided the model of rice-based mixed meals with specific GI values that can enhance endurance performance. The dietary intervention approach that employed a Malaysian rice-based mixed meal as a main meal prior to exercise training reflects a realistic scenario commonly observed in the Malaysian athletes' population. This is in line with the findings from the early phase of the present study, which showed that rice consumed with protein sources and vegetables was the common choice of foods among Malaysian endurance athletes. Hence, the findings of this research project have contributed novel insights to the field of sports nutrition, encompassing both theoretical and practical aspects.

1.5 Conceptual framework

Figure 1.1 illustrates the conceptual framework of the study. This study focused on the effect of pre-exercise LGI rice-based mixed meal on endurance exercise performance in a heat stress environment. Exercise in a heat stress environment has been shown to impair endurance performance (Bennett et al., 2024). The mechanism

of reduction in exercise capacity and performance with heat stress condition was due to the cardiovascular and thermoregulatory strains (Charoensap et al., 2023; Kamaruddin et al., 2023) and changes in substrate metabolism towards higher CHO utilisation (Bennett et al., 2023; Maunder et al., 2020; Rosbrook et al., 2024).

Several factors affect exercise performance, namely, physical fitness, nutritional status, general health status, exercise training, psychological state (Duan et al., 2024), physiological state, sex (Santisteban et al., 2022), genetics (Varillas-Delgado et al., 2022), and environmental factors (Lei & Wang, 2021). This study focused on the effect of pre-exercise dietary intake on endurance exercise performance in a heat stress environment. Specific nutritional considerations to ensure optimum substrate availability and hydration are crucial to mitigate the debilitating effects of heat stress (Bennett et al., 2024).

Sufficient macro- and micronutrients are required to enhance endurance exercise performance in a heat stress environment (Kerksick et al., 2018; Thomas et al., 2016). In addition to adequate nutrient intake, it is crucial to emphasise the quality of CHO, namely, the GI of the meals. It was shown that the consumption of pre-exercise LGI meals in a TN can enhance endurance exercise performance (Heung-Sang Wong et al., 2017; Moitzi & König, 2023). However, limited evidence was available regarding ingesting pre-exercise LGI in the form of mixed meals on endurance exercise performance, particularly in a heat stress environment (Burdon et al., 2017; Heung-Sang Wong et al., 2017) which warrants further investigation in this field.

In order to achieve the objectives of this study, the pre-exercise LGI mixed meals based on the commonly consumed foods of the locally trained endurance

athletes were determined prior to the experimental dietary intervention in a heat stress condition among trained endurance runners. On these notes, this study aimed to determine a pre-exercise LGI rice-based mixed meal and its effect on endurance exercise performance in a heat stress environment.

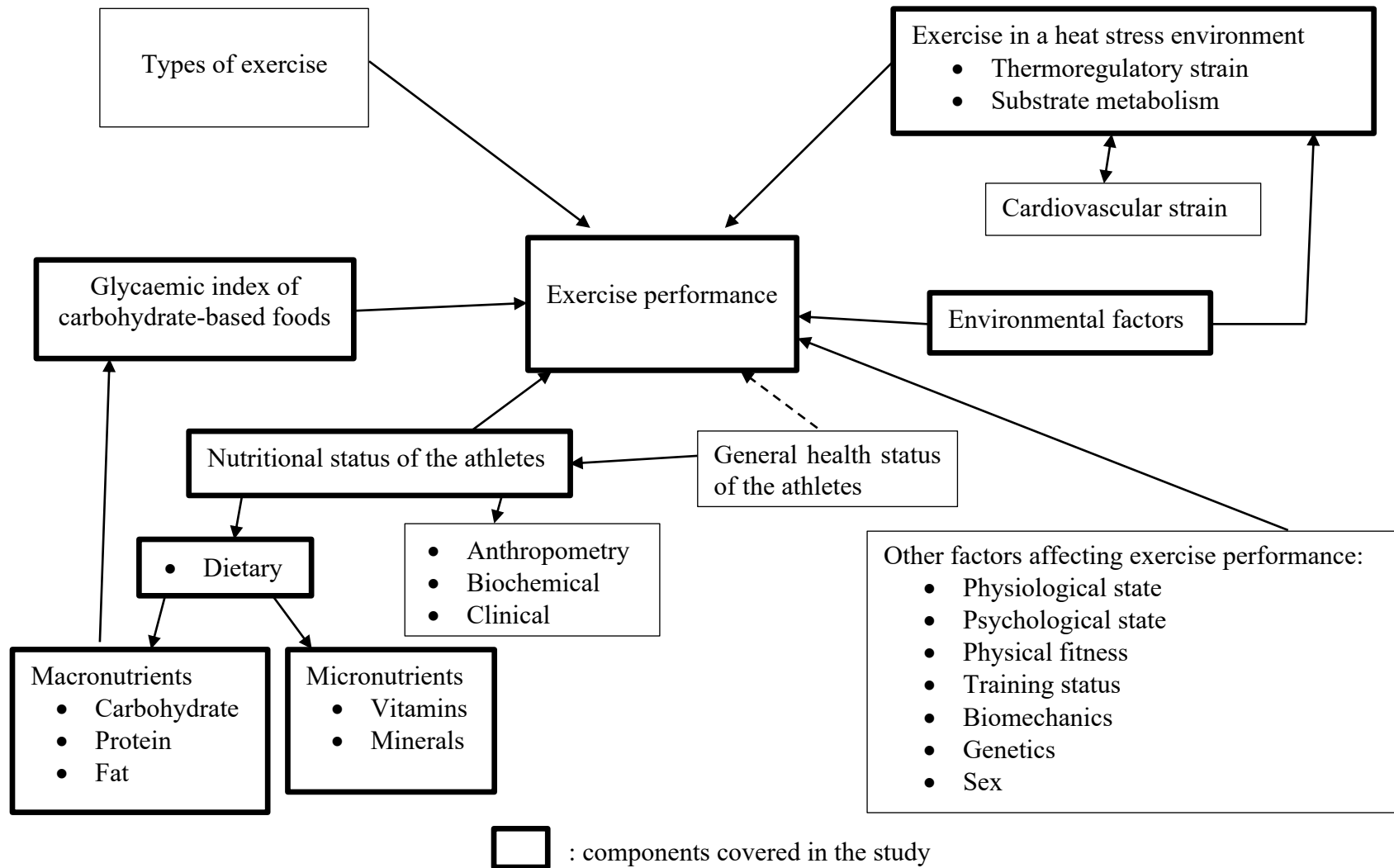


Figure 1.1 Conceptual framework of the study

CHAPTER 2

LITERATURE REVIEW

2.1 Nutrition in endurance exercise performance

2.1.1 Energy pathways in endurance exercise

Exercise is fuelled by anaerobic (phosphagen and glycolytic) and aerobic (fat and CHO oxidation) pathways of the energy system (Hargreaves & Spriet, 2020). The phosphagen pathway offers a rapid energy source for muscle contraction. However, it cannot provide a sustained energy supply for more than ~10-s. The anaerobic glycolytic pathway efficiently metabolises glucose and muscle glycogen through the glycolytic cascade. It is the main pathway that provides energy for high-intensity exercise lasting between 10 to 180-s (Figure 2.1).

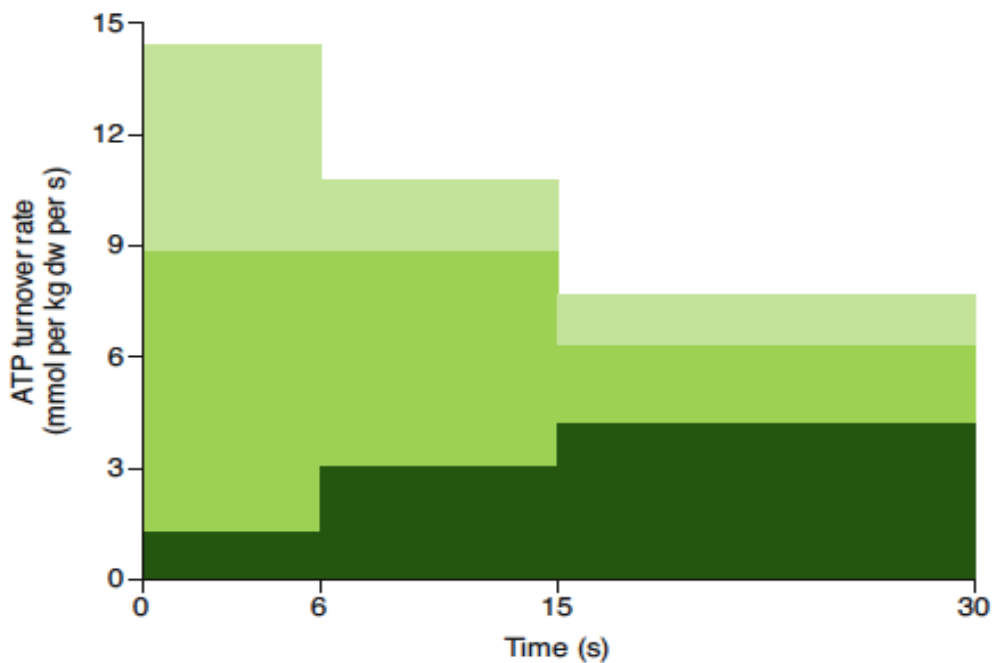


Figure 2.1 Muscle energy metabolism during intense exercise
Contribution of phosphocreatine (light green), glycolysis (medium green) and oxidative phosphorylation (dark green) to ATP turnover during maximal exercise. dw = dry weight. Adapted from Hargreaves & Spriet (2020).

Due to the inability of the phosphagen and the glycolytic pathways to supply fuel for muscle contraction during longer-lasting events, in events more than ~2 min, the primary source of fuel was provided through the aerobic pathway (Alghannam et al., 2021). The primary sources of energy are glycogen stored in the muscle and liver, lipids stored within muscle tissue, triglycerides stored in adipose tissue, as well as amino acids derived from the liver, muscle, gut, and blood (Figure 2.2). As the availability of oxygen increases, the body relies increasingly on aerobic pathways and reduces its reliance on anaerobic routes such as phosphagen and glycolytic processes (Spriet, 2014).

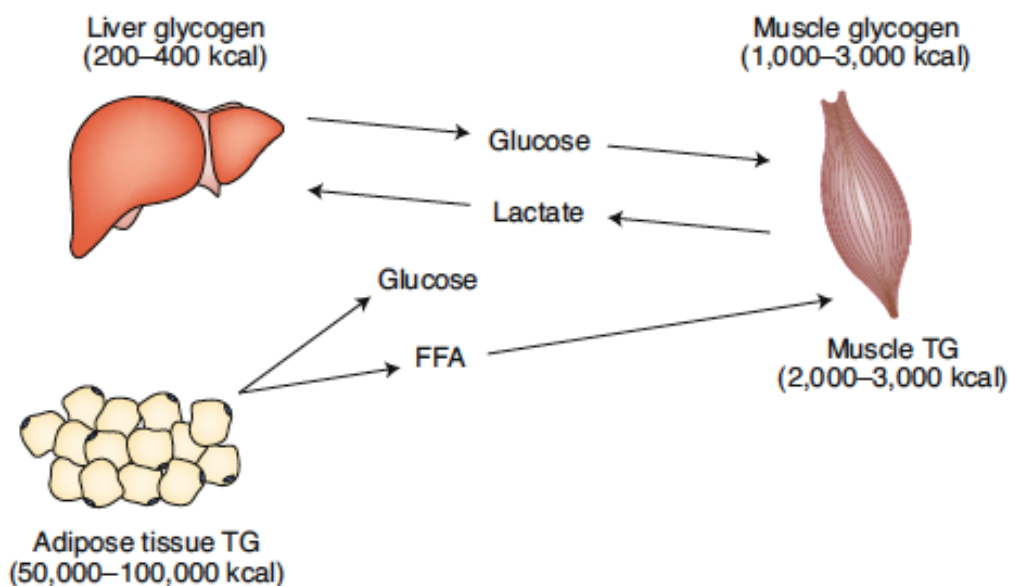


Figure 2.2 Intramuscular and extramuscular fuel sources for exercise
TG = triglyceride; FFA = free fatty acids. Adapted from Hargreaves & Spriet (2020).

During high-intensity endurance exercise, the contraction of skeletal muscles relies on CHO oxidation, specifically muscle glycogen. This is because CHO provides a higher output of energy per unit of time, resulting in an increasing dependence on glycogen and glucose (Alghannam et al., 2021). Conversely, at lower exercise intensity, fat oxidation is more pronounced. The most efficient fat oxidation occurs at

exercise intensity around 60-65% of $\dot{V}O_{2max}$ (Achten & Jeukendrup, 2003). This is because the mechanisms responsible for delivering fatty acids to the muscles and the metabolic pathways that break down fat and produce adenosine triphosphate (ATP) in the muscles are slower than the CHO pathways. However, during extended durations of submaximal exercise, fat can serve as a source of energy for prolonged periods and possesses a significantly greater ability to generate ATP than CHO (Hargreaves & Spriet, 2020).

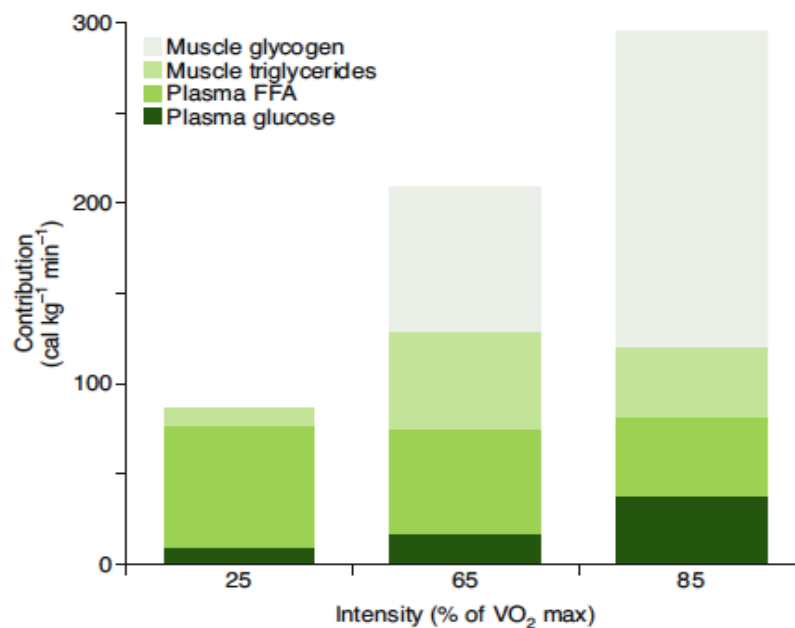


Figure 2.3 Relative contributions of carbohydrate and fat fuel sources during different exercise intensities
 FFA = free fatty acids; cal = calorie. Adapted from Hargreaves & Spriet (2020).

In endurance events lasting 2 - 2.5 hrs, participated by high-performance athletes, the exercise intensity was higher, approaching 80 - 100% $\dot{V}O_{2max}$. In these situations, the primary fuel used is CHO, and the reliance on fat is less (Hawley & Leckey, 2015). This is because the production of energy from CHO is more efficient than that from fat. CHO oxidation yields greater power output, but lesser capacity than fat oxidation. In the extended endurance event or training, the liver and skeletal muscle

glycogen storage may become exhausted, causing a decrease in power output, which requires athletes to slow down. The episodes of hypoglycaemia and fatigue occur, thus, nutrition intervention through CHO ingestion was able to mitigate the fatigue episodes (Hargreaves & Spriet, 2020; Spriet, 2014).

The relative contribution of energy pathways is determined by several factors, including the type of training, intensity, duration, frequency, sex, individual level of fitness, prior nutritional intake, and substrate availability (Alghannam et al., 2021; Thomas et al., 2016) Therefore, the nutritional guidelines on the amount and timing of energy, macro-, and micronutrients intake for the athletic performance should be in line with the understanding of how the interactions between training and nutrient influences energy pathways, availability of substrate, and training adaptations.

2.1.2 Pre-exercise nutrition for endurance exercise performance

The nutrition strategies for endurance athletes should align with the physiological demands and biochemical changes experienced by the athletes. Nutrition plans for athletes need to be individualised, considering the performance goals, training intensity, food preferences, and practical challenges. The aim of nutrition strategies prior to training and competition is to provide sufficient fuel for optimum exercise performance (Thomas et al., 2016). This is crucial to reduce premature fatigue during prolonged training and competition, especially in a challenging environment such as hot-humid (HH) condition. Burke et al. (2019) highlighted that the physiological and nutritional limitations to performance in endurance running were mainly fatigue related to glycogen depletion. The CHO loading approach has been shown to minimise the decline in speed, usually at the late stage of training and competition, thus enhancing exercise performance. Besides CHO, protein, fat, and micronutrients have unique roles in enhancing athletic performance.

CHO is a primary fuel for the muscle and central nervous system during exercise at various intensities, as it can be utilised by both anaerobic and aerobic pathways (Thomas et al., 2016). However, CHO reserves are limited to prolonged continuous exercise (Spriet, 2014). The depletion of muscle glycogen resulted in early fatigue and reduced exercise intensity (Burke, Jones, et al., 2019). Inadequate CHO also impairs the function of the central nervous system, which is crucial in regulating the perceptions of fatigue, motor skills, and focus (Spriet, 2014). The pre-exercise CHO intake must consider the metabolic effects of high insulin release, resulting in reduced fat oxidation and increased CHO oxidation, which can cause premature fatigue in some individuals. One of the approaches suggested is the selection of pre-exercise meals LGI CHO-rich foods. This approach may help to minimise the hyperglycaemic effects after consuming CHO foods and provide a more consistent release of CHO throughout the exercise (Moitzi & König, 2023).

Protein is essential for athletes to maintain and improve skeletal muscle mass, leading to improved performance, increased muscle size, and faster recovery (Amawi et al., 2024). The structural constituents of proteins, namely amino acids, provide the building blocks for all tissues. Protein consumption among athletes involved in vigorous exercise or competitions is crucial to rebuilding and restoring skeletal muscle and connective tissues. The quantity, time, and protein consumption type influence the degree of muscle remodelling. Consuming protein together with CHO within 3 to 4 hrs before exercising can aid in preserving muscular growth and improving muscle recovery (Jäger et al., 2017). The theoretical framework on the protein intake for athletes is presented in Figure 2.4.

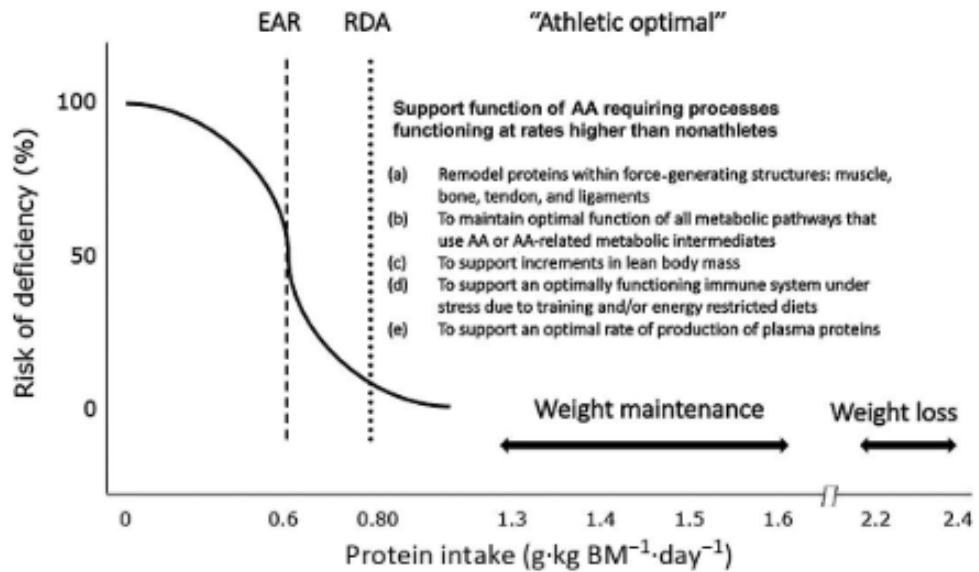


Figure 2.4 Framework on the dietary protein intake recommendation for athletes. AA = amino acid; EAR = estimated average requirement; RDA = recommended daily allowance; BM = body mass. Adapted from Witard et al. (2019).

Fat is one of the macronutrients essential in providing energy, building blocks for cell membranes, and facilitating the absorption of fat-soluble vitamins. The fat intake recommendation ranges from 20 to 35% of athletes' total daily energy intake (TDEI), and the intake of saturated fat should be limited to less than 10% of TDEI (Thomas et al., 2016). Omega-3, a polyunsaturated fatty acid, regulates the body's inflammatory response. Regarding athletic performance, Omega-3, commonly found in fish oil, can delay the onset of muscle soreness, enhance oxygen delivery during aerobic exercise, and reduce exercise-induced oxidative stress (D'Angelo & Madonna, 2020).

Micronutrients are vital substances the human body cannot produce and must be received from a nutritionally balanced diet in small quantities. The recommended amount of intake is based on Recommended Nutrient Intakes (RNI) (Thomas et al., 2016). The athlete's nutritional needs can be met by following a balanced diet, making

it generally feasible to meet the requirement for vitamins and minerals. The micronutrients deficiencies were due to low-energy intake, vegetarianism, injuries, and illness (Ghazzawi et al., 2023). Iron, vitamin D, calcium, and antioxidants are several micronutrients of interest for athletic performance. Iron deficiency can impair muscle function and limit work capacity, reducing training adaptation and sports performance. Suboptimal iron status frequently occurs due to insufficient consumption of iron from heme dietary sources and poor energy intake (Castell et al., 2019; Pal et al., 2021). Vitamin D regulates the absorption and metabolism of calcium and phosphorus and is crucial for maintaining bone health. Calcium plays a crucial role in the growth, maintenance, and repair of bone tissue, as well as in the control of muscle contractions, nerve impulses, and blood clotting. Low energy availability, disordered eating, and inadequate dietary calcium intake enhance the risk of stress fractures and low bone mineral density (Beck et al., 2021; Capling et al., 2021). Due to chronic training, antioxidants, such as vitamins A and E have crucial functions in protecting cell membranes against oxidative damage (Thomas et al., 2016). Thus, it is essential to advocate for a varied and nutrient-rich diet to ensure that athletes have sufficient micronutrients, consequently minimising the likelihood of nutritional deficiencies (Amawi et al., 2024).

In line with the crucial role of nutrition in enhancing sports performance, several well-documented guidelines on the nutritional requirements for athletes were established (Burke et al., 2019; Thomas et al., 2016; Witard et al., 2019). Recommendations for some nutrients, specifically energy, CHO, and protein, were made depending on the individual's body mass to account for the wide range of body sizes among athletes. Table 2.1 outlines the nutrition recommendations for athletic training and performance.

Table 2.1 Nutrition recommendations for athletic training and performance

Nutrients	Recommendations
CHO	<ul style="list-style-type: none"> • Pre-race refuelling <ul style="list-style-type: none"> • Normalization of glycogen = 7 - 12 g.kg⁻¹.day⁻¹ for 24-hr. • CHO loading = 10 - 12 g.kg⁻¹.day⁻¹ for 36 – 48-hr. • Pre-event fuelling <ul style="list-style-type: none"> • 1 - 4 g.kg⁻¹ CHO in 1- to 4-hr pre-race. <p style="text-align: right;">(Burke et al., 2019)</p>
Protein	<ul style="list-style-type: none"> • The recommended protein intake ranged from 1.3 to 1.7 g.kg⁻¹.day⁻¹. • The optimum protein intake per serving of meal ranged between ~0.3–0.4 g.kg⁻¹, for maximal stimulation of muscle protein synthesis. • The intake of protein more than 1.6 g.kg⁻¹.day⁻¹ and as high as 2.2 g.kg⁻¹.day⁻¹ does not provide further benefits in terms of increasing lean body mass in those who are already weight-stable and trained. <p style="text-align: right;">(Witard et al., 2019)</p>
Fat	<ul style="list-style-type: none"> • The recommended fat intakes ranged from 20% to 35% of TDEI. <p style="text-align: right;">(Thomas et al., 2016)</p>
Micronutrients	<ul style="list-style-type: none"> • The essential micronutrients were iron, vitamin D, calcium, and antioxidants. • The recommendation for micronutrients were based on the RNI or Adequate Intake. <p style="text-align: right;">(Thomas et al., 2016)</p>
Hydration	<ul style="list-style-type: none"> • Aim to keep net fluid deficit <2% to 3% body mass, especially in hot weather. • To achieve euhydration state, it is recommended to drink 5 to 10 mL.kg⁻¹ body weight within 2 to 4 hours pre-exercise. This time frame allows sufficient time to void the excess fluid. <p style="text-align: right;">(Armstrong et al., 2009)</p>

CHO = carbohydrate; g = gram; kg = kilogram; TDEI = total daily energy intake; RNI = recommended nutrient intake

Another aspect that must be considered in pre-exercise nutrition is nutrient timing. It is a nutritional approach that involves consuming specific nutrients at specific periods before, during, or after exercise to enhance exercise performance and long-term adaptations (Kerksick et al., 2017). The timing of pre-exercise nutrition is approximately < 1-hr up to 4-hr before engaging in exercise (Thomas et al., 2016).

During this phase, the main goal of nutritional intake is to ensure a sufficient energy reserve for the muscles, hence improving performance during exercise (Kerksick et al., 2017). The precaution to avoid the occurrence of rebound hypoglycaemia must be taken in pre-exercise CHO feeding. Consuming larger amount of CHO within one hour before exercise potentially resulted in a significant increase in blood glucose and insulin followed by a dramatic drop in blood glucose, which may impair the exercise performance (Ormsbee et al., 2014). As the timing of pre-exercise meal is crucial for an athlete to optimise the stores of glycogen for utilisation during high-intensity exercise, thus, it should be carefully adjusted to ensure sufficient glycogen stores and favourable metabolic responses.

2.1.3 Dietary practice of endurance athletes

Previous studies have consistently found that the inadequacy of energy, macronutrients and micronutrients intake was reported across various athletes' populations (Baranauskas et al., 2015; Beermann et al., 2020; Masson & Lamarche, 2016; Moss et al., 2023; Noh et al., 2020; Nunes et al., 2018). A study by Moss et al. (2023) among trained endurance athletes in the United States revealed the majority of endurance athletes are not meeting the requirements for several macronutrients and micronutrients. This was evidenced by the insufficiency of CHO intake by 95.8% of the participants, and more than 50% had inadequate vitamin D, E, and K intakes. Similarly, Masson & Lamarche (2016) reported that only 46% of Canadian multisport endurance athletes consumed the CHO in amounts equal to or above $6 \text{ g.kg}^{-1}.\text{day}^{-1}$.

Athletes prefer affordable CHO sources of natural foods, and CHO foods such as rice, lentils, potatoes, oats, raisins, and honey are effective pre-exercise CHO sources (Naderi et al., 2023). Beis et al. (2011) reported that East African runners have significantly different dietary patterns than those in the Western world. Their diets

primarily consist of CHO, which provide 60-80% of their energy. They heavily rely on vegetables, which comprise 80-90% of their diet, in contrast to animal-based food sources which contribute only 10-20%. Their food choices are limited, with staple foods such as rice, pasta, potatoes, kidney beans, cabbage, ugali maize meal, and injera flatbread being the main components of their diet. Regarding the Asian athletes population, Fujita et al. (2020) reported that the daily sources of CHO in Japanese athletes were rice, noodles, and bread, along with protein sources such as meat and fish, as well as vegetables. Noh et al. (2020) indicated that the preferred sources of CHO were white rice and wheat noodles among a group of university endurance athletes in Malaysia.

Several factors influence the dietary choices of athletes. These include physiological, cultural background, socio-demographic, psychological, sports types, and situational factors (Pelly et al., 2022). Stokes et al. (2018) reported that social influences by peers and family members, and sport-specific factors determined the choices of foods in elite rugby players. The choices of foods considered the nature of the game, whereas healthy eating was employed during game season. Pelly and Thurecht (2019) reported that the choices of foods among competitive athletes were mainly based on the nutritional content of meals, whereas athletes choose foods that can benefit their exercise performance. The food choice was also due to food preferences based on the usual eating practices. In addition, Thurecht and Pelly (2020) showed that the choice of foods among experienced athletes was modulated by the competition phase, as the athletes were concerned about exercise performance and nutrition.

2.1.4 Endurance exercise and heat stress

Endurance sports demand a very high individual's $\dot{V}O_{2\max}$ to sustain the continuous endurance performance of >30 min, lasting up to 4 – 5 hours. These include several types of sports such as running, race walking, cycling time trials, cycling road races, Ironman triathlon, and cross-country skiing events (Burke, 2021; Burke, Jones, et al., 2019). Each is further divided into various categories involving different durations and intensities, contributing to various physiological and nutrition challenges. For example, in distance events, the International Association of Athletics Federations recognises various running categories, namely, 10,000 m track, road half marathon (21.1 km), and road marathon (42.2 km). It was shown that during the 10,000 m track, the intensity was approximately 90 – 95% of $\dot{V}O_{2\max}$, while during the road half marathon and marathon, the intensity was 85 – 90% and 80 – 90% of $\dot{V}O_{2\max}$, respectively (Burke, Jones, et al., 2019).

Many endurance events take place in hot environment where temperatures can surpass 30°C, such as, the Doha 2019 World Championships and Tokyo 2020 Olympic Games. Exercise in a heat stress environment has been shown to impair endurance performance (Bennett et al., 2024). Rodrigues et al. (2023) demonstrated that training in heat resulted in a decline in endurance running performance, as it needs an additional 14.1 ± 4.8 min to finish a 10 km time-trial (TT) at 35°C compared to 25°C. Also, Charoensap et al. (2023) showed that mean power output during heart rate-matched moderate-intensity cycling was significantly lower in heat (33°C, 60% RH) compared to temperate (18°C, 60% RH) condition. The mechanism of reduction in exercise capacity and performance with heat stress condition was due to the cardiovascular and thermoregulatory strains, characterised by increases in core temperature, heart rate, sweat rate, peripheral blood flow, and dehydration

(Charoensap et al., 2023; Kamaruddin et al., 2023). Concomitant to changes in cardiovascular and thermoregulatory functions, there is a shift in substrate metabolism towards higher CHO utilisation and lower lipid oxidation (Bennett et al., 2023; Maunder et al., 2020; Rosbrook et al., 2024).

Rosbrook et al. (2024) showed that there was an increase in CHO oxidation ranging between $0.5 \text{ g}\cdot\text{min}^{-1}$ and $0.68 \text{ g}\cdot\text{min}^{-1}$ during 90 min of loaded walking in the hot-dry condition (37°C , 20% RH) compared to temperate condition (20°C , 40% RH). Maunder et al. (2020) demonstrated that CHO oxidation was increased to 10.7% during endurance cycling at a higher relative intensity ($\sim 81\% \dot{V}\text{O}_{2\text{max}}$) in heat (34°C) compared to temperate conditions (18°C). Furthermore, Bennett et al. (2023) demonstrated that exercise in heat stress led to an elevation in protein breakdown, as indicated by an increase in circulating amino acids such as glutamate, alanine, and isoleucine.

Several strategies were suggested to address the exercise performance and health challenges associated with heat stress, namely, acclimatisation, appropriate pacing, and precooling activities (Lei & Wang, 2021). In addition, specific nutritional considerations to ensure optimum substrate availability and hydration are crucial to mitigate the debilitating effects of heat stress (Bennett et al., 2024). Kamaruddin et al. (2023) demonstrated that mouth rinsing, whether CHO consisted of 6% glucose or placebo solution consisting of artificial sweeteners, provides an ergogenic benefit to running endurance in a heat stress environment (30°C , 70% RH). Similarly, in a study conducted by Che Muhamed et al. (2014), it was shown that rinsing the mouth with either a CHO (6% CHO electrolyte beverage) or a placebo solution had performance-enhancing effects compared to not rinsing the mouth during a $\text{TT}_{10\text{km}}$ cycling

performance in a heat stress environment among Ramadan fasted participants. In addition, Alhadad et al. (2023) reported that the ingestion of ice slurry improves endurance capacity, evidenced by the longer TTE running test compared to ambient drink among physically active males native to the tropical country of Singapore.

2.2 Glycaemic Index (GI)

2.2.1 The concept of glycaemic index

The GI concept was introduced in 1981 (Jenkins et al., 1981), refers to the ability of a defined portion of available CHO (25 g or 50 g) to cause change in postprandial blood glucose concentration over a period of 120 min, relative to a CHO-matched standard, commonly glucose or white bread (Brouns et al., 2005; Jenkins et al., 1981; International Organisation for Standardisation, 2010). It indicates the relative rate of digestibility of the available CHO of the food, which can reflect the quality of CHO. The GI of food is divided into three distinct categories, namely, low (GI value ≤ 55), medium (GI value = 56 – 69) and high (GI value ≥ 70). Foods with lower GI values exhibit a slower rate of CHO absorption into the bloodstream, resulting in a modest increase in blood glucose levels (Wolever, 2013) (Figure 2.5).

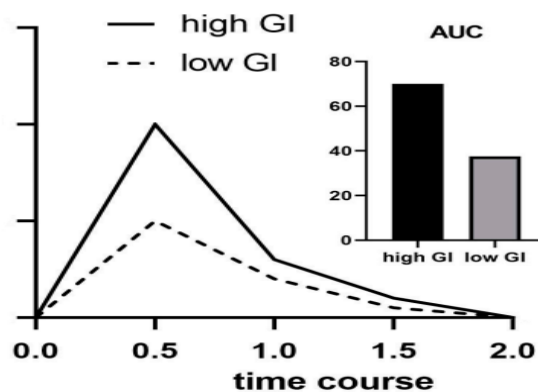


Figure 2.5 Blood glucose response and area under the curve for low and high GI foods

AUC = area under the curve. Adapted from Moitzi & König (2023).

A systematic review of the GI values based on the food category indicated that potatoes had the highest average GI values (71 ± 15), followed by rice (67 ± 17), vegetables other than potatoes (66 ± 19), and Asian-Indian regional foods (65 ± 13). The lowest GI values were observed in meal replacement products (30 ± 9), dairy products (35 ± 11), legumes (34 ± 14), sports energy bars (32 ± 15), and nuts (22 ± 2) (Atkinson et al., 2021).

2.2.2 Glycaemic index and physiological significance

Several lines of evidence have shown that the LGI diet reduces glycaemic response, enhances fat oxidation, and affects appetite regulation (Esfahani et al., 2009; Henry et al., 2017; Kaur et al., 2016). This is attributed to a reduced insulin response, which could lead to increased fat oxidation and a more prolonged feeling of satisfaction and fullness. In contrast, HGI foods lead to a higher increase in blood glucose levels and subsequently trigger a higher insulin release. This, in turn, hinders the breakdown of fats (lipolysis) and promotes the use of CHO for energy instead of fatty acids. A higher fasting respiratory quotient after consuming HGI food indicates reduced fat oxidation and increased CHO oxidation. This metabolic state has been linked to an increased likelihood of weight gain and fat accumulation in the future (Henry et al., 2017).

The metabolic benefits of LGI foods are primarily due to their slow rate of glucose absorption from the small intestine. This leads to a reduced increase in circulating insulin and gut hormones. The enhanced regulation of blood glucose levels is significant for those with insulin resistance, such as those who are obese or have a sedentary lifestyle, and those with prediabetes or diabetes (Esfahani et al., 2009). In relation to weight management, LGI foods promote fat oxidation and increase feelings of fullness. While HGI foods resulted in the rapid decline of blood glucose mediated