THE EFFECT OF PRE-EXERCISE CARBOHYDRATE INTAKE IN THE MORNING ON APPETITE REGULATION AND SUBSEQUENT RESISTANCE EXERCISE PERFORMANCE

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THE EFFECT OF PRE-EXERCISE CARBOHYDRATE INTAKE IN THE MORNING ON APPETITE REGULATION AND SUBSEQUENT RESISTANCE EXERCISE PERFORMANCE

ABSTRACT

Breakfast, which is typically consumed within 2-3 hours after waking up, is considered by many to be the most important meal of the day. Its carbohydrate (CHO) content ranges between 50-60% of its energy, meaning breakfast could replenish carbohydrate (glycogen) stores after a long overnight fast. A number of studies have shown the detrimental effect of omitting breakfast on endurance exercise, however, little is known about the effects on resistance exercise. Considering the prevalence of omitting breakfast among exercisers, commonly due to logistical/practical reasons, examining breakfast consumption versus omission on resistance exercise performance is of particular interest. To initially investigate this, the study reported in Chapter 3 compared performance in 4 sets to failure of back-squat and bench press at 90% of 10 repetition maximum (10-RM), between an ecologically valid breakfast (BC), containing 1.5 g carbohydrate/kg body mass, and a water only breakfast (BO). As hypothesised, total repetitions of back squat and bench press were less during BO compared to BC. Correspondingly, hunger was elevated, whilst fullness was decreased in the BC condition. These results demonstrate that omission of a pre-exercise breakfast might impair resistance exercise performance.

However, it cannot be discounted that, as subjects were aware of when they were consuming breakfast or not, that the exercise performance responses were confounded by psychological factors (i.e. placebo/nocebo effects). Therefore, a double-blind study was conducted (Chapter 4), with the aim to compare resistance exercise performance after consuming a water only control breakfast (WAT) or two identical semi-solid breakfasts,

one a virtually energy-free placebo (PLA), the other containing 1.5 g carbohydrate/kg body mass (CHO). CHO and PLA breakfasts were eaten with a spoon from a bowl and contained 4.25 mL/kg body mass water, 0.75 mL/kg body mass sugar-free orange squash and 0.1 g/kg body mass xanthan gum as a thickener, with addition of 1.5 g/kg body mass of maltodextrin in the CHO breakfast. Back-squat total repetitions were greater in both CHO and PLA compared to WAT. Correspondingly, CHO and PLA similarly suppressed hunger and increased fullness relative to WAT. This study indicated that breakfast likely exerted its effect on resistance exercise performance via a psychological effect. However, when higher volume resistance exercise was applied (Chapter 5), consisting of sets of 10 repetitions of leg extension to exhaustion at 80% 10-RM, an ergogenic role of carbohydrate was evident, as CHO produced greater total repetitions compared to PLA.

Whilst the studies in Chapter 3 and 4 suggested that breakfast influenced performance via a psychological effect, appetite also responded correspondingly, raising the question as to whether appetite might influence resistance exercise performance. In a follow-up study (Chapter 6) two breakfasts containing 1.5 g carbohydrate/kg body mass were provided, but one included 0.1 g/kg body mass of xanthan gum (SEM), whilst the other did not (LIQ), with the aim of manipulating appetite without affecting carbohydrate intake. Interestingly, back squat total repetitions were greater following the SEM compared to LIQ and this correspond with decreased hunger and increased fullness in SEM compared to LIQ.

In conclusion, the results from these experiments demonstrate that the perception of breakfast consumption, rather than carbohydrate/energy *per se*, improves resistance exercise performance. The ergogenic role of pre-exercise carbohydrate only seems to benefit extremely high-volume resistance exercise performance. Whether these effects are still apparent when pre-breakfast/meal glycogen stores are not optimal is unknown (i.e. if a not fully replaced from a previous training session). However, when subjects are well-fed, high-intensity intermittent exercise like resistance exercise might be influenced by sensation of fullness and a pre-exercise meal might exert its effects through this novel mechanism. In situations where the amount carbohydrate or the metabolic effects of the carbohydrate consumed before exercise are unlikely to influence performance (such as resistance exercise), consumption of meals that decrease sensations of hunger might be a simple strategy to enhance performance.

Keywords: breakfast, weight training, nutrition, fasting, strength performance.

KESAN PENGAMBILAN SARAPAN KARBOHIDRAT SEBELUM SENAMAN PADA WAKTU PAGI PADA REGULASI APETIT DAN PRESTASI LATIHAN BEBANAN

ABSTRAK

Sarapan yang biasanya diambil dalam masa 2-3 jam selepas bangun tidur adalah hidangan yang dianggap paling penting. Dengan peratusan karbohidrat (CHO) antara 50-60%, sarapan pagi boleh menambah tenaga selepas tempoh panjang berpuasa semalaman. Beberapa kajian lepas telah menunjukkan kesan buruk pada latihan ketahanan dalam mod berlari apabila sarapan tidak diambil. Walau bagaimanapun sehigga hari ini, tidak ada kajian yang pernah dilakukan pada mod latihan bebanan. Memandangkan dewasa ini telah menjadi satu kelaziman bagi pelatih untuk tidak mengambil sarapan atas alasan logistik, kajian terhadap sarapan terhadap prestasi latihan bebanan adalah penting untuk dikendalikan. Untuk membuktikan ini, kajian 1 dijalankan dengan membandingkan prestasi 4 set senaman cangkung belakang dan bangku tubi sehingga mencapai kelesuan pada 90% dari 10 pengulangan maksimum (10-RM), selepas pengambilan sarapan berbentuk hidangan biasa (BC), yang menagndungi jumlah karbohidrat sebanyak 1.5 g/kg/ berat badan, dan dengan tiada sarapan dimana hanya digantikan dengan air kosong (BO). Seperti yang diramalkan, jumlah ulangan senaman cangkung belakang dan bangku tubi adalah rendah pada BO berbanding BC. Sejajar dengan itu, persepsi kelaparan meningkat dengan bertentangan dengan persepsi kekenyangan. Ini menunjukkan meninggalkan sarapan mungkin menjejaskan prestasi latihan bebanan.

Walau bagaimanapun, berbezaan yang dilihat dalam prestasi senaman tersebut mungkin disebabkan subjek semasa BO sedar bahawa meraka tidak menagmbil sarapan sebelumnya, dan ini membuat prestasi senaman disamarkan oleh faktor psikologi. Oleh itu untuk kajian 2, kajian dua-buta telah dijalankan dengan premis untuk membandingkan

prestasi senaman seperti kajian 1, bagi dua sarapan semi-pepejal yang kelihatan sama, tetapi salah satu daripadanya adalah plasebo, terhadap sarapan hanya air (WAT). Sarapan yang mengandungi karbohidrat (CHO) dan plasebo (PLA) dimakan dengan sudu dari mangkuk yang mengandungi 0.75 mL/kg berat badan perasa tiruan sifar gula, 0.1 g/kg berat badan xanthan gum sebagai pelikat, dan 1.5 g/kg berat badan maltodekstrin cuma dalam CHO. Apa yang menarik, terdapan kesan placebo dimana ulangan senaman rintangan adalah lebih besar pada PLA, iaitu sama seperti CHO, berbanding dengan WAT, Sejajar dengannya, CHO dan PLA juga mengalami rasa kelaparan yang lebih rendah dan kekenyangan yang tinggi berbanding WAT. Walau bagaimanapun, apabila senaman rintangan dengan volum yang lebih tinggi digunakan dalam kajian 3 iaitu lurusan kaki sebanyak 10 set ulangan sehingga mencapai kelesuan pada 80% dari 10-RM, peranan karbohidrat sebagai agen ergogenik baru dapat dilihat di mana CHO menghasilkan pengulangan yang lebih besar berbanding dengan PLA.

Perbezaan kelikatan makanan dilihat boleh memepengaruhi sensasi kekenyangan dan seterusnya memberi kesan terhadap prestasi senaman. Untuk kajian 4, perbandingan prestasi senaman bebanan seperti kajian 1 dan 2 dibandingkan selepas subjek mengambil dua jenis sarapan samada semi-pepejal (SEM), atau cecair (LIQ). Menariknya, ulangan senaman cangkung belakang bagi SEM adalah lebih besar daripada LIQ dan ini selari apabila subjek di SEM dilaporkan berasa kurang lapar berbanding LIQ sepanjang ujikaji ini.

Kesimpulannya, hasil daripada eksperimen-eksperimen ini menunjukkan bahawa persepsi pengambilan sarapan, tetapi bukan karbohidrat / tenaga, secara psiklogi dilihat boleh meningkatkan prestasi latihan bebanan. Peranan ergogenik karbohidrat hanya berperanan pada volum latihan rintangan yang lebih tinggi, tetapi tidak pada volum rendah dimana aspek psikologi dilihat lebih dominan. Ini menunjukkan bahawa sarapan

pagi boleh bertindak sebagai plasebo untuk meningkatkan prestasi senaman perlawanan dengan mengurangkan rasa lapar.

Kata kunci: sarapan, latihan bebanan, pemakanan, puasa, prestasi kekuatan

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PREPHASE

Several elements of the work presented in this thesis have been published in peer-reviewed journals and/or presented at conferences:

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Manuscript Under Review

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Papers Presented (Oral)

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Yusof, A., & Naharudin, M. N. (2018). Chronological changes during 10-day intermitent fasting with low energy intake on high-intensity aerobic performance and lipid constituents. The 1st Conference on Interdiciplinary Approach in Sports of Faculty of Sports Science, Universitas Negeri Yokyakarta, 26 – 27 October 2018 in Yokyakarta – Indonesia (International).

Paper Presented (Poster)

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°/s	:	degree per second (unit for isokinetic torque)
µg	:	microgram
15-RM	:	fifteen repetition maximum
10-RM	:	ten repetition maximum
5-RM	:	five repetition maximum
3-RM	:	three repetition maximum
1-RM	:	one repetition maximum
ANOVA	:	analysis of variance
ATP	:	adenosine triphosphate
BC	:	breakfast consumption
BMI	:	body mass index
BMR	:	basal metabolic rate
BO	:	breakfast omission
BP	:	bench-press
BS	:	back-squat
Ca^+	:	calcium
CLOCK	:	Circadian locomotor output cycle kaput
CGM	:	central governor model
CHO	:	carbohydrate
DIT	:	dietary induced thermogenesis
DTE	:	desire to eat
EDTA	:	Ethylenediaminetetraacetic acid
ELISA	:	enzyme-linked immunosorbent assay

EMG	:	electromyogram
g	:	gram/grams
g/day	:	gram ratio per day
g/kg body mass	:	gram ratio per body mass
GHS-R	:	ghrelin/growth hormone secretagogue receptor
GI	:	glycaemic index
GIP	:	glucose-dependant insulinotropic peptide
GLP-1	:	glucagon-like peptide-1
h	:	hour/hours
kcal	:	kilocalorie
kg	:	kilogram/ kilograms
kg/m^2	:	metric unit for BMI (kilogram/meter square)
kJ	:	kilojoule
L	:	litre/litres
LIQ	:	liquid meal treatment
m	:	metre/ metres
mg/mL	:	milligram per millilitre
min	:	minute/ minutes
MIPS	:	multi ingredient pre-workout supplement
mL	:	millilitre/millilitres
mL/kg body mass	:	millilitre per kilogram body mass
mm	:	millimetre/millimetres
mmol/L	:	millimole per litre of blood markers concentration
PFC	:	prospective food consumption

PAEE	:	physical activities energy expenditure
PCr	:	phosphocreatine
PLA	:	placebo treatment
PYY	:	peptide tyrosine-tyrosine
REE	:	resting energy expenditure
reps	:	repetitions
SD	:	standard deviation
SEM	:	semi-solid meal treatment
O_2	:	oxygen consumption
O_2max	:	maximal oxygen consumption
W	:	watt (power)
WAT	:	water control treatment
WHO	:	World Health Organisation
W/kg body mass	:	watt per kilogram body mass

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CHAPTER 1: NTRODUCTION

Breakfast may be considered the first meal of the day, consumed within 2-3 h of waking up and usually taken in the morning before beginning daily activities. It is believed that 'breakfast' is simply derived from the words 'break the fast' where one would have his/her first meal of a day after a long period of overnight fasting, typically lasting ~10-13 h. The period of overnight fasting reduces liver glycogen, with a single serving of a carbohydrate-containing breakfast replacing this overnight loss and possibly helping to fuel activities of the day. Many researchers have advocated that low muscle glycogen level tends to reduce prolonged strenuous physical performance due to performance being dependent on glygogenolysis/glycolysis (Coyle *et al*., 1984; Coyle *et al*., 1985; Coyle *et al*., 1986; Hulston & Jeukendrup, 2009; Gonzalez *et al*., 2016). With regards to resistance exercise, less is known about how to fuel in advance of a session and specifically whether carbohydrate is required to optimise performance. Although studies have demonstrated that breakfast omission following an overnight fasting can impair prolonged endurance exercise, there is a paucity of research investigating the effect of breakfast on resistance exercise performance.

In general, breakfast consists of around 50-60% of energy as carbohydrate, which can replenish liver glycogen depleted through the overnight fast. In this context, breakfast could also serve as a pre-exercise supplement when it precedes a bout of resistance exercise, since carbohydrate intake before other forms of exercise may enhance performance (Neufer *et al*., 1987; Sherman *et al*., 1989: Chryssanthopoulos *et al*., 2002; Ormsbee *et al*. 2014). Some studies have looked at the effect of carbohydrate intake during resistance exercise, reporting that carbohydrate does not affect performance in resistance exercise bouts that last only a few sets, however, when resistance exercise is relatively low intensity and of longer duration, carbohydrate intake during exercise appears to enhance performance (Coyle *et al.*, 1986; Lambert *et al*. 1999; Haff *et al.*, 1999; Haff *et al.*, 2000; Haff *et al*., 2001; Jagim *et al*., 2016; Oliver *et al*., 2016). In turn, apart from the potential metabolic effect of breakfast consumption on exercise, psychological (or perceptual) factors could also influence performance (Mears *et al*., 2018). Exercise performance could possibly be influenced by the athlete's perception of what they have eaten before exercising. Mears *et al*. (2018) reported that placebo and carbohydrate (2 g/kg body mass) breakfasts similarly improved high-intensity endurance performance (~20 min cycling time trial) compared to a no breakfast control trial. However, whether this effect is apparent for a breakfast meal consumed before resistance exercise is unknown. Therefore, an investigation to separate the physiological and psychological factors that could influence resistance exercise performance following a breakfast consumption is warranted. Therefore, this thesis is focussed on yielding novel insight into if and how a pre-exercise breakfast meal might influence resistance exercise performance to hopefully allow coaches and athletes to better understand the role of breakfast in this context.

1.1 Effect of breakfast consumption and omission on exercise performance

With a typical breakfast representing ~20-35% of total daily energy intake, breakfast provides an important amount of energy to assist with meeting daily energy requirements of athletes and non-athletes alike, to help fuel daily activities. In particular, breakfast consumption has been shown to benefit both physical (Clayton *et al*., 2015; Clayton & James, 2015), and cognitive (Galioto & Spitznagel, 2016) performance. On the flip side, omitting breakfast has been shown to reduce liver glycogen by up to 40% (Nilsson & Hultman, 1973) which could be harmful not just on physical performance, but also alter mood (Lloyd *et al*., 1996; Foster *et al*., 2007). In addition, regular omission of breakfast is associated with a sedentary lifestyle and diseases such as overweight, obesity, type-2 diabetes and cardiovascular disease (Haines *et al*., 1996; Odegaard *et al*., 2013). Therefore, many experts have suggested that breakfast is an important part of a healthy lifestyle.

Breakfast omission is common place in the general population, with increasing prevalence reported in the United States between 1965 and 1991 (Haines *et al*., 1996). In another study, 36% of UK adults were reported to either sometimes or always omit breakfast (Reeves *et al*., 2013). According to a survey, the most common reason for omitting breakfast is to help with facilitating body mass management (Zullig *et al*., 2006). As such, breakfast is the meal that is most commonly omitted for the reason to reduce daily energy intake (Zullig *et al*., 2006). In another survey among exercisers, the negative effects of breakfast on gastrointestinal comfort (stomach discomfort, bloating and heart-burn) while performing physical activity is another reason given for why it is often omitted (Veasey *et al*., 2015). This may however depend on the type of breakfast consumed, with breakfasts containing a high content of low-digestible carbohydrates (i.e. fibre, resistance starch and sugar alcohol) possibly exacerbating these effects (Grabistke *et al*., 2009). On the other hand, it is also thought that exercisers tend to avoid breakfast due to logistical issues such as lack of time to consume breakfast before a morning exercise session or to ensure adequate sleep.

Hypothetically, skipping a pre-exercise meal could lead to a shortage of available fuel for use during exercise, which might be detrimental to physical performance.

Although refraining from consuming a pre-exercise meal could create a negative energy balance, the body's appetite regulatory system may compensate for this perturbation by metabolic and behavioural modifications (Martin *et al*., 2000). In line with this, perturbations in anaerobic and aerobic exercise performance were evidenced after the second day of reducing daily energy intake by 40% (Naharudin & Yusof, 2018). This suggests that omitting a meal only once might not effect exercise performance, however, this should not to be discounted for more prolonged and strenuous exercise where small differences in substrate availability could influence performance outcomes (Fairchild *et al*., 2016).

1.2 General problem statement

With resistance exercise being carried out at all times of the day, including in the morning, the effect of breakfast provision on performance in such bouts of exercise is of scientific and practical interest. Besides, omitting breakfast has become an increasing trend in society, where many believe that it would help to control body mass (Haines *et al*., 1996; Zullig *et al*., 2006; Reeves *et al*., 2013). Although a number of studies have investigated the effect of consuming/omitting breakfast on endurance exercise performance, its impact on short term resistance exercise performance remains unknown. Therefore, the theme of this thesis is to focus on the effect of breakfast consumption/omission on subsequent performance in an intermittent resistance exercise session. To better understand the effects of breakfast on resistance exercise performance, both metabolic and psychological factors that could alter performance outcomes were studied, including components of energy balance (i.e. appetite-related hormones and subjective appetite). Several problem statements to answer the gap of knowledge have been identified and listed as follows:

1) To date, no study has examined the effect of consuming/omitting an ecological (close to a person's habitual practice) breakfast meal on subsequent resistance exercise performance.

2) It is not certain whether changes in resistance exercise performance are due to either psychological (perception of energy intake) or physiological (availability of substrate-i.e. glycogen stores) reasons.
3) It remains unknown, how hormones and subjective appetite sensation (sensation of fullness and hunger) might be involved in the effects that any pre-exercise breakfast meal might have on resistance exercise performance.
4) It remains unknown how sensations of hunger and fullness might affect resistance exercise performance outside of any metabolic effects of the meal's nutritional contents.

1.3 Conceptual framework of the study

Consuming breakfast, which typically contains a high carbohydrate content, would replenish liver glycogen used during overnight fasting. This would therefore improve stored fuel availability. Besides this, energy intake would eventually influence appetite hormones (i.e. ghrelin), which could be associated with the sensation of hunger. Correspondingly, increased fullness and decreased hunger could perceptually signify to an individual that they have nourished themselves. Collectively, consuming breakfast could improve resistance exercise performance via the combination from both metabolic and psychological factors, considering the potential ergogenic role of carbohydrate.

Although some researchers suggest that both metabolic and psychological factors of ingesting meal can be matched with one another (Flint *et al*., 2000; Bellisimo & Akhvan, 2015), it remains unclear as other factors including individual food preference (i.e. solid, semi-solid, liquid) could independently modulate subjective appetite sensation independent of a meal's energy content (Almiron-Roig *et al.*, 2003; Ranawana & Henry, 2011). Hence, systematic investigations to isolate metabolic, psychological and perceptual factors associated with breakfast consumption are needed to fill this gap of knowledge. Conceptual framework of this study is presented in **Figure 1.1**.

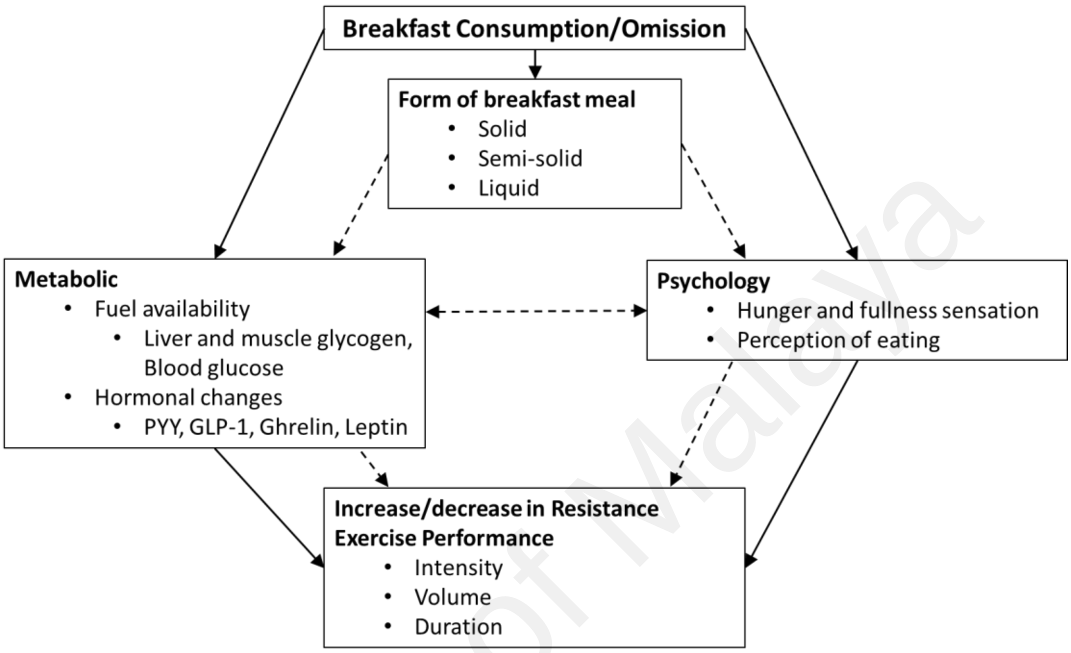


Figure 1.1. Conceptual framework of the studies demonstrating metabolic and psychology factors associated with a pre-exercise meal that could influence subsequent resistance exercise performance. Solid arrows indicate factors from a breakfast (i.e. pre-exercise meal) that influence resistance exercise performance. Dashed arrows indicates ambiguous link between breakfast and resistance exercise performance yet to be determine in these studies.

1.4 Research objectives

Several general objectives for this work are listed as below:

1) To investigate how consumption or omission of an ecological (close to subject's habitual) breakfast with high proportion of carbohydrate, effects subsequent resistance exercise performance of different volumes of exercise.

2) To investigate resistance exercise performance if metabolic effects in a pre-exercise meal was isolated. This was achieved by providing a high-viscous placebo and carbohydrate meal before a bout of resistance exercise to separate metabolic and psychological effects of pre-exercise meal.
3) To investigate resistance exercise performance following different appetite sensation of hunger and fullness induced by two isocaloric pre-exercise meals of different viscosity. This work aimed to determine the role they play in any performance effects caused by a pre-exercise meal.

1.5 General and specified research hypothesis

Generally, it is hypothesised that; breakfast omission would be detrimental to resistance exercise performance. However, some of the effects of a pre-exercise meal would be caused by a placebo effect associated with the knowledge of having eaten before resistance exercise. On a similar line, it was hypothesised that increasing the sensation of fullness whilst supressing hunger could also improve resistance exercise performance, possibly explaining some of the ergogenic effects of a pre-exercise breakfast meal.

Specifically, four alternative hypotheses (H_a), each representing an experimental chapter of this thesis, have been listed down to reject null hypotheses (H_0) which are;

1) Omitting an ecological breakfast meal is detrimental to subsequent resistance exercise performance for both back squat and bench press.
2) Performance in resistance exercise would be worse after a placebo breakfast meal containing virtually no energy compared to a high-carbohydrate breakfast meal, but that both meals would lead to better performance that a water-only control meal.

3) Consumption of a carbohydrate containing breakfast meal would increase work completed in a high-volume resistance exercise bout (i.e. multiple bout leg extension exercise) compare to a placebo breakfast meal.
4) A high viscosity semi-solid breakfast meal would reduce sensations of hunger compared to low viscosity liquid meal and subsequently increase resistance exercise performance.

1.6 Significance of study

This thesis explored the effect of perceived and actual consumption of breakfast on hunger, fullness and appetite hormones in the morning and their effects on resistance exercise performance. Outcomes form this thesis provide robust information to better understand pre-resistance exercise fuelling and the role of breakfast and appetite sensations (i.e. hunger/fullness) in this regard. This information is of benefit to gym goers and athletes to better understand the role of breakfast (or pre-exercise nutrition) on performance of brief intermittent high intensity exercise.

CHAPTER 2: LITERATURE REVIEW

2.1 Energy balance, including components of energy intake and expenditure

In physiology, energy balance is a biological process that involves the coordinated homeostatic regulation of food consumption (energy intake), energy storage and energy expenditure. When someone is under energy deprivation, the hypothalamic melanocortin system in the brain, plays a central role in regulating energy balance by generating the sense of hunger, which is integrated from numerous biochemical signals. This regulation will integrate peripheral signals which then modulate behaviour and the activity of peripheral organs (Kim, Leyva & Diano, 2014). Ideally, consuming a food/beverage is the way the body gains energy to fuel the fundamental physiological systems, as well as supplying energy for use in a person's physical activity energy expenditure.

The amount of energy that is available for metabolism from a meal is dependent on several factors such as gut microflora, food preparation and chemical composition of the food (Hall *et al*., 2012). However, conventional estimation of the amount of energy intake from a meal/beverage can be computed from its macronutrient compositions, where it was reported as 4 kcal/g (17 kJ/g) for carbohydrate and protein; 9 kcal/g (38 kJ/g) for fat; and 2 kcal/g (8 kJ/g) for fibre; (Hall *et al*., 2012). Thus, daily dietary intake for a typical adult male of average weight (~70 kg), consistent with recommendations from the World Health Organisation (WHO; 50, 35 and 15% of energy as carbohydrate, fat and protein, respectively), will provide ~2500 kcal (~10460 kJ). Absorbed carbohydrates, fat and to a lesser extent, protein, may be stored as glycogen, triglycerides or body fat, then transferred to relevant cells before it can be converted to chemical energy in the form of adenosine triphosphate (ATP) to fuel metabolic activities, or dissipated as heat (Hall *et al.*, 2012).

Glycogen, one of the quickest energy storage forms of the body, which is naturally hydrophilic with ratio of ~3 g of water to ~1 g of glycogen, is stored in the liver (~100g) and in greatest amount in the muscle (~300-750 g) (Knuiman *et al*., 2015). Depending on factors like body size, carbohydrate consumption, and variation pattern of energy intake versus energy balance, estimation of total glycogen stores in adults is ~400-850 g. This means only a relatively small and finite amount of glycogen can be stored for energy utilisation. Unlike glycogen, fat in the form of adipocyte cells, is a more efficient type of energy storage with only ~10% of water in the total amount of adipocyte tissue across the body (Sawka *et al*., 1990). For instance, an average male of 70 kg with 15% fat percentage would store ~94,500 kcal (340,000 kJ) of energy contained within ~35 billion adipocytes, each with ~0.4-0.6 μg triglycerides (Hall *et al*. 2012). Since the capacity of energy storage for glycogen is limited, an energy surplus from carbohydrate will be either oxidised for energy or converted to fat and stored in adipocytes, which reflects a state of net positive energy balance (Schrauwen, 2007).

Digested macronutrients that have been converted to simplified substrates (i.e. glucose, free fatty acids, amino acids etc.) will be absorbed, stored and ready for metabolic process. There are 3 primary components of a total energy expenditure which are; resting energy expenditure (REE), dietary induced thermogenesis (DIT) and physical activity energy expenditure (PAEE). REE, sometimes referred to as basal metabolic rate (BMR), is the energy utilisation for the fundamental human physiological systems, such as breathing, circulating blood and cell renewal (Doucet, 2001). For an average sedentary individual, REE comprise for about 60-70% of a total energy expenditure, and varies depending on body size and composition (Johnstone *et al*., 2005). Whilst DIT, which is the smallest component of energy expenditure, is a type of energy expenditure that is utilised during the process of digestion, absorption and assimilation of consumed macronutrients in foods. Depending on the composition of macronutrients, DIT usually comprises only 10% of daily energy expenditure (Westerterp, 2004). Indeed, both REE and DIT are process of energy expenditure that occur perpetually even during resting and overnight sleeping. However, the most significant proportion that contributes to the variation of total energy expenditure is that due to physical activities (i.e. physical activity energy expenditure; PAEE). For example, PAEE of a sedentary individual accounts only ~20% from their daily total energy expenditure, but it could be increased up to ~75% during periods of prolonged strenuous exercise (Westerterp & Saris, 1991). In short, energy expenditure is continuous but is elevated during periods of physical activity and reduced during sleep. However, energy intake is intermittent in nature (only usually occurring at meal times), with this mismatch between supply and utilisation of energy accounting for the need to store energy in the body.

Conceptually, consuming a food/beverage produces a net positive energy balance, with the excess energy stored to enable physiological maintenance to occur or for use in any physical activities. However, if utilised energy storage was not replaced (i.e. skipping meal within a day), negative energy balance will occur. This will stimulate energy demand at the brain's hypothalamus by increasing the sensation of hunger. This implies that the energy level of a person fluctuates within and between days, depending on factors including the type and composition of food, timing of food consumed, and level of physical activities.

2.2 Resistance exercise and its metabolic response

Resistance exercise is a physical activity mode that is characterised as brief, intermittent, and usually performed at moderately-high to high intensity. This exercise is performed by many athletes, often as part of a wider training programme, with performance in such sessions having potential implications for adaptation to the resistance exercise itself, as well as possibly for other aspects of the athlete's performance (e.g. sport-specific strength) or health (e.g. injury prevention/rehabilitation from injury). In most, hypertrophy resistance training scenarios, exercise typically performed at intensity about 0–60% of 1 RM for lower body exercises; 30–60% of 1 RM for upper body exercises, for three to five sets with 3–5 min of rest in between (Ratamess *et al*., 2009). This exercise mode will utilise anaerobic/aerobic glycolysis as the major energy system to resynthesize the depleting phosphate pool during strenuous muscle contractions (Haff *et al*., 2003; Knuiman *et al*., 2015).

Studies have shown muscle glycogen stores are typically reduced by between ~17-40%, depending on the duration, intensity and total workload performed (Robergs *et al*., 1991; Tesch *et al*., 1998; Haff *et al*., 2000; Haff, *et al*., 2003). In general, the energy required to perform high-intensity exercise is initially supplied by intra-muscular stores of phosphagens (ATP and PCr), with subsequent energy contributions to ATP-PCr re-synthesis coming predominantly from muscle and liver glycogen (MacDougall, *et al*., 1977). In experiments where all out 6 s sprints repeated for 10 bouts and interspersed by rest period of 30 s, have shown muscle glycogen breakdown, PCr hydrolysis and lactate accumulation all substantially decline as the number of sprints bout increases (Gaitanos *et al*., 1993). In another study, when two bouts of 30 s maximal isokinetic cycling exercise was performed with 4 min of recovery in between, the extend period for PCr re-synthesis during recovery was positively correlated with work output during the second bout of exercise (Casey *et al*., 1996). In this study, it was demonstrated that the rate of hydrolysis of PCr during the first bout was 35% but dropped to 33% during the second bout, which was attributable to incomplete re-synthesis of PCr in the muscle.

Collectively, muscle glycogen availability seems not entirely responsible for fatigue during short-term high intensity exercise, but instead it was caused by an inability to sufficiently restore ATP and PCr stores between exercise bouts. Hydrolysis of PCr is vital during the initial phase of every exercise bout, and re-synthesis will take approximately 4 min. Therefore, a reduce rate of resynthesis of PCr on successive demanding high intensity resistance exercise bouts could be the main reason of fatigue.

2.3 Importance of breakfast

Breakfast can contain up to ~35% of total daily energy requirements and is often described as the most important meal of the day. A number of cross-sectional studies have associated breakfast consumption with better cognitive performance (Galioto & Spitznagel, 2016; Giovannini *et al*., 2008), health and/or body composition (Maki *et al*., 2016). On the other hand, some researchers have associated the habit of omitting breakfast with overweight/obesity and other adverse health outcomes, including an increase in the prevalence in type-2 diabetes (Haines *et al*., 1996; Odegaard *et al*., 2013). Metabolically, food consumed in the morning, compared to later in the day produces a larger glucose response, which could be caused by an increase in glucose appearance to the circulation or a decrease in glucose disappearance (Kobayashi *et al*., 2014). This effect is believed to be due to daily regulatory pattern in releasing glucose/appetite-related hormones (i.e. glucagon-like-peptid-1, peptide tyrosine tyrosine), following the consumption of a meal

(Jakubowicz *et al*., 2015; Morgan, *et al*., 1999; Yoshino *et al*., 2014). Most importantly, breakfast, which typically contains a proportionally large amount of carbohydrate contributes to significantly increasing liver glycogen (Nilsson & Hultman, 1973), and to a lesser extent muscle glycogen (Taylor *et al*., 1993; Chryssanthopoulos *et al*., 2004). Thus restoring glycogen from the effect of overnight fasting could benefit physical performance in some athletic settings.

Furthermore, a high fibre meal in a semi-solid/solid form, could provide sustained fullness and alleviation of hunger above its energy content, which could potentially improve habitual dietary intake (Almiron-Roig, *et al*., 2003; Ranawana & Henry, 2011). Therefore, consumption of a viscous/solid meal could regulate glucose, insulin and appetite sensation differently, hence, potentially affect subsequent exercise performance. Although, many have reported pre-exercise carbohydrate intake to improve endurance performance, for resistance exercise, the effect of pre-exercise carbohydrate intake on resistance exercise seems to vary depending on volume and intensity of resistance exercise. Thus, consumption of food following an overnight fast has a host of metabolic, physiological and psychological effects that may interact with human health and performance.

With regards the importance of breakfast on athletes' performance, this review presents issues surrounding breakfast consumption/omission on appetite regulation; which consist of both physiological (metabolic) and psychological (appetite sensation) responses. In addition, discussion will also be focussed on how different subjective appetite sensations, produced by different pre-exercise meal states (solid, liquid, semi-solid)/viscosity, might affect resistance exercise performance.

2.4 Regulation of appetite following breakfast consumption

Generally, appetite regulation can be observed from two different perspectives; psychology (i.e. sensations of hunger, fullness etc.) and physiology/metabolic responses (i.e. glucose, insulin, and signals of gastrointestinal origin). Most literature to date suggests that these two perspectives are actually synchronised with one another (Flint, *et al*., 2000; Bellissimo & Akhavan, 2015). It does, however, remain unclear since other factors, including meal viscosity and individual meal preferences, could independently modulate subjective appetite sensation independent of a meal's energy content (Almiron-Roig *et al*., 2003; Ranawana & Henry, 2011)

There is compelling evidence that, psychological aspects like sensations of hunger and fullness are determined by the gradual build-up, during the meal, of hormones and other signals secreted by the gastrointestinal tract (Woods, 2003; Woods & D'Alessio, 2008). Rationally, breakfast consumption would alleviate sensations of hunger and at the same time increase satiety (fullness). To systematically report this, Flint *et al*., (2000) suggested a self-reported 100 mm analogue scale to measure subjective responses, which has been shown to be reliable for appetite-based research, because this method is not influenced by prior diet standardization (Flint, *et al*., 2000). Studies have shown that adequate energy ingestion (including carbohydrate) in the morning, ~350-550 kcal (~1464-2301 kJ) and ~20-30% of required daily energy intake (Astbury *et al*., 2011; Chowdhury, *et al*., 2015; Clayton, *et al*., 2016), reduces the sensation of hunger and subsequent energy intake compared to when breakfast was omitted. In fact, apart from contributing to feelings of satiety, consuming breakfast could also contribute metabolic effects by refuelling energy utilised overnight (Clayton & James, 2016).

Metabolically, consuming an adequate amount of breakfast will increase plasma glucose and therefore stimulate insulin secretion compared to when breakfast is omitted (Clayton & James, 2016). Glucose uptake by the muscle from a meal in the morning will increase, when the blood glucose concentration are low due to long overnight fasting (Kamegai *et al*., 2004). Correspondingly, following breakfast orexigenic or hunger hormones like ghrelin are supressed, whilst anorexigenic or satiety hormones like PYY and GLP-1 are increased (Batterham & Bloom, 2003; Adam *et al*., 2006).

Additionally, glucose and insulin could respond differently at different times of a day. Several studies have demonstrated that insulin sensitivity is greater in the morning compared to in the afternoon or late evening (Morgan *et al*., 1999; Saad *et al*., 2012; Yoshino *et al*., 2014). Increased insulin sensitivity in the morning compared to late evening/night could be due to the diurnal response that occurs from the habitual pattern of meals. For example, the cause of this diurnal variation throughout a day could be related to increases plasma free fatty acid (FFA) in the evening, which can alter systemic FFA availability and muscle fatty acid metabolism, causing insulin resistance in skeletal muscle (Roden *et al*., 1996). Moreover, in a rodent model, Circadian Locomotor Output Cycle Kaput (CLOCK) genes, which regulate circadian rhythm, could also contribute to diurnal variation in muscle insulin action (Maury, Ramsey, & Bass, 2010). In this context, strategies to improve dietary intake from the cycles of sleep/wakefulness and feeding/fasting may ameliorate physiological processes including appetitive behaviour or carbohydrate and lipid metabolism. Thus, having breakfast in the morning might be important in terms of metabolic efficiency in refuelling energy.

Appetite sensation features psychological perception of a consumed meal and could be influenced by someone's habitual dietary preference. On the other hand, appetite hormone responses can underline a specific metabolic mechanism following meal consumption. However, whether appetite sensations would correspond to metabolic responses is yet to be investigated.

2.4.1 Subjective appetite sensation following breakfast consumption

Measurement of subjective appetite sensations is a method for assessing the regulation of an individual's appetite. Perceived appetite sensations, which can be assessed by a 100 mm visual analogue scale consisting of 4 domains; hunger, fullness, desire to eat, and prospective food consumption, is a convenient and reliable method in assessing appetite regulation (Flint *et al*., 2000). It is widely accepted that breakfast consumption suppresses appetite, whilst omission on the other hand increases appetite and hunger. Several studies have validated this method with glucose, hormonal responses and measurement of subsequent meal size following initial meal consumption (Flint *et al*., 2000; Bellissimo & Akhavan, 2015). However, this method is somewhat questionable and can be confounded by other factors such as perception on the type of meal and a person's dietary habits (Blundell, 1990; Almiron-Roig *et al*., 2003; Ranawana & Henry, 2011).

2.4.2 Glucose and insulin response to breakfast consumption

Glucose is important as a fuel substrate for energy metabolism. Following metabolic processing in the liver, consumed macronutrients in a typical breakfast meal, especially carbohydrate, can be detected in the peripheral blood circulation (DeFronzo & Ferrannini, 1982; Schenk, *et al*., 2003). During an overnight fast between 6 to 10 hours, a normal person's blood glucose is between 3.9-5.5 mmol/L (Nilsson *et al*., 2008). This blood glucose value can fall to 3.3 to 3.6 mmol/L if no energy/carbohydrate containing foods/beverages are consumed and it is often associated with the sensation of hunger (Whitney & Rady, 2004). This baseline value will increase after consuming a meal containing carbohydrate, with the increase generally proportional to the amount of energy consumed (Wolever & Bolognesi, 1996). For example, a study investigating different proportion of <45%, 45-65% and >65% of carbohydrate in an ecological breakfast meal, increased blood glucose to ~6.3, ~6.4 and ~5.3 mmol/L respectively (Kang Xin *et al*., 2013). Whilst in a study by Nilsson *et al*. a group of healthy young subjects were given 50 g of white wheat bread, which substantially elevated blood glucose to ~8.5 mmol/L at 30 minutes after consumption (Nilsson, *et al*., 2008). However, in the same study, consuming 50 g of barley kernels only increased blood glucose to ~4.5 mmol/L. Collectively, these studies demonstrate that the amount and type of carbohydrate ingestion could influence postprandial glucose responses, which is termed Glycaemic Index. The elevation in blood glucose is also positively correlated with plasma insulin.

Insulin is a hormone produced by the β-cells of the islet of Langerhans in the pancreas and plays a critical role in the short term and long term regulation of glucose and energy homeostasis (Plum, *et al*., 2001). Roles of insulin are to; increase cellular glucose uptake, increase glycogen synthesis in liver and muscle, increase fat storage, increase cellular uptake of amino acids, increase the synthesis of protein and inhibit protein catabolism (Cooney, *et al*., 1985). However, of these roles, insulin is most commonly known for its role in promoting cellular glucose uptake. Insulin is usually expected to increase in response to plasma glucose elevation. Postprandial glucose elevation will eventually decrease over time, as glucose is taken up by the muscle and liver. Peripheral administration of insulin has been shown to increase glucose uptake into cells as demonstrated by Loh *et al*. as shown in **Figure 2.1** (Loh *et al*., 2017).

Many studies have demonstrated the response of insulin following either a mixed meal (Coyle, *et al*., 1985; Farshchi, *et al*., 2005; Astbury, *et al*., 2011; Clayton *et al*., 2015) or in an isolated individual macronutrient (Haff *et al*., 1999; Jensen, *et al*., 2011). Elevations in plasma insulin typically suppress its counter-regulatory hormones, glucagon and ghrelin. It also inhibits gluconeogenesis (Yki-Jarvinen, *et al*., 1989) and glycogenolysis (Petersen, *et al*., 1998). However, exercise, either resistance (McMillan *et al*., 1993) or aerobic (Pruett & Oseid, 1970), has been shown to decrease plasma insulin concentrations. Although exercise in general will supress insulin secretion, it synergistically promotes lipolysis of free fatty acids. Within the central nervous system, previous experiments on administration of exogenous insulin produce a net catabolic effect by reducing food intake (Woods, *et al*., 1979). On the flip side, low central insulin concentrations may increase the anabolic effects of food consumption. The regulation of the glucose-insulin relationship is simplified in **Figure 2.2.** Interestingly, although no study has been carried out on humans, experiments on rats have shown that the increase in plasma insulin concentration is directly proportional to energy expenditure (Müller *et al*., 1997) and respiratory quotient, thus increasing the reliance on carbohydrate as source of energy (Menéndez & Atrens, 1989).

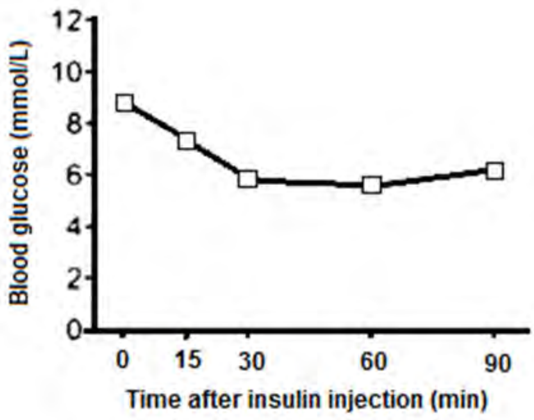


Figure 2.1 Infusion of insulin with time is directly proportional to blood glucose concentration. Note the drop in glucose levels proportion to insulin injection. Adapted from (Loh *et al*., 2017).

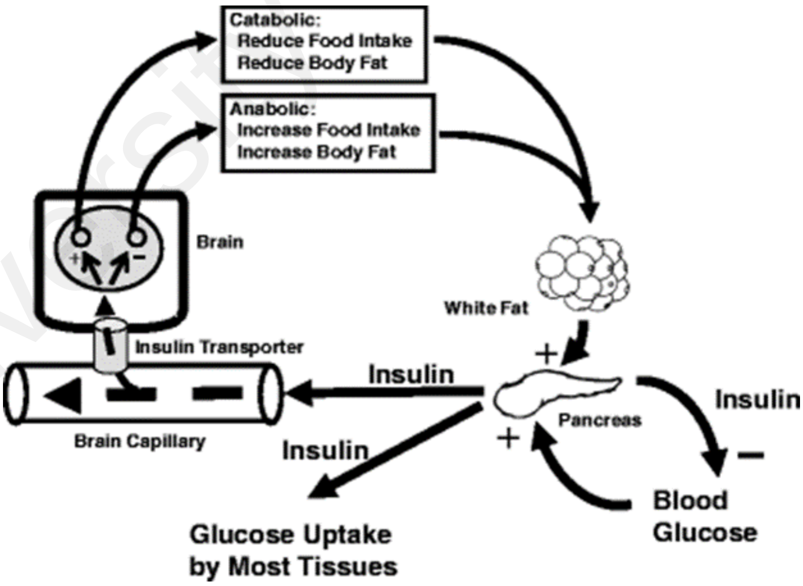


Figure 2.2 From the pancreas, insulin is secreted into the blood in response to circulating blood glucose and in direct proportion to the level of fat stored in white adipose tissue. Adapted from (Begg & Woods, 2012).

2.4.3 Orexigenic and anorexigenic hormonal response to breakfast omission/consumption

Many intervention studies have been conducted to obtain a deeper understanding of breakfast manipulations on indices of energy balance, focussing on appetite hormones. Generally, appetite hormones can be divided into two categories which are orexigenic, the appetite stimulator (i.e. ghrelin, glucagon) and anorexigenic, the appetite inhibitor (i.e. PYY, GLP-1, insulin) hormones. These hormones are homeostatically regulated and interact with one another to achieve normal energy balance (Kim, Leyva & Diano 2014). Understanding the function of each hormone and how they interact with one another, may provide valuable information about metabolism that might benefit health and/or performance.

Ghrelin or acylated ghrelin (active ghrelin) is a type of peptide hormone produced by ghrelinergic cells in the gastrointestinal tract and is secreted when the body system is undernourished (Sakata & Sakai, 2010). This hormone functions as a neuropeptide in the central nervous system and binds to ghrelin/growth hormone secretagogue receptor (GHS-R) regulating eating behaviour, glucose metabolism and memory (Burger & Berner, 2014). In the context of energy metabolism, ghrelin is secreted when the stomach is empty. Therefore, scientists often refer to ghrelin as a 'hunger hormone'. With its orexigenic attribute, ghrelin stimulates food intake and promotes positive energy balance. Thus, many studies show that plasma ghrelin is elevated during a fasting state and suppressed following energy intake (Asakawa *et al*., 2001; Toshinai *et al*., 2001). In other words, circulating ghrelin concentrations are inversely correlated with the presence of energy (and therefore macronutrients) in the gastrointestinal tract. For instance, a study by Williams *et al.* (2003), looking at the effect of intragastric load of glucose on plasma ghrelin found that the active ghrelin level was reduced by approximately 50% under normal gastric emptying state (Cummings *et al*., 2003). The same effects have also been reported with free fatty acids (Gormsen *et al*., 2006) and protein (Foster-Schubert *et al*., 2008) administration, both also decreasing plasma ghrelin. These however are not universal findings.

Since glucose availability could stimulate ghrelin secretion, infusion of glucagon which reduces glucose uptake by the muscles and the liver has been shown to transiently increase plasma active ghrelin concentration (Kamegai *et al*., 2004). Studies found that ghrelin concentration was proportional to the glucagon treatment infused (Kamegai *et al*., 2004), and this effect was mediated by the glucagon receptor on ghrelin secreting cells in the gastrointestinal tract (Katayama *et al*., 2007).

In a study by Astbury *et al*. no difference in plasma ghrelin was observed following breakfast omission (Astbury *et al*., 2011). Similarly, in another study, ghrelin concentrations were found to be unaffected by habitual consumption or omission of breakfast (Thomas, *et al*., 2015). These findings seem to suggest that habituation to a certain dietary regimen over time could lead to metabolic adaptation. Plasma ghrelin and other gut hormones response to food consumption can be observe in **Figure 2.3**.

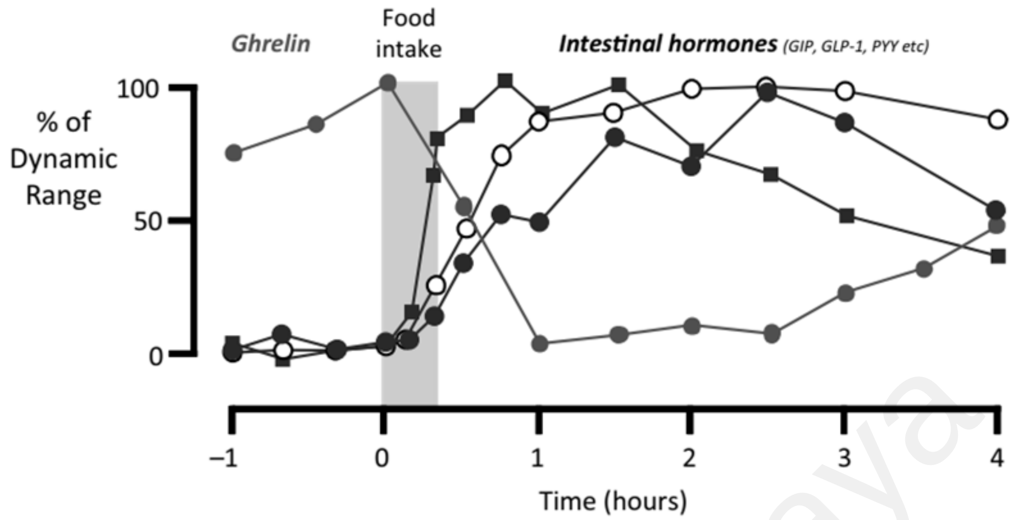


Figure 2.3. The response of appetite hormones after food consumption. All appetite hormone responses are normalized to their percentage of lowest to highest concentration. It is noted that there is a high concentration of ghrelin preprandially, which is suppressed by food intake, whilst glucose-dependent insulinotropic peptide (GIP), peptide YY (PYY), and glucagonlike peptide (GLP)-1 are low preprandially and increase following food intake. Grey circle (●) indicates ghrelin, black square (■) indicates PYY, white circle (○) indicates GLP-1, and black circle (●) indicates GIP plasma concentration. Adapted from (Engelstoft & Schwartz, 2016).

Glucagon-like-peptide-1 (GLP-1) is a 30 amino acid peptide hormone produced and secreted by intestinal enteroendocrine L-cells and certain neurons within the nucleus of the solitary tract in the brainstem following food intake (Dailey, *et al*., 2012). GLP-1 is an anorexigenic hormone, and concentrations in the blood increase following food consumption (Nadkarni *et al*., 2014). Synergistically, it has been reviewed that intestinal GLP-1 is released into the circulation to stimulate pancreatic insulin secretion upon meal intake when blood glucose is elevated, subsequently minimising development of hyperglycaemia (Holst, 2004; Nadkarni, Chepurny, & Holz, 2014; Engelstoft & Schwartz, 2016). GLP-1 is commonly released in a biphasic fashion with the early phase at 10-15 min postprandial and followed by a later phase 30-60 min postprandial, with this depending on the rate of gastric emptying and entry of nutrients into the small intestine (Verdich *et al*., 2001). For example, a study by Atsbury *et al*. reported that GLP-1 was significantly elevated at 30 minutes after breakfast consumption of a ~251 kcal liquid meal compared to omitting it (Astbury *et al*., 2011).

Besides GLP-1, peptide tyrosine-tyrosine (PYY) is another anorexigenic hormones that is released from the gastrointestinal tract, proportionally to the energy content of a meal (Batterham *et al.*, 2002; Le Roux *et al*., 2006). Therefore, many breakfast theme studies have shown the elevation of plasma PYY following breakfast consumption (Chowdhury, *et al*., 2015; Thomas *et al*., 2015; Chowdhury, *et al*., 2016;). PYY has been shown to have several biological actions, including vasoconstriction, inhibition of gastric acid secretion, reduction of pancreatic and intestinal secretion, and inhibition of gastrointestinal motility (Batterham & Bloom, 2003). Additionally, consumption of dietary fibre increases the speed of transit of intestinal contents into the ileum, to raise PYY and induce satiety (Juvonen *et al*., 2009).

In summary, it is clear that overnight fasting increases orexigenic hormones (i.e. ghrelin) and increase gastric motility, thus promoting food intake (Cumming & Overduin, 2017). Following consumption of an energy containing meal at breakfast, the presence of energy in the gastrointestinal track would suppress orexigenic hormones, and promote secretion of anorexigenic hormones (i.e. GLP-1, PYY) to inhibit food intake. Additionally, these anorexigenic hormones will also increase the secretion of insulin, therefore promoting glucose uptake into muscle and synthesis of muscle and liver glycogen.

2.5 Exercise performance following pre-exercise carbohydrate consumption.

Many studies have reported increases in endurance performance following a high carbohydrate pre-exercise meal (Clayton *et al*., 2015; Ormsbee *et al*., 2014). Ensuring optimal muscle glycogen levels is believed to benefit demanding exercise that is longer than 80 minutes (Sherman *et al*., 1989; Sherman, *et al*., 1981), since fatigue during this mode of exercise is often associated with muscle glycogen depletion (Duhamel, Perco & Green, 2006; Ørtednblad *et al*., 2011). Similarly, stored glycogen in the liver provides an important fuel source during endurance exercise. In a study by Duhamel *et al*. cycling at 70% VO_2peak that was carried out under low glycogen levels was reported to drastically reduce the uptake and release of sarcoplasmic reticulum Ca^+ during exercise (Duhamel *et al,*. 2006). In another study, Ørtenblad *et al*., showed that ingestion of carbohydrate during 4 h of recovery following exercise, can normalize both subject's muscle glycogen content and sarcoplasmic reticulum Ca^+, compared to the occasion where they omitted it (Ørtenblad *et al*., 2011). This can be evidenced by the deleterious effect on endurance exercise, where performance was measured following 12 h fasting where liver glycogen stores will usually suboptimal (Nilsson & Hultman, 1973; Neufer *et al*., 1987).

Regarding the effect of breakfast on endurance performance, reviews in the area have suggested that consumption of a high carbohydrate breakfast could generally increase subsequent endurance performance (Ormsbee *et al*., 2014; Clayton & James 2016). Indeed, some studies have even shown that consumption of a high carbohydrate breakfast in the morning, can enhance endurance performance later in the day compared to omitting breakfast, even when performance takes place after ad-libitum food intake at lunch (Clayton *et al*. 2015; Cornford & Metcalfe, 2018). On the contrary, omitting breakfast following an overnight fast can contribute to premature fatigue due to limited energy stores in the body. Performing exhaustive exercise under deprived energy conditions would utilise reserved phosphocreatine (PCr), at the same time hindering the re-syntheses of both PCr and ATP. Although the amount of liver and muscle glycogen is relatively small compared to endogenously stored fat, glycogen is recognized as the major source during prolonged moderate to high intensity endurance exercise (Knuiman *et al*., 2015). Without much sparing of glycogen , plus the accumulation of metabolism by-products like inorganic phosphate, protons, lactate and free Mg^{2+}, that directly affect the mechanical machinery of the muscle cell and limit performance (Ament & Verkerke, 2009). Besides, it has been reported that the capability of skeletal muscle to exercise is impaired when the glycogen store is reduced to a certain level, even though there is sufficient amount of other energy sources available (Bergstrom & Hultman, 1967).

Whilst there is a wealth of literature that has focussed on the effect of pre-exercise carbohydrate/energy intake on endurance performance, very little work has focussed on performance of resistance exercise. Ingesting adequate carbohydrate before resistance exercise could offset muscle glycogen depletion and, if muscle glycogen is implicated in fatigue during resistance exercise (Haff *et al*., 2003), enhance performance. In a typical breakfast meal, which commonly contains high carbohydrate (1.0-2.0 g carbohydrate/kg body mass; Timlin & Pereira, 2007) muscle glycogen concentration could potentially increase by up to 11% (Chryssanthopoulos *et al*., 2002).

For resistance exercise, there is only one previous study that has isolated the effects of pre-exercise feeding on performance. In this study, Fairchild *et al*. (2016) observed that ingesting 75 g of glucose immediately before performing exercise, did not result in any difference in 3 repetitions maximum (3-RM) isokitenic leg extension for 7 sets at 60 °/s compared to a placebo. However, in most, but not all, resistance training scenarios, exercisers perform 3-5 sets of 8-12 repetition maximum (Ratamess *et al*., 2009), meaning the study of Fairchild *et al*. performed significantly less repetitions than what is experienced by most using resistance exercise training. Therefore, the protocol is unlikely to resemble the real situation in the gym. Moreover, most studies have supplied carbohydrate through a combination of immediately before and during exercise (Lambert *et al*., 1991; Robergs *et al*., 1991; Haff *et al*., 2000; Haff, *et al*., 2003; Kulik *et al*., 2008), meaning the effects of carbohydrate intake at a pre-exercise meal cannot be determined.

2.5.1 Pre-exercise carbohydrate intake in various modes of resistance exercise training

As discussed, multiple bout resistance exercise training utilises a substantial amount of muscle glycogen (Haff *et al*., 2000; Haff, *et al*., 2003; Robergs *et al*., 1991; Tesch *et al*., 1998). This is due to the high rate of energy utilisation for the subsequent demand of ATP and PCr production through glycolysis for successive bouts (Robergs *et al*., 1991; Tesch *et al*., 1998; Haff *et al*., 2000; Haff *et al*., 2003). Haff *et al*. suggested that muscle glycogen depletion appears to be directly associated to the volume of muscular work achieved, with high-repetition, moderate-load exercise resulting in the greatest reduction (Haff *et al*., 2003). Therefore, maximising muscle glycogen stores via dietary carbohydrate intake/carbohydrate supplementation, hypothetically, could improve muscle glycogen availability and assist ATP re-synthesis to improve high-volume resistance exercise performance.

Research has consistently reported that adequate pre-exercise carbohydrate intake can delay the onset of fatigue (Hargreaves, *et al*., 2004), thereby prolonging endurance exercise duration (Clayton *et al*., 2016; Clayton *et al*., 2015; Coyle & Coggan, 1984). However, for resistance exercise, many (Dalton *et al*., 1999; Lambert *et al*., 1991; Mitchell, *et al*., 1997; Kulik *et al*., 2008; Raposo, 2011; Fairchild, *et al*., 2016), but not all, (Haff *et al*., 1999; Haff *et al*., 2001; Jagim *et al*., 2016; Oliver *et al*., 2016) have reported that carbohydrate intake (mainly during exercise) elicits no effect. These effects could be due to the nature of resistance exercise itself, which is typically very intense and intermittent in nature, meaning substrate replenishment during rest between sets might prevent any effects on performance between dietary interventions. Exercising at high intensity normally reduces exercise duration, therefore dampening the potential for any metabolic influence on performance. For example, a study by Mitchell *et al*. reported there was no ergogenic effect of a high carbohydrate diet compared to a low carbohydrate diet observed for back squat, leg press and knee extension exercise (~14 reps/5 sets) at 100% of 15-RM (Mitchell *et al*., 1997). In line with this, a placebo effect was observed where no difference in high-intensity cycling time trial performance between taste and texture match placebo and carbohydrate-containing breakfasts (Mears *et al*., 2018). However, when a design that involved exercising at slightly lower intensity with a higher exercise volume was employed, with subjects performing sets of 10 repetitions of leg extension at a workload equivalent to 80% of 10-RM, until failure (190 reps/ ~17 sets), a higher number of repetitions was performed when carbohydrate was provided during the exercise bout compared to when a placebo was provided (Lambert *et al*., 1991). Although the results were not quite statistically significant ($P = 0.067$), there was a strong trend for an improvement in performance. Therefore, it appears that performance in longer duration resistance exercise (i.e. higher volume exercise) might benefit from pre-exercise carbohydrate intake, although no study has examined this, to date. Supporting this notion, a few studies have reported that low intensity (55 to 85% of 1 to 10-RM) resistance exercise to exhaustion is enhanced by carbohydrate intake immediately before and during exercise (Haff *et al*., 1999; Haff *et al*., 2001; Oliver *et al*., 2016). Therefore, based on this evidence, it may be suggested that higher volume resistance exercise (i.e. lower intensity for a more prolonged exercise duration) could potentially be enhanced by carbohydrate intake either before and/or during exercise, but again, no study has specifically explored the role of carbohydrate consumed in the pre-exercise meal. Related studies assessing various modes of resistance exercise performance on subsequent carbohydrate intake are presented in **Table 2.1**.

Table 2.1 Intervention studies assessing strength exercise performance preceded by pre-exercise carbohydrate supplementation vs. placebo. Studies were arranged from higher exercise intensity/small set to lower intensity/big set (in **bold**)

Reference	Intervention	Study design	Finding
Mitchell *et al*., 1997	High CHO diet = 7.66 g/kg body mass vs. Low CHO diet = 0.37 g/kg body mass. Diet were consumed 48 h preceding exercise.	Eleven resistance-trained males performed **five sets** of squats, leg press and knee extension to failure at **100% from 15-RM**.	High CHO diet shows no difference in performance compared to Low CHO diet.
Sawyer *et al*., 2013	Seven days of normal CHO diet = 47% CHO: 22% protein: 34% fat vs. 7 days of restricted CHO diet = 5.4% CHO; 35.1% protein; 53.6% fat.	Sixteen men and fifteen women performed hand grip dynamometer, vertical jump, **single rep of 100% from 1-RM** test bench press and back squat, bench press to exhaustion and 30 second Wingate cycling.	No difference in all performance following 7 days of normal and restricted CHO dietary regimen. Despites, reduction in body mass.
Fairchild *et al*., 2016	CHO drink every ~15 min until 90 min = 75 g vs. placebo drink.	Eleven males and 6 females performed **100% from 3-RM** isokinetic contraction at $60°s^{-1}$.	CHO supplementation does not alter performance
Dalton *et al*., 1999	CHO drink = 1 g/kg body mass vs. placebo drink vs. Control drink. These drinks were consumed 30 min before performance test. Drink intervention and exercise performance were done after 11 days of negative energy balance dietary regimen.	Eight men for CHO and placebo trial, whilst 6 men for control trial Subjects performed leg extension and bench press at **80% of 10-RM** to **exhaustion.**	CHO intake following negative energy balance does not improve resistance exercise number of repetitions
Raposo, 2011	CHO drink = 1.0 g/kg body mass vs. placebo drink consumed 60 min before beginning exercise bouts.	Thirteen women performed **5 sets** at **75% of 1-RM** for bench press and leg press.	There was no statistical difference between CHO and placebo drink treatment.
Kulik *et al*., 2008	CHO drink = 0.3 g/kg body mass right before and during exercise vs. placebo drink.	Eight resistant trained males perform squat at **85% from 1-RM** to **exhaustion**.	CHO supplementation does not improve squat to exhaustion.

Lambert *et al*., 1991	CHO drink = 1.0 g/kg body mass right before exercise vs. placebo drink	Seven experience resistance athlete performed multiple bout leg extension at **80% from 10-RM**, **set of 10 to exhaustion.**	CHO supplementation shows no difference but potentially improved number of repetitions during multiple bout resistant exercise.
Haff *et al*., 1999	CHO meal = 1.2 g/kg body mass and drinks = 0.3 g/kg body mass before and during exercise respectively vs. placebo drink	Six males performed squat at **55% from 1-RM**, for **10 sets to exhaustion** (multiple bout to exhaustion)	CHO supplementation improved number of sets.
Haff *et al*., 2001	CHO drink = 1.0 g/kg body mass before exercise and 0.51 g/kg body mass at set 1, 6, 11 vs. placebo drink	Eight males performed isokinetic contraction for **16 sets of 10 reps** at 120°s^{-1}.	CHO supplementation improved total and average work but not peak and average torque.
Jagim *et al*., 2016	MIPS drink consists of 4 g CHO vs. placebo drink	Twelve males performed back squat and bench press at **85% from 5-RM** to **exhaustion** followed by anaerobic sprinting cycling.	MIPS drink improve bench press number of repetition and anaerobic sprinting cycling mean power.
Oliver *et al*., 2016	Low molecular mass CHO drink = 1.2 g/kg body mass vs. High molecular mass CHO drink = 1.2 g/kg body mass vs. placebo drink.	Sixteen resistance-trained males performed **5 sets** of 10 maximal explosive repetition of back squat at **75% from 10-RM**.	Both Low and High molecular weight CHO drink increase power output than placebo. No difference between both carbohydrate trials.

Abbreviations: CHO, carbohydrate; RM, repetition maximum; MIPS, multi ingredient pre-workout.

2.5.2 Effects of carbohydrate quantity on resistance exercise

As discussed previously, studies which reported an improvement in resistance exercise performance with carbohydrate supplementation immediately before and during resistance exercise bouts involved exercise with a much larger work volume (Lambert *et al*., 1991; Haff *et al*., 1999; Haff *et al*., 2001) compared to studies which reported insignificant effects (Fairchild, *et al*., 2016; Kulik *et al*., 2008; Raposo, 2011). In a review by Haddock & Wilkin, it was suggested that high volume resistance exercise can significantly increase net energy expenditure compared to lower work volume (Haddock & Wilkin, 2006), therefore utilising greater muscle glycogen. In a study by Haff *et al*. 3 sets of isokinetic leg extensions performed at 120°/s has been shown to reduce muscle glycogen in the vastus lateralis by 17% (Haff *et al*., 2000). In the same study, a multiple-set resistance-training session, consisting of back-squats, speed squats, 1-leg squats performed at 65, 45, and 10% of 1-RM resulted in a 27% decrease in muscle glycogen of the same muscle. Similarly, Robergs *et al*. reported that 6 sets of 6 and ~12 reps of leg extensions performed at 70 and 35% of 1-RM respectively, significantly reduced muscle glycogen by 39% and 38% respectively via glycogenolytic process (Roberg *et al*., 1991). In another study, Tesch *et al*. reported muscle glycogen depletion of 40%, following 5 sets of 10 repetitions of concentric knee extensions performed at 60% of 1-RM (Tesch *et al*., 1998). Taken together, the above mentioned studies suggest that the level of muscle glycogen depletion observed during resistance exercise appears to be a function of the amount of work performed.

Since prolonged low to moderate intensity resistance exercise to exhaustion (high volume) likely utilises more muscle glycogen (due to the higher volume), the quantity of carbohydrate consumed might play a role in the ergogenicity of carbohydrate intake in and around resistance exercise. Kulik *et al*. found that 0.3 g/kg body mass carbohydrate supplement drink in the morning taken before and during exercise did not improve performance in squat exercise at 85% of 1-RM (Kulik *et al*., 2008). However, Haff *et al*. (1999) reported that consuming 1.2 g carbohydrate/kg body mass in the morning, and 0.38 g carbohydrate/kg body mass during every completed sets of squats performed to exhaustion, increased the number of sets and repetitions for leg squat at 55% 1-RM compared to a placebo drink (Haff *et al*., 1999). Moreover, the majority of the studies reviewed provide carbohydrate in the form of beverages during exercise, rather than in a meal before exercise. Thus, these studies do not entirely represent breakfast omission or consumption *per se*.

In summary, the studies reviewed suggest that carbohydrate intake immediately before and during exercise, if sufficient, can increase performance in high volume, but not with low volume resistance exercise. However, whether carbohydrate intake at a pre-exercise meal influences resistance exercise performance is not known.

2.5.3 Effects of carbohydrate mouth-rinse on resistance exercise performance

It has been well-reviewed by Haff *et al*. that the ergogenic role of pre-exercise carbohydrate intake on resistance exercise performance is via increase availability of readily available carbohydrate stores (blood glucose, muscle, and liver glycogen) (Haff *et al*., 2003). However, in an earlier study, Jeukendrup *et al*. argued that carbohydrate supplementation is unlikely to enhance high intensity exercise as it was relatively small amount of exogenous carbohydrate (5 – 15 g) can be oxidised in the first hour of exercise. It was thought to be too small to improve exercise performance and there is no clear metabolic explanation for this effect on performance (Jeukendrup *et al*., 1997). On the other hand, emerging studies in the literature have demonstrated that CHO mouth rinse (without swallowing) could modulate exercise performance by modulating fatigue (Carter *et al*., 2004; Fraga *et al*., 2017), optimise cognitive performance (Promportes *et al*., 2017), improve time-trial performance in well-trained cyclists (Jensen *et al*., 2017), improved morning performance of countermovement jump height, 10m sprint times (Clarke *et al*., 2017) and improve resistance exercise number of repetitions (Decimoni *et al*., 2018).

In the perspective of physiology, CHO mouth rinse could trigger receptors within the oral cavity, therefore influencing centrally mediate effects enhancing neural drive and inhibiting fatigue (Chambers *et al*., 2009). The presence of CHO in the mouth may activate a phenomenon where it may enhance corticomotor output and attenuate declines in motor function associated with fatigue, providing a neurological basis for enhancements in motor performance observed in many behavioural studies (Turner *et al*., 2014).

2.6 Effects of form of meal (solid vs. liquid) on appetite sensation regulations

Many studies have compared the regulation of appetite between meals of different form (mainly solid vs. liquid). Solid/semi-solid meals take a longer time to be digested, at least partially due to a slower rate of gastric emptying compared to liquid meal (Berry *et al*., 2003). Hence, retention of food/fluid in the gastrointestinal tract, due to the slow digestion rate, could prolong postprandial satiety (Almiron-Roig *et al*., 2003; Ranawana & Henry, 2011) and possibly influence hormonal mediators of appetite. **Table 2.2** summarises literature findings comparing between solid versus liquid meals on appetite sensation. Collectively, it can be concluded that a solid meal in the morning could better preserve the sensation of satiety. This is supported by studies reporting higher energy intake at a subsequent meal following ingestion of a liquid meal compared to a solid meal (DiMeglio & Mattes, 2000; Apolzan *et al*., 2007).

Table 2.2 Intervention studies assessing appetite sensation following solid versus liquid forms of 'breakfast'. Studies arranged accordingly to chronological order.

Reference	Intervention	Study design	Finding
DiMeglio and Mattes, 2000	Two groups of; -Liquid = soda (450 kcal) -Solid = jelly beans (450 kcal) Meals were isocaloric and iso-carbohydrate.	Fifteen subjects (7 males and 8 females) participated in this cross over study. Following and overnight fast, subjects consumed allotted treatment.	Solid elicits precise energy compensation whilst Liquid elicits positive energy balance by 17%. No difference in sensation of hunger. That could due to solid food given was just snack.
Berry *et al*., 2003	Two groups of; -Solid = CHO drink + ground beef (740 kcal) -Liquid = CHO drink (200 kcal) Treatments were not isocaloric and non-homogenous.	Twelve subjects participated in this cross over study. Following an overnight fast, subject consume allotted treatment.	Solid food with ground beef delayed gastric emptying and increase heart rate.
Almiron *et al*., 2004	Equal energy load between; Liquid = regular cola (300 kcal) Solid = raspberry cookies (300 kcal) Both meals were isocaloric but not isocarbohydrate, where Liquid higher in CHO than Solid	Thirty-two subjects participated in this cross over study. Appetite sensation and energy compensation at lunch were measured.	No difference in sensation of satiety and subsequent energy intake between trials. Liquid reduces subsequent water intake compared to Solid.
Tieken *et al*., 2007	Two meals replacement product in a form of; Liquid = 540 kcal Solid = 540 kcal Both meals were isocaloric but not isocarbohydrate where Liquid higher CHO than Solid. Both treatments were non-homogenous.	Nine men participated in this cross over study. After an overnight fasting, subjects consumed either Liquid of Solid consists of	Liquid elicit greater sensation of hunger. Insulin and ghrelin were higher during Liquid.

Stull *et al*., 2008	Two meal replacement products of; Liquid = 559 kcal (water, sugar, maltodextrin, sunflower oil etc.) Solid = 559 kcal (yogurt coating, corn syrup, raisins, honey, crisp rice etc.) Treatments were not iso-carbohydrate and non-homogenous and were different type of food.	Twelve men and twelve women participated in this cross over study. After an overnight fasting, subjects consumed either Liquid of Solid.	Liquid elicit greater sensation of hunger from 15 to 120 min. Subjects consumed 13.4% more oatmeal after the liquid vs solid
Pfeiffer *et al*., 2010	Three treatments of; 1. Drink = 1.55 g of CHO/min 2. Bar = 1.55 g of CHO (with other macronutrients + plain water) 3. Water = plain water Both meals were just isocarbohydrate but not isocaloric.	Eight well trained subjects participated in cross over study design. After overnight fasting, subjects exercise on a cycle ergometer for 2 hours at moderate intensity. This preceded by ingesting one of the 3 experimental treatment and measurement of fuel oxidation.	Solid bar increases CHO oxidation rate compared to drink, with higher sensation of fullness.
Apolzan *et al*., 2011	Four groups of; -Sedentary (solid) -Sedentary (liquid) -Trained (solid) -Trained (liquid) All solid vs. liquid are isocaloric and homogenous (~258 kcal)	Eighteen sedentary and sixteen trained elderlies participated in this study. Mixed model cross over design comparing solid versus liquid on sedentary and resistance. Following an overnight fast, subjects consume 12.5% from total daily intake.	Solid food increase satiety but does not influence appetite hormones regulation and subsequent food intake

Abbreviations: CHO, carbohydrate.

2.6.1 Glucose response in a solid vs. liquid breakfast meal

The rate at which blood glucose reaches peak concentrations is influenced by the form of the meal ingested; either solid or liquid. In assessing glucose response upon meal ingestion, Jenkins and colleagues have introduced the glycaemic index (GI) method, which is defined as the area under the curve measured two hours after consuming 50 g of carbohydrate in relation with 50 g of glucose (Jenkins, *et al*., 1981). GI represents the elevation (due to consumption) and depletion (due to cellular uptake) rate curve of particular carbohydrate type, within 2 hours of the solid or liquid meal, following 10-12 hours of overnight fasting (Salmerón, 1997; Liu *et al*., 2000; Foster-Powell, *et al*., 2002).

The glucose response depends on factors such as carbohydrate type (glucose, fructose, galactose, sucrose etc.), entrapment of carbohydrate molecules within the form of the meal, other macronutrient content in the meal, organic acids, amount of salts in the meal and the meal's viscosity (Mondazzi & Arcelli, 2009). Studies have suggested that the absorption rate of a meal could be dependent on its fibre content. Solid/high fibre meals could facilitate a slower digestion rate (Adams *et al*., 2016), resulting in reduced postprandial glucose and insulin responses compared to liquid meals (Berry *et al*., 2003; Ranawana & Henry, 2011). Additionally, a slower digestion rate could also produce a greater and more prolonged sensation of satiety (Almiron-Roig *et al*., 2003; Ranawana & Henry, 2011).

2.6.2 Exercise performance with different sensation of hunger and fullness

In almost every double-blind study, pre-exercise carbohydrate intake, treatment interventions have been provided in liquid form (Lambert *et al*., 1991; Conley & Stone, 1996; Mitchell *et al*., 1997; Haff *et al*., 1999; Dalton *et al*., 1999; Haff *et al*., 2000; Kulik *et al*., 2008; Haff *et al*., 2001; Raposo, 2011; Fairchild *et al*., 2016; Jagim *et al*., 2016; Oliver *et al*., 2016). However, this does not resemble the exact sensations if subject's habitual form of morning/pre-exercise meal is solid/semi-solid. Subjective appetite sensations have been shown to be influenced by the form of meal ingested, (Almiron-Roig *et al*., 2003; Ranawana & Henry, 2011), meaning that if appetite might influence exercise performance, then the form of meal and its subsequent effects on appetite might influence performance. In a review article by Noakes *et al*. the psychobiological effects explained in the Central Governor Model (CGM) of exercise regulation, where unpleasant feelings, due to non-habitual nature of certain new modified circumstances could mediate exercise performance (Noakes *et al*., 2012). Although this model does not entirely replicate the scenario of appetite sensation that could modulate exercise performance, the effect of what was explained in CGM can be linked to a 'learning effect' of particular exercise. In a study where a group of well-trained athletes were asked to perform different types of an unfamiliar endurance exercise time trial in 6 different occasion, demonstrated ~6% and ~10% improvement in time and power output in the third and sixth attempt, respectively (Foster *et al*., 2009). This study suggests that learning the new set of unfamiliar exercises, increases confidence and leads to better performance. Therefore, the psychological states of a person who anticipates what they expect to happen potentially optimises performance beyond physiological/metabolic effects. Thus, it is of interest to observe how manipulation of different appetite sensation (hunger and fullness) effects resistance exercise performance. This will answer whether psychological factors related to a meal might influence exercise performance besides the metabolic effects.

2.7 General summary from literature

In summary, several studies have investigated the effect of consuming or omitting breakfast on endurance exercise performance, however, this effect on resistance exercise is not clear. Given that resistance exercise is routinely included in the training programmes of athletes and sports persons, as well as recreationally active individuals, the effect of a pre-exercise meal/breakfast on performance is of particular interest. Of note, the results of previous experiments might be confounded by the participant's knowledge of the study intervention (i.e. they knew when they ate or skipped breakfast) or the manner in which the pre-exercise meal was provided (i.e. liquid meals). Furthermore, the influence of appetite and the performance effects of a pre-exercise meal in this regard has not been examined. Therefore, the comprehensive investigation of how pre-exercise energy/carbohydrate intake influences resistance exercise performance is warranted. In particular, the role that subjective and hormonal appetite regulation might play in this relationship is of interest and has received no attention in the scientific literature to the author's knowledge. This will allow the true effect of energy intake in the morning (i.e. breakfast) on resistance exercise performance to be determined.

CHAPTER 3: BREAKFAST OMISSION REDUCES SUBSEQUENT RESISTANCE EXERCISE PERFORMANCE

3.1 Introduction

Number of studies in the literature have demonstrated detrimental effect of omitting breakfast on endurance exercise performance. Indeed, reduce glycogen level, especially in the liver, following an overnight fasting is believed the major reason for drop in endurance exercise performance. For resistance exercise, studies have shown it is also a type of glycogen-dependent activity, which refraining from consuming breakfast following overnight fasting could undoubtedly render liver and muscle glycogen deficit, therefore potentially reduce performance outcome. However, none of this has been published in the scientific literature. Thus, this study compares a single exposure of breakfast consumption or omission on strength performance, as well as components of energy balance and energy balance regulation (i.e. energy expenditure, subjective appetite, appetite-related hormones and ad-libitum energy intake).

3.2 Literature review

Resistance exercise is performed by many athletes, often as part of a wider training programme, with performance in such sessions having potential implications for adaptation to the resistance exercise itself, as well as possibly for other aspects of the athlete’s performance (e.g. sport-specific strength performance) or health (e.g. injury prevention/recovery). High intensity exercise largely relies on the utilization of endogenous carbohydrate (glycogen) stores to supply energy for muscular contraction, and as such current recommendations suggest consuming 1-4 g carbohydrate/kg body mass in the 1-4 h before exercise (Burke, *et al*., 2011). Whilst much research has examined the influence of pre-exercise carbohydrate intake (Ormsbee *et al*., 2014) and breakfast (Clayton & James, 2015) on endurance exercise performance, little is known about how pre-exercise carbohydrate intake effects performance in resistance-type exercise.

Glycogen depletion of up to 40% has been reported following a single bout of resistance exercise (Robergs *et al*., 1991; Tesch *et al*., 1998; Haff *et al*., 2000; Haff *et al*., 2003). The degree of glycogen depletion is likely dependent on the type, intensity and duration of the exercise session, with hypertrophy-type resistance exercise (i.e. higher repetition, moderate load exercise) likely to produce larger reductions in muscle glycogen (Slater & Phillips, 2011). Previous studies have demonstrated that commencing resistance-type exercise with suboptimal muscle glycogen levels can impair performance capabilities (Jacobs *et al*., 1981; Leveritt & Abernethy, 1999). Although this is not a universal finding (Mitchell *et al*., 1997), muscle glycogen appears to be an important fuel source for resistance exercise performance, and pre-exercise glycogen stores might therefore effect performance and possible training quality/ adaptation.

Morning training sessions are common place for both athletes and recreational exercisers, and many athletes report skipping breakfast in the morning (Zullig *et al*., 2006; Veasey *et al*., 2015;). Therefore, it is likely that at least some training will take place in a fasted state, where glycogen levels (at least liver glycogen) will be suboptimal. Consumption of a high carbohydrate meal (i.e. breakfast) in the morning after an overnight fast, increases liver (Bawden *et al*., 2014) and to a less extent muscle (Coyle *et al*., 1985; Chryssanthopoulos *et al*., 2004;) glycogen levels, and has been shown to enhance endurance performance (Neufer *et al*., 1987; Ormsbee *et al*., 2014). In contrast, the effect of morning carbohydrate intake before resistance exercise has not been well studied.

Carbohydrate intake before and during a bout of resistance exercise, increases (Haff *et al*., 1999; Haff *et al*., 2000) or tends to increase (Lambert *et al*., 1991) performance when sets of ~10 repetitions are performed to exhaustion. In contrast, carbohydrate intake before or during more intense but lower volume (i.e. sets of 5 reps) resistance exercise (Kulik *et al*., 2008), or fixed repetition (3 sets of 10 reps) isokinetic dynamometer exercise (Haff *et al*., 2000), does not appear to influence performance. These studies suggest that carbohydrate ingestion around resistance exercise is more likely to augment performance when the volume of the training session is greater.

It is not possible to isolate the specific effects of pre-exercise carbohydrate feeding in these experiments, as carbohydrate (and placebo) drinks were provided both before and during exercise. The only study, to our knowledge, to isolate the effect of pre-exercise carbohydrate intake on resistance exercise performance reported no benefit of carbohydrate intake on performance of 3 maximal efforts on an isokinetic dynamometer, for up to 90 min after ingestion (Fairchild *et al*., 2016). However, given the findings of previous studies, the low volume nature of the exercise performed in this study might not be expected to be influenced by carbohydrate intake or manipulation of pre-exercise glycogen stores. Additionally, whilst the provision of carbohydrate in drink form might allow the impact of nutrient ingestion to be elucidated, it might not represent a typical breakfast consumed prior to exercise. Therefore, the purpose of this study was to examine the effect of a typical high carbohydrate breakfast meal on subsequent performance of four sets of resistance exercise at 90% 10-RM to failure (back squat and bench press exercise).

3.2.1 Objectives of study

In order to establish how breakfast consumption/omission affects appetite sensation and resistance exercise performance, this study had the following objectives:

1) Primary objective: to investigate the effect of an ecological breakfast meal versus breakfast omission on subsequent performance of back squat and bench press.
2) Secondary objective: to investigate the effect of an ecological breakfast meal versus breakfast omission on subjective appetite sensation of hunger, fullness, desire to eat and prospective food consumption.

3.3 Methodology

3.3.1 Experimental approach to the problem and main outcome measures

To investigate the problem, subjects, in a cross-over fashion, consumed a typical breakfast meal or a water-only breakfast, two hours before completing four sets of back-squat and bench press, with each set performed to failure. For this study, selection of 4 sets at 90% from 10 RM to exhaustion was meant to resemble a hypertrophy training session scenario as suggested by Ratamess *et al*. (2009). The main outcome measures of this study was the number of repetitions performed in each set which was recorded during both trials to quantify performance.

3.3.2 Subjects

To participate in the study, subjects were required to be non-smokers, habitually consuming breakfast 3 times a week and habitually performing resistance exercise ≥2 times a week for at least 2 years, and to include back squat and bench press in their training routine. Subjects who indicated that they were not habitual breakfast consumers and were not familiar with back squat and bench press were excluded from this study. The sample size for this study was estimated from G*Power 3.0.10 software using an α of 0.05, statistical power of 0.95 and estimated correlation between group of 0.5. After consideration of drop-out rate, it was estimated that 16 subjects would be sufficient to detect a 10% difference in performance between trials. The study received ethical approval from the Loughborough University Ethic Approvals (Human Participants) Sub-Committee and all subjects provided written consent and completed a medical screening questionnaire before commencing the study.

3.3.3 Procedures

3.3.3.1 Pre-trial standardization

In the 24 h before the first experimental trial, subjects weighed and recorded all dietary intake. Subjects also recorded all low intensity habitual activity for the 48 h before the first trial and any physical activity undertaken between 48-72 h before the first trial. These diet and activity patterns were replicated in the 72 h before the second experimental trial. Subjects refrained from any strenuous exercise or alcohol intake in the 48 h before trials.

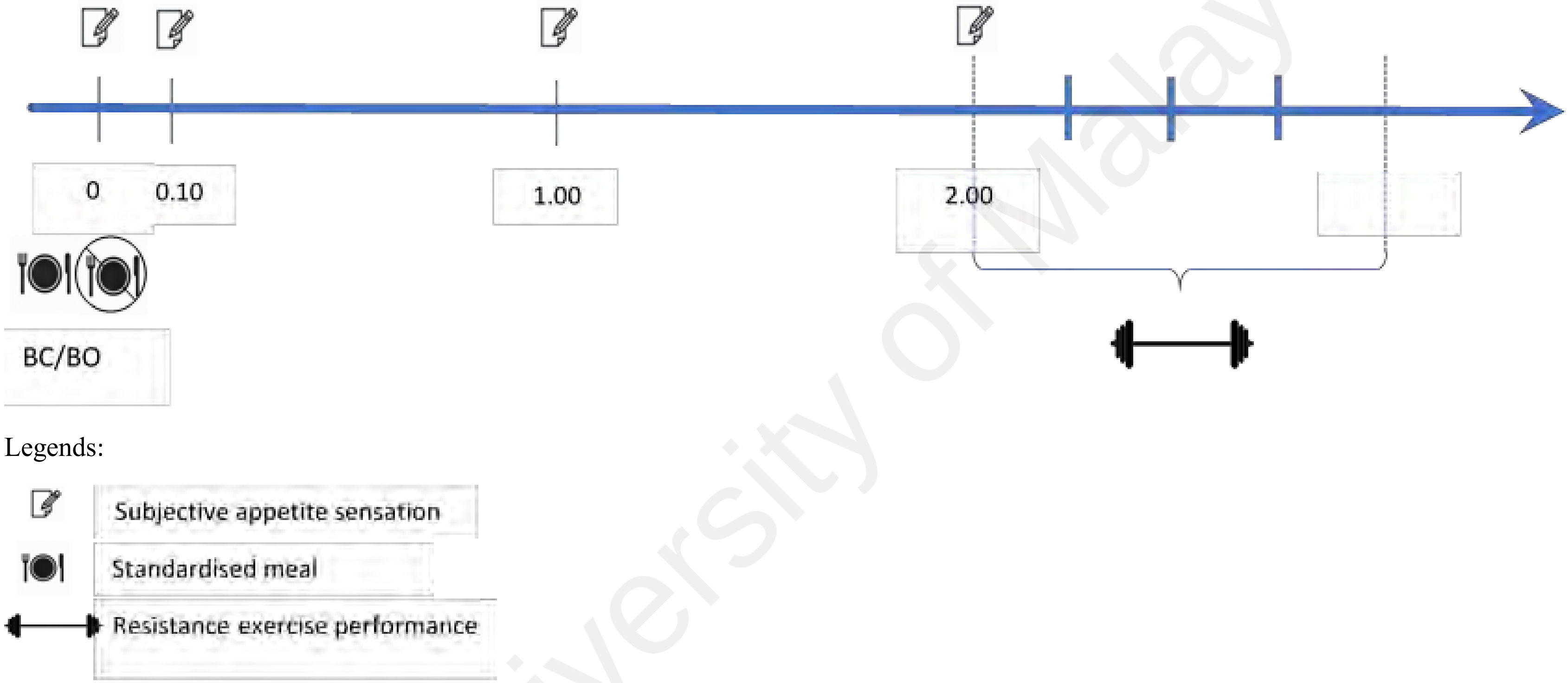
3.3.3.2 Preliminary/familiarization trial

At the preliminary trial, subjects were briefed on the study, before completing consent and screening forms. Subject's physical characteristics (body mass and height) were then measured before their 10-repetition maximum (10-RM) was determined for two bilateral resistance exercises (back-squat and bench-press). Before exercise, subjects performed a 5-min cycling warm-up at 1.5 W/ kg body mass (Monark 894E, Vansbro). They then completed the 10-RM testing in back squat, followed by bench press, each of which was preceded by a 5 min self-selected exercise-specific warm up. Subjects completed 10 repetitions of the exercise, with the load continuing to increase until they were unable to complete 10 repetitions. The last completed set was termed the subjects 10-RM and was used to determine the workload for familiarization and experimental trials, nominally 90% of 10-RM. Following the 10-RM testing and 30 min of rest, subjects were familiarized with the exercise component of the experiment trials, as well as the measurement of subjective appetite (both described in detail below).

3.3.3.3 Experimental trials

For experimental trials, subjects arrived at the laboratory after an overnight fast (approximately 10 h) at a time typical for them to consume breakfast (i.e. approx. 0800-0900) and baseline measurements of body mass, and subjective appetite, were recorded.

During the breakfast consumption (BC) trial, subjects consumed a standardized breakfast meal consisting of rice cereal, milk, bread, butter, jam, and orange juice (Tesco, Cheshunt, United Kingdom) providing ~20% of their estimated energy requirements and 1.5 g carbohydrate/ kg body mass. During breakfast omission (BO), no food was consumed, but subjects consumed water to match the total water content of the BC meal. Meals were consumed over 10 min and were followed by 2 h seated rest in the laboratory. Trials were arranged in a cross-over randomised counter balance, separated by ≥ 4 days in between to allow energy replenishment (Haddock *et al*., 2006). Schematic timeline of this study is presented in **Figure 3.1** whilst the energy and macronutrient content of the breakfasts is provided in **Table 3.1**.



** Time duration approximately 3-4 hours*

Figure 3.1. Schematic timeline for a typical subject on each visit.

Table 3.1 Macronutrient, energy and water intake during each trial.

	Breakfast meal	
	BO	**BC**
Protein (g)	0 ± 0	14.7 ± 1.4
Carbohydrate (g)	0 ± 0	116.3 ± 10.7
Fat (g)	0 ± 0	8.4 ± 0.8
Fibre (g)	0 ± 0	3.8 ± 0.4
Energy (kJ)	0 ± 0	2511 ± 230
Water (ml)	514 ± 72	514 ± 72

Breakfast consumption, BC; Breakfast omission, BO. Values are presented as Mean ± SD.

3.3.3.4 Resistance exercise performance

To assess resistance exercise performance, subjects performed 4 sets to failure of back squat followed by bench press at 90% of each subject's 10-RM. Subjects initially performed a 5-min cycling warm-up, as previously described. For each exercise, subjects then performed 5 min of individually standardized self-selected stretching and exercise-specific warm up, followed by two warm up sets of 10 repetitions at 30% and 60% of 10-RM. All exercise sets were followed by 3 min rest. For each exercise, subjects performed standardized lifting technique, with two spotters assisting them to reach the starting position for each set. For the squat, the bar was held across the back of subject's shoulders and they started with knees fully extended, lowering themselves until their thighs were parallel to the floor, before returning to the starting position. For bench press, subjects started with their elbows fully extended and lowered the bar until it lightly touched their chest, before returning to the starting position. Each correctly completed repetition was counted by an investigator and failure defined as when subjects were unable to complete a repetition.

3.3.3.5 Subjective appetite sensations

Subjects rated their sensations of hunger, fullness, desire to eat (DTE) and prospective food consumption (PFC) using a visual analogue scale before BC/BO (~0820), after BC/BO (~0830), as well as 1 h (~0930) and 2 h (~1030) after BC/BO. Written anchors of "not at all" /"none at all" and "extremely"/ "a lot" were placed 0 and 100 mm, respectively (Flint *et al*., 2000).

3.3.4 Statistical analyses

Data were reported as mean and standard deviation (M ± SD) and were analysed using SPSS software (Version 23.0; IBM Corp., Armonk, NY). The Shapiro-Wilk test was initially used to determine the normality of data. The Levene's test was used to assess the homogeneity of variance between groups. Data containing two factors were analysed using 2-way repeated measures ANOVA, with significant effects followed by Holm-Bonferroni-adjusted paired *t*-test or Holm-Bonferroni-adjusted Wilcoxon's Signed Rank test, as appropriate. Data containing one factor were analysed using paired *t*-test or Wilcoxon's Signed Rank test, as appropriate. Statistical significance was set at $P < 0.05$.

3.4 Results

3.4.1 Descriptive demographic

Sixteen resistance trained males (age 23 ± 4 years, body mass 77.56 ± 7.13 kg, height 1.75 ± 0.04 m, BMI 25.3 ± 2.3 kg/m^2) completed this study. On average, subjects consumed breakfast 5 ± 2 times/week and performed resistance exercise 4 ± 2 times/week, with back squat and bench press performed 2 ± 1 times/ week and 2 ± 1 times/week, respectively.

3.4.2 Pre-trial measures and breakfast perceptions

Pre-trial body mass was similar between trials (BO: 77.78 ± 7.33 kg; BC: 77.58 ± 7.21 kg; P = 0.355). Subjective feelings of hunger (P = 0.083), fullness (P = 0.245), DTE (P = 0.088) and PFC (P = 0.775) were also similar between trials (Table 2). Subjects rated the breakfast consumed during BC as more pleasant (BO = 7 ± 13 mm; BC = 63 ± 21 mm; P < 0.001) and more filling (BO = 42 ± 21 mm; BC = 77 ± 14 mm; P = 0.001) than the water consumed in BO.

3.4.3 Strength performance

There were trial (P < 0.001), time (P < 0.001) and interaction (P = 0.027) effects for back squat performance. Over the four working sets, total repetitions completed were ~10% lower during the BO trial (BO = 58 ± 11 reps; BC = 68 ± 14 reps; P < 0.001) **(Figure 3.2 A)**. Repetitions in sets 1 (BO = 21 ± 5 reps; BC = 26 ± 6 reps; P = 0.001) and 2 (BO = 15 ± 2 reps; BC = 17 ± 4 reps; P = 0.008) were lower during BO compared to BC, whilst repetitions in sets 3 ($P = 0.54$) and 4 ($P = 0.13$) were not different between trials **(Figure 3.2 B)**. For bench press performance, there were trial ($P = 0.001$) and time ($P < 0.001$) effects, but no interaction effect ($P = 0.297$). Total repetitions completed were ~5% lower during the BO trial (BO = 38 ± 5 reps; BC = 40 ± 5 reps; $P < 0.001$) **(Figure 3.3 A)**. Similarly, repetitions in sets 1 (BO: 14 ± 2 repetitions; BC: 15 ± 2 repetitions; $P = 0.009$) and 2 (BO = 9 ± 2 repetitions; BC = 10 ± 2 repetitions; $P = 0.038$) were lower during BO compared to BC, whilst repetitions in sets 3 ($P = 0.24$) and 4 ($P = 0.46$) were not different between trials **(Figure 3.3 B)**.

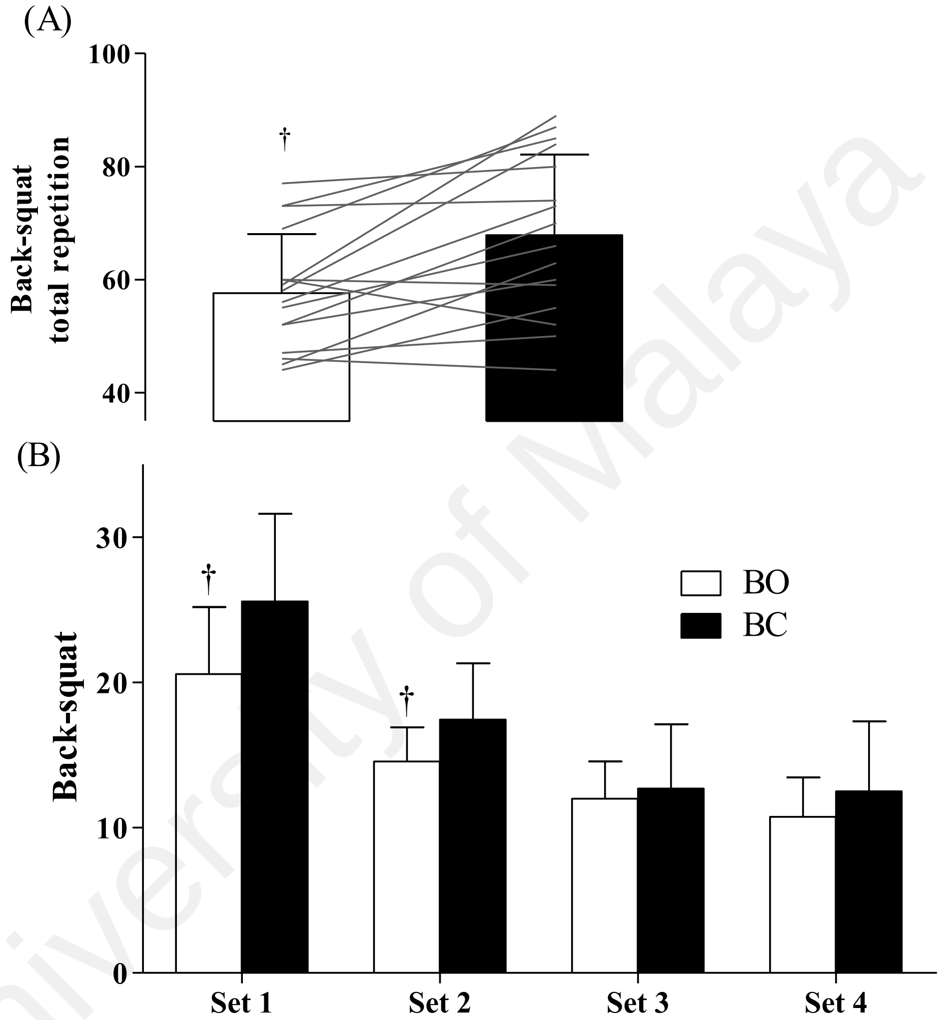


Figure 3.2 (A) Total repetitions over the four sets of back-squat and **(B)** repetitions performed in each back-squat set. Bars are mean values, vertical error bars represent SD and lines represent individual subject data, n = 16. Dagger (†) denotes significantly different from BC ($P < 0.05$).

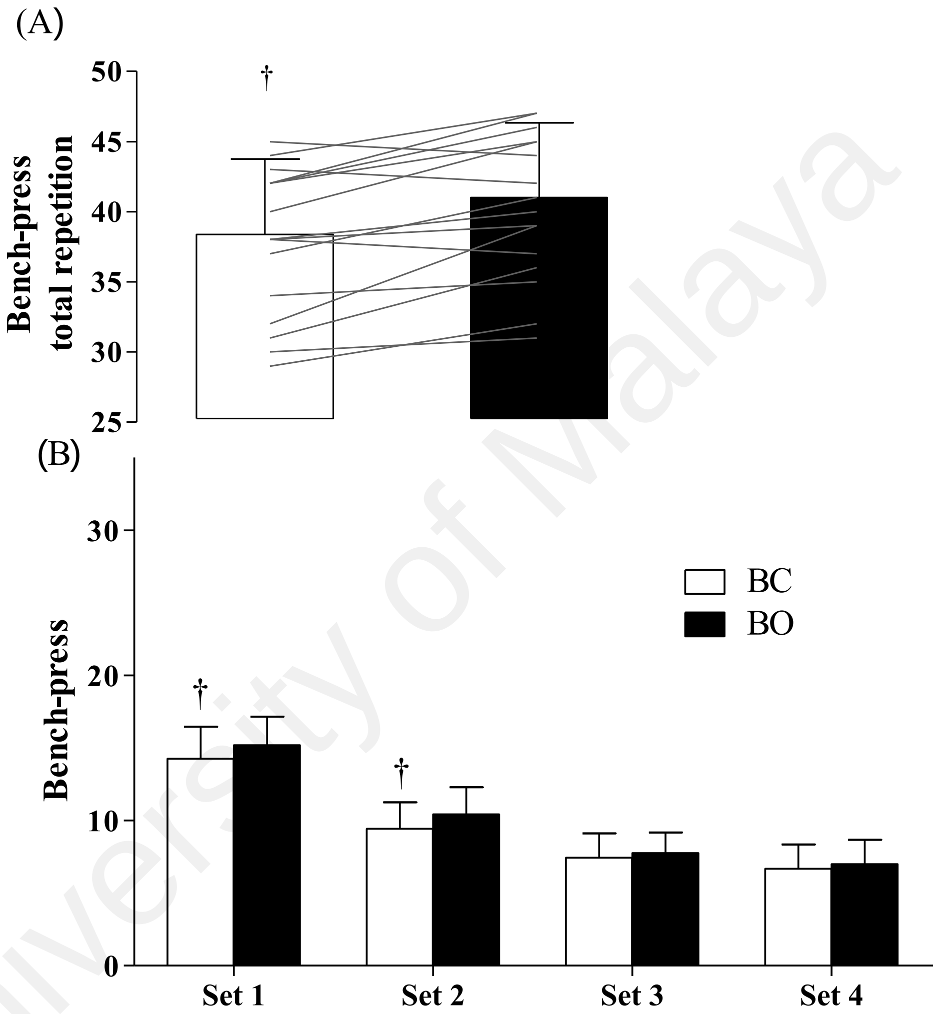


Figure 3.3 (A) Total repetitions over the four sets for bench-press and (**B)** repetitions performed in each bench-press set. Bars are mean values, vertical error bars represent SD. Dagger (†) denotes significantly different from BC (*P* < 0.05).

3.4.4 Subjective appetite sensations

There were trial (P < 0.001), time (P < 0.001), and interaction (P < 0.001) effects for all subjective appetite sensations **(Figure 3.4)**. At all-time points post-meal, fullness was greater, whilst hunger, DTE and PFC were all lower after BC compared to BO (P < 0.001). Compared to pre-meal values, the breakfast during BC decreased hunger, DTE and PFC, and increased fullness immediately and 1 h post-meal ($P \leq 0.001$), with the effects for fullness and DTE persisting to 2 h post-meal ($P \leq 0.043$). In contrast, compared to pre-meal, the water-only breakfast in BO increased fullness immediately post-meal (P = 0.009) and increased hunger and DTE 2 h post-meal ($P \leq 0.002$).

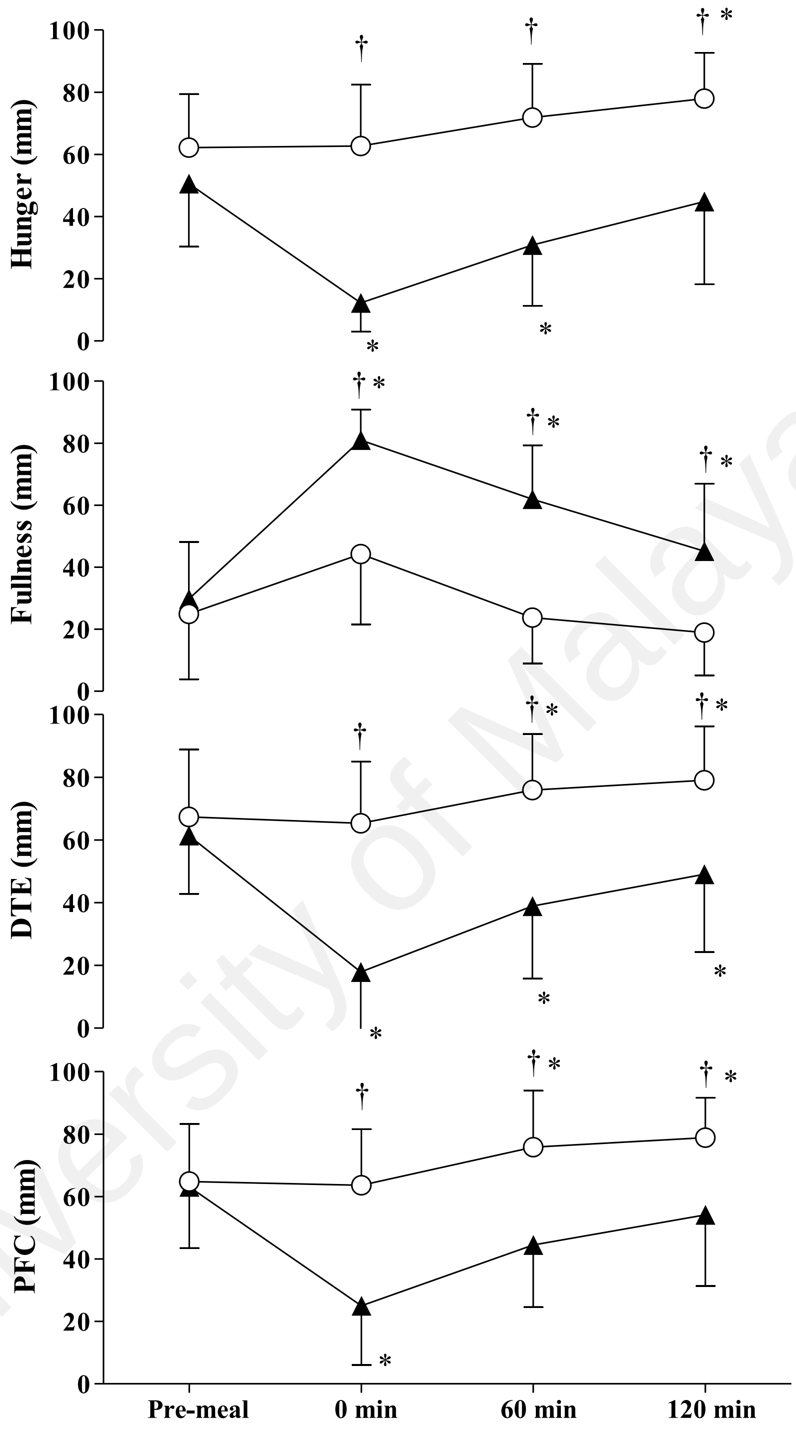


Figure 3.4. Subjective appetite ratings of hunger, fullness, desire to eat (DTE), and prospective food consumption (PFC) throughout the experimental trial. White circle (○) represents the breakfast omission (BO), and black triangle (▲) represent breakfast consumption (BC). Dagger (†) denotes significantly different from BC, whilst asterisk (*) denotes significant different from pre-meal (*P* < 0.05).

3.5 Discussion

This study is the first to report the effect of an ecologically valid high carbohydrate breakfast on subsequent resistance exercise performance. The main findings of this study were that participants completed ~15% more repetitions of back squat and ~6% more repetitions of bench press when they consumed the high carbohydrate breakfast (providing 1.5 g carbohydrate/kg body mass) compared to when they consumed a water only breakfast. This suggests that a high carbohydrate meal might be a beneficial pre-exercise strategy to augment an increased training volume at a morning resistance exercise session.

Whilst there is a wealth of literature suggesting that pre-exercise carbohydrate/energy intake enhances prolonged endurance performance, little is known about how resistance-type exercise performance is influenced by pre-exercise nutrition. Thus, this study provides novel data suggesting that resistance exercise performance can be enhanced by the consumption of a high carbohydrate pre-exercise meal. This finding contrasts the results of the only other study to investigate the isolated effects of pre-exercise carbohydrate/ energy intake on resistance exercise performance (Fairchild *et al*., 2016). These disparate results might be explained by the nature of the resistance exercise performed, where different mechanisms are likely to limit performance. Performance in the study of Fairchild *et al*. was measured through 3 maximal efforts on an isokinetic dynamometer, with this performance unlikely to be dependent on muscle glycogen availability (Fairchild *et al*., 2016). In contrast, the higher volume nature of the exercise used in the present study, which represents a more ecologically valid resistance training scenario, is more likely to rely on glycogen as a fuel source (Lambert *et al*., 1991), potentially explaining the observed results.

Indeed, some evidence supports the notion that pre-resistance exercise carbohydrate intake/glycogen stores might be an important determinant of performance. Leveritt and Abernathy reported that a muscle glycogen depleting regimen (cycling exercise followed by 2 days low carbohydrate diet) produced a ~20% reduction in the number of repetitions completed in 3 sets of back squat to fatigue (Leveritt & Abernethy, 1999). Interestingly, Leveritt and Abernathy also measured performance in 5 sets of 5 repetitions of isokinetic dynamometry, observing no difference between conditions (Leveritt & Abernethy, 1999). This suggests, as mentioned above, that pre-exercise glycogen stores might play a more important role where the volume of work performed is higher. Similarly, Haff *et al*. (Haff *et al*., 2000) and Oliver *et al*. (Oliver *et al*., 2016) reported that performance during resistance exercise a few hours after a bout of glycogen depleting exercise was enhanced when carbohydrate was provided between the two exercise bouts. Although muscle glycogen was not measured in these studies, the ingestion of carbohydrate in one trial, but not the other would be expected to alter glycogen re-synthesis and glycogen content at the start of the second bout of exercise. Mitchell *et al*. manipulated muscle glycogen before a bout of resistance exercise with subjects performing cycling exercise, followed by 48 h of either high or low carbohydrate intake (Mitchell *et al*., 1997). In contrast to previous studies, performance in 5 sets to fatigue (~10-15 reps) of squat, leg press and leg extension was not affected by this pre-exercise regimen (Haff *et al*., 2000; Oliver *et al*., 2016). Although an explanation for the disparity in findings between studies remains elusive, the lack of a direct measure of muscle glycogen means there is uncertainty about whether muscle (or indeed liver) glycogen stores were different between conditions. On balance, at least, it would seem that starting exercise with high glycogen stores or following a high carbohydrate intake is the most prudent approach to maximise resistance exercise performance, with the findings of the current study perhaps providing further evidence of this.

Muscle glycogen is an important fuel source during resistance-type exercise (Lambert & Flynn, 2002), with studies reporting muscle glycogen depletion by up to 40% following a single bout of resistance exercise (Robergs *et al*., 1991; Tesch *et al*., 1998; Haff *et al*., 2000; Haff *et al*., 2003). For example, Robergs *et al*. (1991) reported that 6 sets of 6 repetitions of leg extension at 70% 1-RM caused a 38% reduction in the glycogen content of the vastus lateralis (Robergs *et al*., 1991). It is well documented that, whilst type-II muscle fibres have greater glycogen stores compared to type I fibres (Greenhaff *et al*., 1994), the rate of glycogenolysis during high intensity exercise is also greater (Greenhaff *et al*., 1994; Judelson *et al*., 2008; Vøllestad *et al*., 1992). Resistance exercise augments a similar response, with selectively greater muscle glycogen use in type-II versus type-I muscle fibres (Robergs *et al*., 1991; Koopman *et al*., 2006;). If, as suggested by Lambert and Flynn, the depletion of muscle glycogen is a contributing factor to the generation of fatigue during resistance exercise, then increasing pre-exercise glycogen stores might have the potential to enhance performance (Lambert & Flynn, 2002).

Consumption of a high carbohydrate meal after an overnight fast has been shown to produce a small, but potentially meaningful, increase in skeletal muscle glycogen content (Chryssanthopoulos *et al*., 2004), which may account for the enhanced performance in the BC trial. Indeed, the fact that carbohydrate intake after an overnight fast only induces a small increase in muscle glycogen, might go some way to explain the pattern of results in the present study. For both back squat and bench press, repetitions completed were greater during BC compared to BO in the first 2 sets only. It is possible that the extra repetitions performed in sets 1 and 2 utilised any additional glycogen present at the start of the exercise in the BC trial, meaning that by the time subjects performed sets 3 and 4, muscle glycogen content was similar between trials. In addition to muscle glycogen, the consumption of breakfast in BC would have substantially increase liver glycogen compared to BO (Nilsson & Hultman, 1973; Hawley & Burke, 1997) . Whilst liver glycogen appears to be an important energy store utilised during endurance exercise (Gonzalez *et al*., 2016), its relevance to resistance-type exercise performance is unknown. However, in the absence of an exogenous carbohydrate source, liver glycogenolysis helps to maintain blood glucose concentrations. Provision of exogenous carbohydrate during resistance exercise has been shown to attenuate muscle glycogen use (Haff *et al*., 2000) and increase performance (Lambert *et al*., 1991; Haff *et al*., 1999;). Therefore, it is possible that starting exercise with greater liver glycogen stores might mean a greater supply of glucose to the working muscle from blood glucose, reducing the reliance on muscle glycogen and enhancing performance capabilities.

Although blood glucose was not measured in the present study, the breakfast used in the BC trial was very similar to those used in previous published studies (Clayton *et al*., 2016a; Clayton, *et al*., 2016b). These previous studies report acute increases in plasma glucose and insulin concentrations, giving us confidence that the same effects were apparent in the present study. Whilst the provision of carbohydrate in the breakfast and the subsequent effects on glycogen stores is the most likely cause of the enhanced performance, other non-nutrient specific mechanisms might also be responsible for the observed effects. The breakfast in the BC trial suppressed appetite after consumption, with hunger, desire to eat and prospective food consumption all lower, and fullness higher in BC compared to BO at all time points after eating. Although speculative, it is possible that the increase in appetite in the BO trial induced some level of discomfort/ distraction that might have reduced exercise performance. Future experiments should attempt to separate the performance effects of nutrient provision from that of the appetite suppression induced by eating.

Whilst the present study demonstrates a pre-exercise meal (i.e. breakfast) enhances resistance exercise performance, the results are not without limitation. Whilst the purpose of the present study was to examine the impact of an ecologically valid breakfast on resistance exercise performance, this meant, by design, that whilst the study included a control trial (i.e. the BO trial), the results observed could be caused by subject's knowledge of whether they consumed breakfast or not. It is possible that the breakfast in the BC trial might have acted as a placebo to enhance performance. Recently, Mears *et al*. reported that a short duration cycling time trial (~20 min) was similarly enhanced compared to a water control trial by a placebo breakfast (a very low energy thickened breakfast drink) and a high carbohydrate breakfast (the same breakfast drink plus 2 g carbohydrate/ kg body mass) (Mears *et al*., 2017). This suggests, that in some situations, breakfast might act as a placebo that can enhance performance, which is something future studies should investigate with resistance exercise performance.

3.6 Conclusion

The results of this study conclude that, for trainers, consumption of a pre-exercise breakfast meal (1.5 g carbohydrate/kg body mass and ~20% from total daily requirement) might enhance resistance exercise performance. This might have implications for the volume of exercise completed, and possibly the subsequent adaptive response to exercise training. Therefore, these results suggest that, at least for exercise sessions where subjects exercise to failure, it might be advisable to recommend the consumption of a high carbohydrate meal before exercise, particularly if the training session is undertaken in the morning. Therefore, answering hypothesis 1, omission of an ecological breakfast was shown to be detrimental to resistance exercise performance in the morning. However, given the paucity of data in this area, future studies should explore optimal amounts and timings of pre-exercise meals to maximise resistance-type exercise performance.

CHAPTER 4: A PRE-EXRERCISE MEAL INCREASE RESISTANCE PERFORMANCE VIA PLACEBO EFFECT

4.1 Introduction

This study follows on from Chapter 3 that demonstrated skipping breakfast can impair resistance exercise performance compared when an ecologically valid breakfast with high portion of carbohydrate was given. However, the nocebo effect of this study, as with many previous studies investigating the effect of breakfast consumption might be confounded by the participant's knowledge of the study intervention which they were in aware when they ate or skipped breakfast. Therefore, this study was designed to isolate the metabolic and psychological effects of a breakfast by using a low-energy gelling agent to increase the viscosity (thickness) and therefore decrease sensations of hunger and increase fullness, of a low-energy placebo solution to give the appearance of energy consumption. This will allow the true effect of calorie intake in the morning (i.e. breakfast) to be determined.

4.2 Literature review

Resistance exercise is regularly performed by athletes/recreational exercisers and performance in such sessions might have important implications for training volume, and consequently gains in muscle mass/strength (Ralston, *et al.*, 2018), as well as for prevention of/recovery from injury. The pre-exercise meal, particularly its carbohydrate content, is an important component of an athlete's nutrition plan (Ormsbee *et al.*, 2014), with current guidelines recommending 1-4 g carbohydrate/kg body mass should be consumed in the 1-4 h pre-exercise (Burke *et al*., 2011). Previous research has demonstrated that consumption of carbohydrate in the hours before endurance exercise enhances performance (Ormsbee *et al*., 2014), but little is known about how such nutrition strategies influence performance in resistance-type exercise. However, whether the beneficial effects of carbohydrate intake before endurance exercise extend to resistance exercise is not well understood.

Carbohydrate intake at the first meal of the day following an overnight fast (i.e. breakfast) increases both the liver (Nilsson & Hultman, 1973) and muscle (Coyle *et al*., 1985; Chryssanthopoulos *et al*., 2002) glycogen. Muscle glycogen appears to be an important fuel source for resistance-type exercise, with a single exercise bout reducing muscle glycogen content by up to 40% (Haff *et al*., 1999; Robergs *et al*., 1991). Some have suggested that this muscle glycogen depletion might play a role in the development of fatigue during resistance exercise (Lambert & Flynn, 2002; Ørtenblad, Westerblad, & Nielsen, 2013). Consequently, the elevation of endogenous glycogen stores through pre-exercise feeding might delay fatigue and enhance performance (Coyle *et al*., 1986). Indeed, commencing a bout of resistance exercise with reduced glycogen stores has been shown to reduce performance by some (Jacobs *et al*., 1981; Leveritt & Abernethy, 1999; Oliver *et al*., 2016), but not all (Mitchell *et al*., 1997) studies. Similarly, we recently reported (Mears *et al*., 2017; Naharudin *et al*., 2019) that compared to a no breakfast trial, an ecologically valid breakfast (containing 1.5 g carbohydrate/kg body mass) increased performance in 4 sets of back-squat and 4 sets of bench-press 2 h later. Collectively, these studies suggest that greater endogenous glycogen stores at the start of resistance exercise might increase performance.

The results of these studies might, at least partially, be explained by the overtness of the methods used (i.e. conscious exercise/diet manipulation). Consequently, these previous studies might have been influenced by subjects' knowledge of, and preconceptions about, the intervention taking place. Indeed, we have recently demonstrated that a virtually energy-free placebo breakfast produces a similar increase in high-intensity cycling performance (~20 min) as a taste/texture matched high carbohydrate (2 g/kg body mass) breakfast, when compared to a water-only control breakfast (Mears *et al*., 2018). This suggests that a pre-exercise meal/breakfast might act as a placebo to enhance high-intensity endurance performance, but whether these effects extend to resistance exercise (another high-intensity activity) is unknown.

Therefore, the aim of this study was to examine the effect of a pre-exercise high-carbohydrate breakfast meal on resistance exercise performance, compared to a texture and taste-matched placebo breakfast and a water control. This was to enable the physiological/metabolic effects of pre-exercise carbohydrate/energy intake to be separated from the potential psychological effects of eating. It was hypothesized that the carbohydrate and placebo breakfast meals would increase resistance exercise performance compared to the control breakfast, with the carbohydrate breakfast meal also increasing resistance exercise performance compared the placebo breakfast meal.

4.2.1 Objectives of study

For this experiment, it is aimed to observe if performance would be affected by preceding breakfast meal thought to contain energy given to a group of gym goers who habitually consume breakfast. The objectives of this study were:

1) Primary objective: to compare pre-exercise meals of water, as well as placebo and maltodextrin containing meals on performance in 4 sets of each of back squat and bench press exercise.
2) Secondary objective: to compare how subjective appetite sensations, plasma glucose, insulin, total $ghrelin_{total}$, $GLP\text{-}1_{total}$ and PYY_{total} were regulated following the consumption of a water-only breakfast, as well as placebo and maltodextrin containing meals.

4.3 Methodology

4.3.1 Experimental approach to the problem and main outcome measures

This study follows on from Chapter 3 that showed that skipping breakfast impaired resistance exercise performance compared to eating breakfast. However, the results of this study, as with many previous studies investigating the effect of breakfast might be confounded by the participant's knowledge of the study intervention (i.e. they knew when they ate or skipped breakfast). Therefore, this study used a low-energy gelling agent to increase the viscosity (thickness) of a liquid breakfast and give the appearance of energy consumption. This allowed the true effect of energy intake (specifically carbohydrate) in the morning (i.e. breakfast) to be determined. The main outcome measure of this study was to determined back-squat and bench press total repetitions following 3 type of pre-exercise meal which were placebo, carbohydrate-containing a water control.

4.3.2 Subjects

For enrolment into the study, which was approved by the Loughborough University Ethical Approvals (Human Participants) Sub-Committee, subjects had to be gym goers, habitually consuming breakfast at least three mornings a week, and who included back squat and bench press as part of their weekly training routine for at least once a week. Subjects who indicated that they were not habitual breakfast consumers or were not familiar with back squat and bench press were excluded from the study. The sample size for this study was estimated from G*Power 3.0.10 software using an α of 0.05, statistical power of 0.95 and estimated correlation between group of 0.5. It was estimated that 22 subjects would be sufficient to detect a 15% difference in performance between trials.

4.3.3 Study design

The study examined the effect of a high carbohydrate pre-exercise breakfast on resistance exercise performance, whilst controlling for any placebo effect associated with breakfast/food intake. Subjects visited the laboratory on 5 separate occasions: 10-repetition maximum (10-RM) measurement; familiarisation trial; and three experimental trials, during which subjects consumed a breakfast and ~2 h later performed an exhaustive bout of resistance exercise. The breakfasts used were a water-only control breakfast (WAT), and two viscous breakfasts containing either 0 g/kg body mass (PLA) or 1.5 g/kg body mass (CHO) of maltodextrin. Trials were arranged in a cross-over randomised counter-balanced design, separated by ≥4 days to allow energy replenishment (Haddock *et al*., 2006) and CHO and PLA breakfasts were administered in a double-blind manner. Subjects were told the purpose of the experiment was to test two energy-containing breakfasts of different macronutrient composition against a no-breakfast control trial. They were not aware one of the breakfast trials contained virtually no energy. Schematic timeline of this study can be observed in **Figure 4.1**.

4.3.4 Preliminary visit and familiarisation trial

After warming up (5 min cycling at 1.5 W/kg body mass) subjects completed 10-repetition maximum (10-RM) testing of back squat and bench press, each of which was preceded by 5 min of self-selected exercise-specific warm-up. After some warm up sets (self-selected), subjects were asked to perform their first attempt of each exercise at a weight close to their estimated 10-RM. The load increased incrementally thereafter until they could no longer complete 10 repetitions. Subjects were given at least 3 minutes of rest between sets. The last completed set of 10 repetitions was termed subject's 10-RM and was used to determine the study exercise workload. During a separate visit, subjects were fully familiarised with all procedures used in the experimental trials.

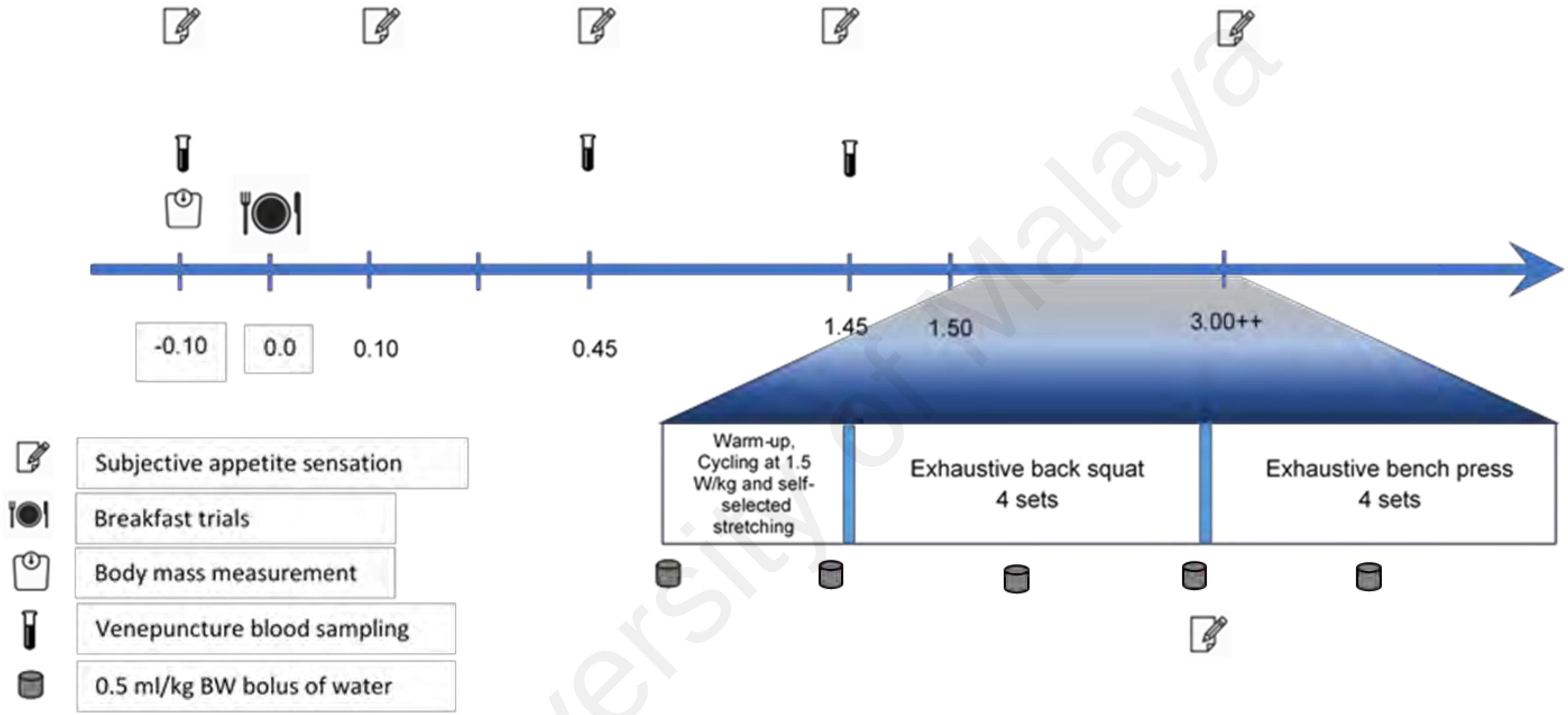


Figure 4.1. Schematic diagram for typical subjects during trial visit.

4.3.4.1 *Pre-trial standardisation*

Subjects were given a diet/activity diary and were asked to record their habitual diet and activities for two days before the first experimental trial and replicated these patterns before subsequent trials. Subjects were asked to refrain from taking part in any vigorous activity or consumption of alcohol in this 48-h pre-trial period.

4.3.4.2 *Experimental trials*

Subjects arrived at the laboratory after an overnight fast (10-13 h) at a time typical for them to consume breakfast (i.e. approx. ~0800-0900). Baseline measurements of body mass and subjective appetite were made, and after 15 min seated rest, a venous blood sample was collected. Subjects then consumed their allotted breakfast meal within 10 min, with additional measures of subjective appetite taken immediately (i.e. 10 min), 45 min and 105 min post-meal. Further venous blood samples were drawn at 45 min and 105 min. Subjects then completed the resistance exercise session described below.

4.3.4.3 *Breakfast meals*

During the two breakfast trials, subjects ate a semi-solid breakfast meal from a standard bowl using a standard spoon. The volume of the meal was 5 mL/kg body mass, of which 15% (i.e. 0.75 mL/kg body mass) was low-energy orange flavoured squash (Double Strength Orange squash, Tesco, Welwyn Garden City, UK), with the remainder made up of tap water. To this mixture, either 0 g/kg body mass (PLA) or 1.5 g/kg body mass of maltodextrin (My Protein, Northwich, UK) was added and mixed thoroughly, before 0.1 g/kg body mass of xanthan gum (My Protein, Northwich, UK) was added and the mixture blended to thicken the solution and enhance the perception of energy intake (Fiszman & Varela, 2013). PLA and CHO breakfasts were taste, texture and colour matched and were made the day before trials by an experimentor not involved in data collection. Additionally, 3 mL/kg body mass of tap water was consumed as a drink with meals. For the WAT trial, subjects consumed 8 mL/kg body mass of tap water to match the water content in PLA and CHO. The nutritional content of the breakfast meals is presented in **Table 4.1**. All meals were consumed over a 10 min period.

At the end of the last experimental trial, subjects were informed of the contents of the breakfasts and the true aim of the study, before being asked if they could identify the breakfasts. If they answered yes, they were asked to say which was which.

Table 4.1. Nutritional content of breakfast meals.

	WAT	PLA	CHO
Protein (g)	0 ± 0	0.8 ± 0.1	0.8 ± 0.1
Carbohydrate (g)	0 ± 0	2.4 ± 0.1	119.2 ± 12.4
Fat (g)	0 ± 0	0.6 ± 0.1	0.6 ± 0.1
Fibre (g)	0 ± 0	5.4 ± 0.6	5.4 ± 0.6
Energy (kJ)	0 ± 0	122 ± 13	2075 ± 216
Water (mL)	623 ± 65	623 ± 65	623 ± 65

Water control trial; WAT, placebo trial; PLA; carbohydrate trial; CHO. Values are present in mean ± SD.

4.3.4.4 Resistance exercise performance

Subjects initially performed a 5 min warm-up on a cycle ergometer at 1.5 W/kg body mass, before performing back squat followed by bench press exercise. Each exercise was preceded by 5 min of individually standardised self-selected stretching and exercise-specific warm up followed by warm-up sets of 10 repetitions at 30% and 60% of 10-RM. Subjects then perform four sets to failure at 90% 10-RM. For each exercise, subjects performed standardised lifting technique, with two spotters assisting them to reach the starting position for each set. For the squat, the bar was held across the back of subject's shoulders and started with knees fully extended, lowered themselves until their thighs were parallel to the floor, before returning to the starting position. For bench press, subjects started with their elbows fully extended and lowered the bar until it lightly touched their chest, before returning to the starting position. Every repetition was counted in silence and verbal standardised encouragement was given to the subjects throughout. All sets were separated by 3 min rest. Additional subjective appetite measures were made after the back squat and bench press exercise. Subjects consumed 0.5 mL/kg body mass of water immediately before the cycling warm up, as well as before sets 1 and 3 of back squat and bench press.

4.3.4.5 Subjective appetite sensations

Throughout experiment trials, subjects rated their subjective sensation of hunger and fullness using visual analogue scales with written anchors of "not at all" /"none at all" and "extremely"/ "a lot" placed 0 and 100 mm, respectively (Flint *et al*., 2000).

4.3.4.6 Blood sampling and analysis

For each sample, ~10 mL blood was drawn by venepuncture from an antecubital/forearm vein after 15 min seated rest. Blood was dispensed into tubes (Sarstedt AG & Co., Nümbrecht, Germany) containing a clotting catalyst or EDTA (1.75 mg/mL), centrifuged 2300 g, 15 min, 4°C) and the resultant serum/plasma was stored at -20°C until analysis. Plasma glucose was determined using a colorimetric assay (Horiba Medical UK, Northampton, UK; CV 0.5%), whilst serum insulin (Immunodiagnostic Systems, Bolden, UK; CV 2.2-3.8%) and total concentrations of plasma ghrelin (CV = 1.7-1.8%), glucagon-like pepetide-1 (GLP-1; CV = 2.5-8.2%) and peptide tyrosine-tyrosine (PYY; CV = 3.8-5.6%; All Merck Millipore Ltd, Watford, UK) were determined using commercially available ELISAs. Due to issues with blood collection with 2 subjects, blood samples were only collected from 20 subjects.

4.3.5 Statistical analyses

Data were analysed using SPSS (Version 23.0; IBM Corp., Armonk, NY). All data were checked for normality using a Shapiro-Wilk test. Data containing two factors were analysed using two-way repeated measure ANOVA. Data containing one factor were analysed using one-way repeated measures ANOVA. Where ANOVA indicated significant effects, *post-hoc* Holm-Bonferroni-adjusted paired sample *t*-test or Bonferroni-adjusted Wilcoxon Signed Rank test were used, as appropriate All statistical significance was set at $P < 0.05$ and data are presented as means ± SD.

4.4 Results

4.4.1 Descriptive demographic

Twenty-four men experienced with resistance exercise (age 23 ± 3 years, body mass 77.9 ± 8.1 kg, height 1.75 ± 0.05 m, BMI 25.2 ± 2.0 kg/m^2) volunteered for this study. However, twenty-two subjects completed the experiment whilst one withdrew due to old injury and the other due to illness, with both of these unrelated to the study protocol. Subjects had 4.7 ± 1.5-year resistance exercise experience, were performing 5 ± 1 resistance training sessions/week, with 2 ± 1 sessions/week of both back squat and bench press. All subjects ate breakfast 7 days a week.

4.4.2 Baseline measures and breakfasts perception

Subjects baseline body mass was comparable between trials (WAT 77.4 ± 8.3; PLA 77.5 ± 8.4; CHO 77.4 ± 8.4 kg; $P = 0.671$). Additionally, hunger ($P = 0.543$), fullness ($P = 0.961$), were similar between trials. Subjects rated the meals similarly pleasant (WAT: 34 ± 19 mm; PLA: 27 ± 19 mm; CHO: 27 ± 23 mm; $P = 0.462$), but rated in the PLA (73 ± 19 mm) and CHO (79 ± 16 mm) meals more filling than WAT (34 ± 24 mm $P < 0.001$), with no difference between PLA and CHO ($P = 0.176$).

Thirteen subjects stated they thought they could detect a difference between PLA and CHO breakfasts, with 11 correctly identifying the trials. Of these thirteen subjects, seven and eight of them performed better in back squat and bench press, respectively, in CHO trial.

4.4.3 Resistance exercise performance

Total repetitions for back-squat (**Figure 4.2A**) were greater in PLA and CHO than WAT ($P < 0.001$), with no difference between PLA and CHO ($P = 1.000$). For back-squat repetitions completed over the 4 sets (**Figure 4.2B**), there were trial ($P < 0.001$), time ($P < 0.001$) and interaction ($P = 0.002$) effects. Repetition in set 1 ($P < 0.001$) and 2 ($P < 0.01$) were greater in CHO and PLA, compared to WAT, whilst no difference between trials in set 3 and 4 were noted. For bench-press, total repetitions were not different between trials (**Figure 4.3A**; $P = 0.130$). There were trial ($P = 0.01$) and time ($P < 0.001$) effects, but no interaction effect ($P = 0.234$) for bench press repetitions completed over the 4 sets (**Figure 4.3B**). Repetitions in set 1 were greater in CHO compared to WAT ($P = 0.039$), with no other differences.

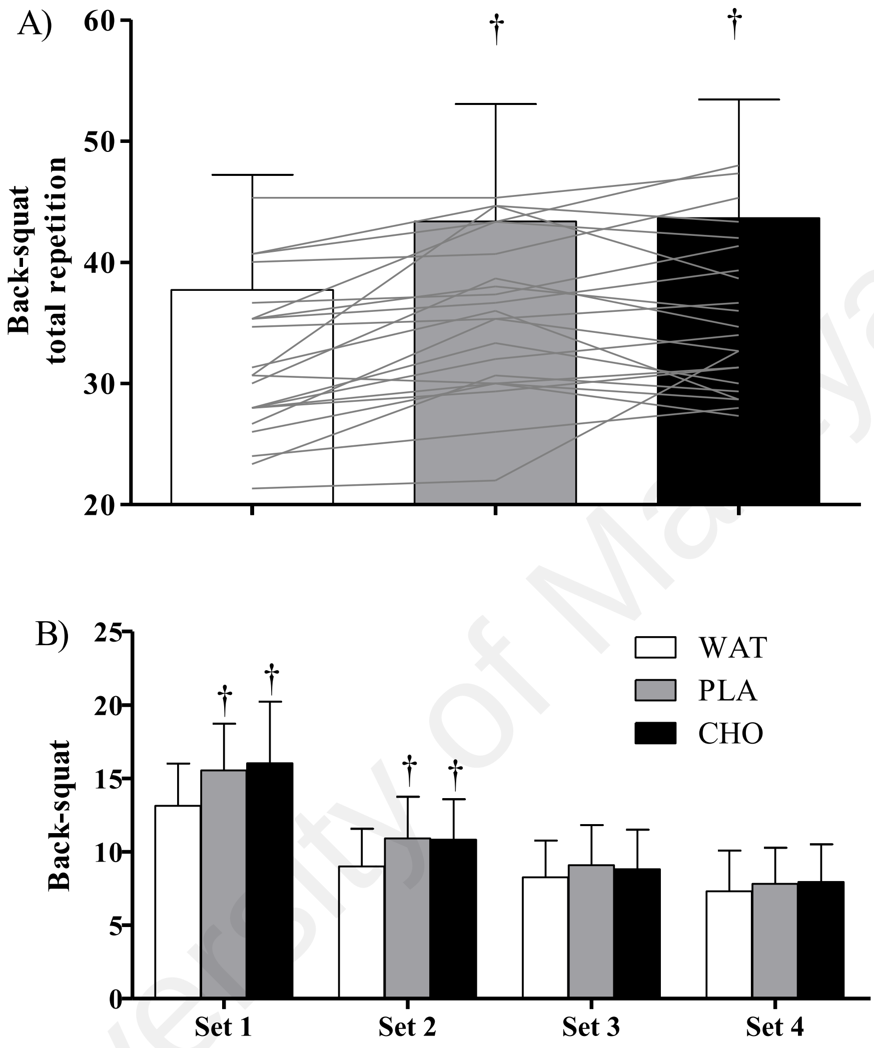


Figure 4.2. (**A)** Back-squat repetitions in total over the four sets and **(B)** in each of the four sets **(B)** during the carbohydrate (CHO), placebo (PLA) and water (WAT) trials. Dagger (†) denotes significantly different to WAT (*P* < 0.05). Values are mean ± SD.

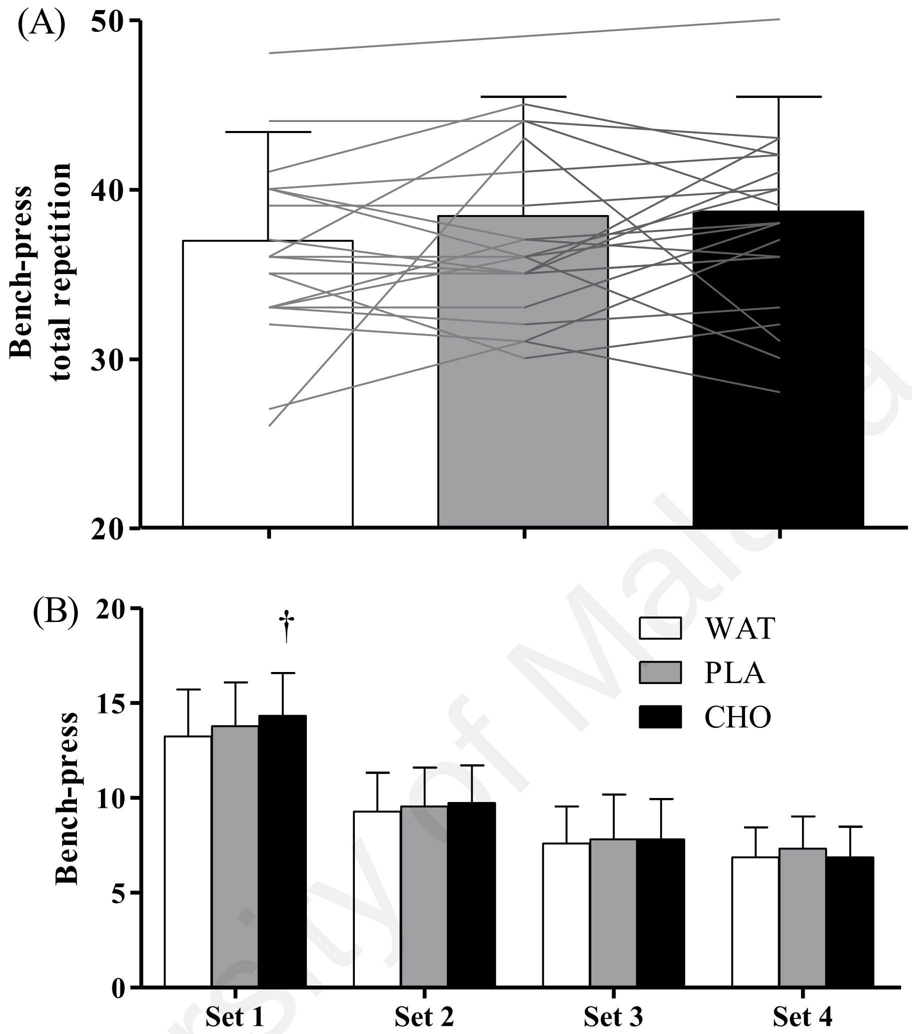


Figure 4.3. (**A)** Bench-press repetitions in total over the four sets and **(B)** in each of the four sets (B) during the carbohydrate (CHO), placebo (PLA) and water (WAT) trials. Dagger (†) denotes significantly different to WAT ($P < 0.05$). Values are mean ± SD.

4.4.4 Subjective appetite sensation

There were trial ($P < 0.001$), time ($P < 0.001$) and interaction ($P < 0.001$) effects for sensations of hunger and fullness (**Figure 4.4**). Hunger was lower during PLA and CHO compared to WAT at all time points after breakfast ($P \leq 0.002$). Conversely, fullness was greater during PLA and CHO compared to WAT at all time points after breakfast ($P \leq 0.027$), with the exception of post-bench press in CHO, which tended to be greater ($P = 0.055$). Compared to pre-meal, hunger was reduced, and fullness was increased at 10 min, 45 min, 105 min in CHO and PLA, and post-back squat in CHO ($P < 0.05$). Hunger and fullness were not different between PLA and CHO ($P \geq 0.144$).

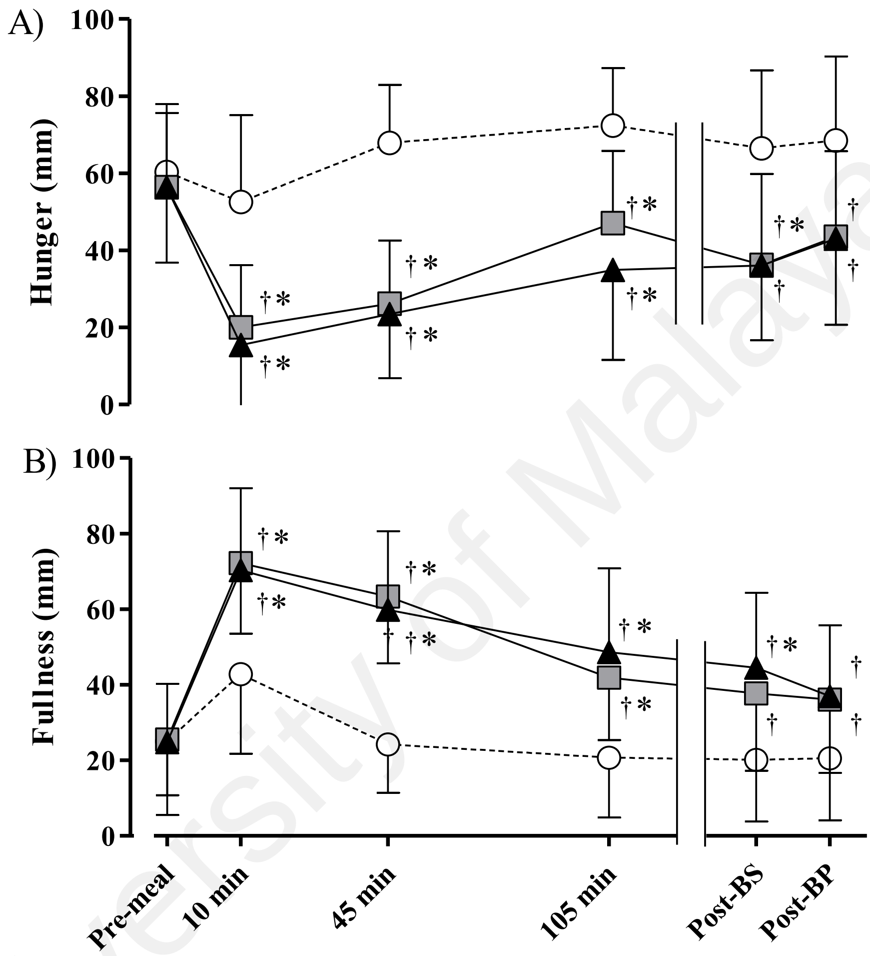


Figure 4.4. Subjective appetite ratings of hunger and fullness throughout the experimental trial. White circle (○) represents the water control (WAT), grey square (■) represents placebo (PLA) and black triangle (▲) represents carbohydrate (CHO) trial. Post-BS (post-back squat) and Post-BP (post-bench press) ratings were measured right after both exercise's final set. Dagger (†) denotes CHO significantly different to WAT whilst asterisk (*) denote significantly different to pre-meal, ($P < 0.05$). Values are mean ± SD

4.4.5 Blood analyses

There was time (*P* = 0.003) and interaction (*P* < 0.001) effects, but no trial (*P* = 0.087) effect for plasma glucose concentration (**Figure 4.5 A**). Compared to pre-meal, plasma glucose was increased at 45 min during CHO, returning to baseline at 105 min. Plasma glucose concentration did not change during WAT or PLA and after Holm-Bonferroni correction there were no between-trial differences. For serum insulin concentration, there were time (*P* < 0.001), trial (*P* < 0.001) and interaction (*P* < 0.001) effects. Insulin concentration (**Figure 4.5 B**) was increased at 45 min and 105 min compared to pre-meal in CHO only (*P* < 0.001) and additionally, was greater at 45 min and 105 min in CHO compared to WAT or PLA (*P* < 0.001). For plasma ghrelin concentration (**Figure 4.6 A**), there were trial (*P* < 0.001) and interaction (*P* = 0.045) effects, but no effect of time (*P* = 0.206). Compared to pre-meal, plasma ghrelin was decrease at 105 min in the CHO trial only (*P* = 0.010) and was decreased in CHO compared to both WAT and PLA at 45 min (*P* < 0.003) and 105 min (*P* < 0.003). For plasma GLP-1 concentration (**Figure 4.6 B**), there were no trial (*P* = 0.940) or interaction (*P* < 0.391) effects, but there was a main effect of time (*P* < 0.001), with an increase at 45 min relative to pre-meal (*P* = 0.008). For plasma PYY concentration (**Figure 4.6 C**), there were trial (*P* = 0.035) and time (*P* = 0.002) effects, but no interaction effect (*P* = 0.329). After Holm-Bonferroni correction, there were no difference between trials or from pre-meal.

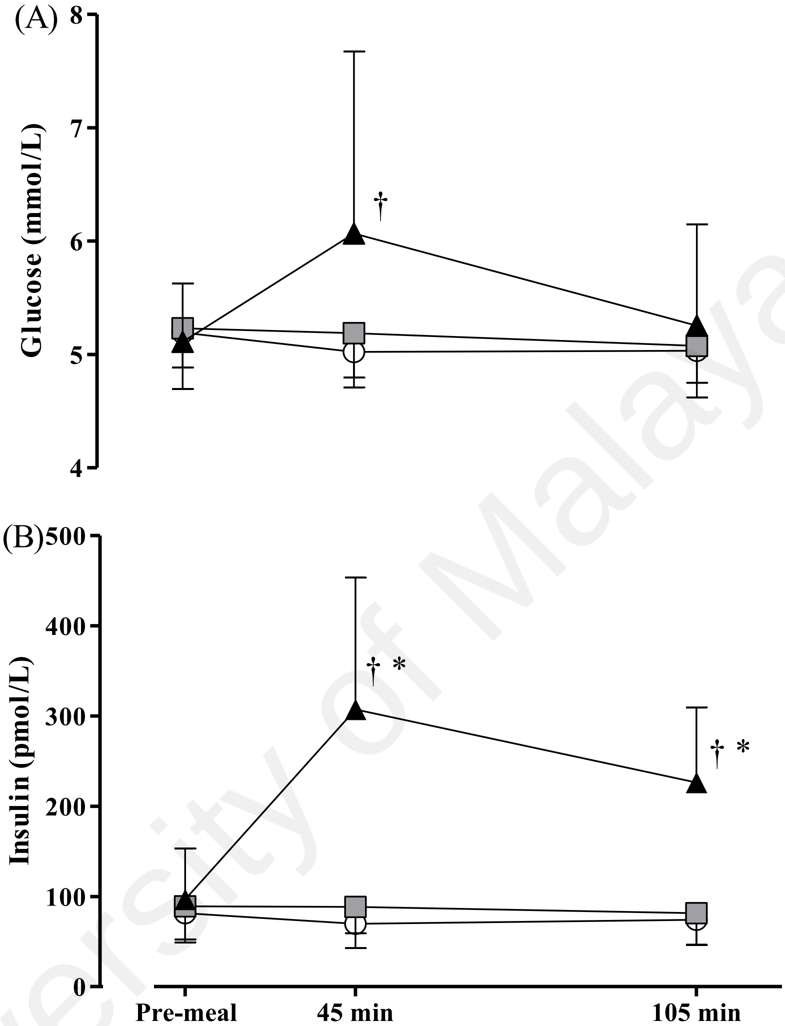


Figure 4.5. **(A)** Plasma glucose and **(B)** insulin measured at specified time-points before the exercise protocol was commenced. White circle (○) represents the water control (WAT), grey square (■) represents placebo (PLA) and black triangle (▲) represents carbohydrate (CHO) trial. Post-BS (post-back squat) and Post-BP (post-bench press). Dagger (†) denotes significantly different to WAT. Asterisk (*) denotes significantly different from pre-meal ($P < 0.05$). Values are mean ± SD

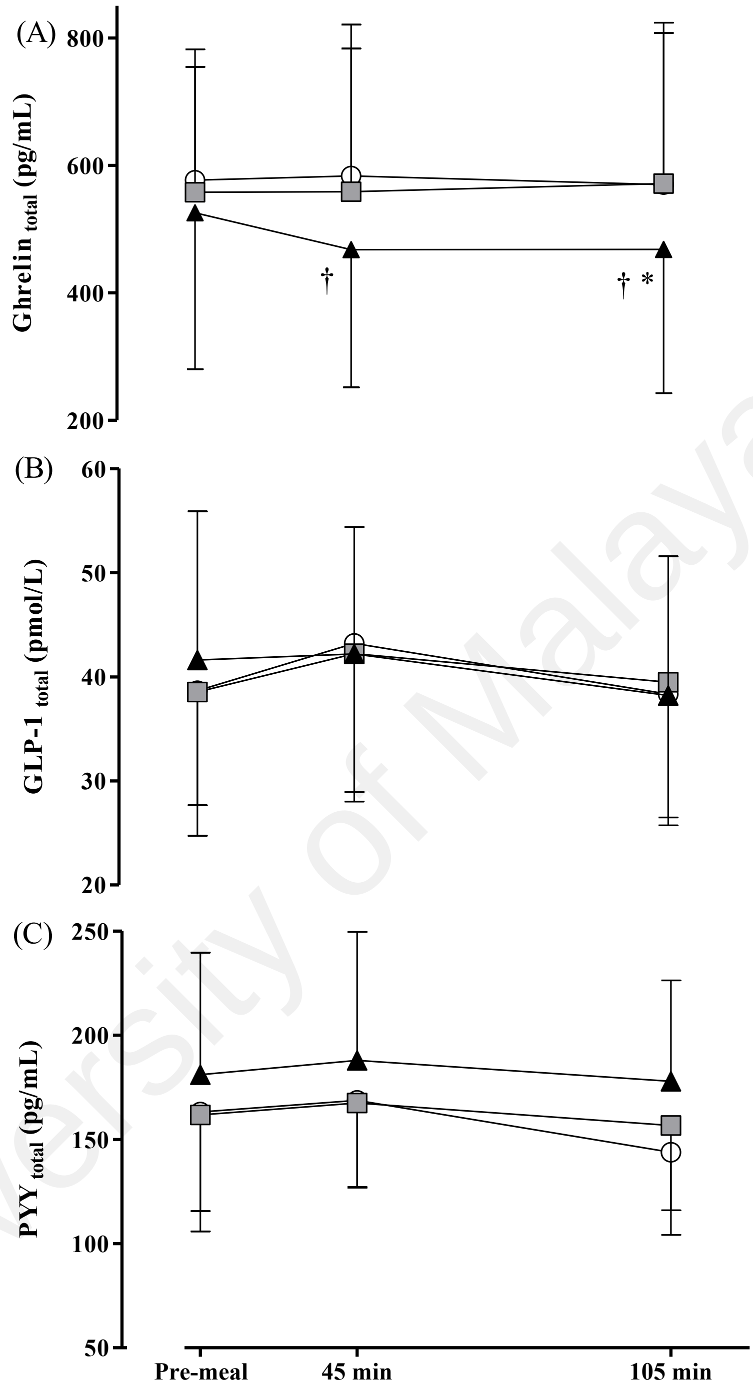


Figure 4.6. Plasma **(A)** Ghrelin$_{total}$ **(B)** GLP-1$_{total}$ and **(C)** PYY$_{total}$, measured at specified time points before the exercise protocol was commenced. White circle (○) represents the water control (WAT), grey square (■) represents placebo (PLA) and black triangle (▲) represents carbohydrate (CHO) trial. Post-BS (post-back squat) and Post-BP (post-bench press). Dagger (†) denotes CHO significantly different to WAT, whilst asterisk (*) denotes significantly different to pre-meal ($P < 0.05$). Values are mean ± SD.

4.5 Discussion

The aim of this study was to investigate the physiological and psychological effects of a pre-exercise high-carbohydrate breakfast meal on performance in a subsequent bout of resistance exercise in trained males. The main findings of the present study were that subjects completed more repetitions of back squat after consumption of a virtually energy-free placebo and high carbohydrate breakfast meal compared to the water-only control trial (PLA +14.9%; CHO +15.7%; $P < 0.001$), with no difference between the placebo and carbohydrate breakfast meals ($P = 1.000$). Smaller (PLA +3.9%; CHO +4.7%), non-significant ($P = 0.130$) effects were observed for bench press. These results suggest that a pre-exercise breakfast meal likely influences resistance exercise performance via a psychological, rather than physiological effect, possibly acting as a placebo to enhance subsequent performance, at least in habitual breakfast consumers.

This study is the first to demonstrate that performance in a single bout of resistance exercise was enhanced when subjects perceive they have consumed an energy-containing pre-exercise meal. This supports previous observations in high-intensity endurance cycling (Mears *et al*., 2017) and yields novel findings to optimise pre-exercise nutritional intake for resistance exercise. Importantly, the present study demonstrates that in rested and trained males, consumption of a high carbohydrate pre-exercise breakfast meal has no additional benefit over that of a placebo when 4 sets of both back squat and bench press are performed.

Previous research has mainly focussed on the effects of a pre-exercise meal on endurance performance, generally demonstrating that a high carbohydrate pre-exercise meal enhances subsequent performance (Coyle & Coggan, 1984; Neufer *et al*., 1987; Ormsbee *et al*., 2014). To our knowledge, only two studies have isolated the effect of a pre-exercise meal on resistance exercise performance (Fairchild *et al*., 2016; Naharudin *et al*., 2019). Naharudin *et al*. observed that performance in 4 sets of back-squat and 4 sets of bench-press were both greater 2 h after a high carbohydrate ecologically valid breakfast (1.5 g carbohydrate/kg body mass from typical breakfast foods) compared to a water only breakfast. The increases in back-squat (~15%) and bench-press (~6%) in this previous study (Naharudin *et al*., 2019) were almost identical to those observed in the present study (~15% and ~4%, respectively), suggesting these previous findings might also be explained by a placebo effect associated with pre-exercise feeding. Interestingly, Fairchild *et al.* (Fairchild *et al*., 2016) reported performance in 3 repetitions of isokinetic knee extension/flexion for up to 90 min after consuming either a 75 g carbohydrate drink or a placebo drink were similar between trials. The failure of carbohydrate to enhance performance when delivered in a placebo-controlled manner in the study of Fairchild *et al.* (Fairchild *et al*., 2016) further supports the theory that a pre-exercise meal/carbohydrate intake might enhance resistance exercise performance via a placebo effect.

Muscle glycogen is an important fuel source for resistance exercise and muscle glycogen depletion, particularly of type-II muscle fibres, and has been shown to decrease maximal strength (Jacobs *et al*., 1981). The degree of muscle glycogen depletion during resistance exercise is related to the work completed (Robergs *et al*., 1991) and thus, if sufficient work is undertaken, muscle glycogen levels could become depleted to a level where performance capabilities are compromised (Lambert & Flynn, 2002). In the CHO trial, plasma glucose was increased at 45 min, whilst serum insulin was increased at 45 min and 105 min, with no changes in the WAT and PLA trials. These findings suggest that the glucose in the CHO meal was absorbed and available for use before/during exercise. Carbohydrate feeding after an overnight fast has been shown to increase liver

(Bawden *et al*., 2014) and to a lesser extent muscle (Chryssanthopoulos *et al*., 2004) glycogen stores, suggesting that augmentation of these stores, at least in a well-rested subject, is not necessary to maximise resistance exercise performance. In the present study, subjects rested for 48 h before each trial, meaning that muscle glycogen stores were likely to be high pre-meal, possibly accounting for the ineffectiveness of the carbohydrate breakfast meal to enhance performance. In many athletic settings, resistance training might occur only a few hours after another training session where glycogen may have been depleted. In this situation, it seems logical that addition of carbohydrate to the meal consumed before resistance exercise is more likely to be ergogenic, as it will also assist with recovery and replacement of glycogen used in the previous exercise bout (Oliver *et al*., 2016).

For endurance exercise lasting ~120 min at ~70% O_2max, consuming carbohydrate (> 1.1 g/kg body mass) in the 1-4 h before exercise appears to enhance exercise performance/capacity by ~9-15% (Sherman *et al*., 1989; Chryssanthopoulos *et al*., 2004; Sherman, Peden, & Wright, 1991). At these submaximal exercise intensities muscle and liver glycogen depletion contributes to fatigue (Coyle & Coggan, 1984; Ørtenblad *et al*., 2013), meaning that small differences in pre-exercise glycogen levels might influence performance (Chryssanthopoulos *et al*., 2002). In contrast, whilst muscle glycogen is used during resistance exercise, 3-6 sets of 6-12 repetitions of a single exercise only reduces muscle glycogen by 17-40% (Robergs *et al*., 1991; Tesch *et al*., 1998; Macdougall *et al*., 1999; Haff *et al*., 2000). Therefore, 4 sets of an exercise, as used in the present study, is unlikely to deplete muscle glycogen to a level that would influence performance. The number of sets of each exercise performed in the present study was chosen to reflect current guidelines for those engaged in resistance training programmes, typically 3-5 sets per exercise (Ratamess *et al*., 2009). Therefore, the present study suggests that any small increase in pre-exercise muscle glycogen levels caused by pre-exercise carbohydrate intake is unlikely to influence performance. Whether pre-exercise carbohydrate intake enhances performance in situations were substantially more than 4 sets are performed is not known and should be investigated in future studies.

Liver glycogen has been shown to be an important fuel source in endurance exercise (Gonzalez *et al*., 2016), but its relevance to performance in resistance exercise is unknown. Although it was not measured, consumption of ~120 g carbohydrate in the CHO would likely have increased liver glycogen (Nilsson & Hultman, 1973), whilst continued fasting in the PLA and WAT trials would likely produce a further decline in liver glycogen (Bawden *et al*., 2014). Therefore, exercise in the PLA and CHO trials likely commenced with very different liver glycogen levels. The finding that performance was not different between these trials, suggests that differences in liver glycogen within the range of normal daily fluctuations are unlikely to influence performance in resistance exercise of this nature.

The results of the present study closely replicate the results of a previous study, where both a high carbohydrate and placebo breakfast, consumed 2 h before exercise, similarly enhanced high-intensity cycling performance (~20 min in duration) relative to a water control trial (Mears *et al*., 2017). The present study and that of Mears *et al.* are the only studies to report the placebo effects of a pre-exercise meal, specifically breakfast (Mears *et al*., 2017). Breakfast is considered an important meal by many (Clayton & James, 2015; Betts *et al*., 2016), and as such it would be interesting to know whether the placebo effect of pre-exercise meals extends to other eating occasions. Regarding carbohydrate intake during exercise, a placebo effect has been observed during ~1 h cycling (Clark, *et al*., 2000), but not during ~3 h of cycling (Hulston & Jeukendrup, 2009). Combined, these studies suggest that any placebo effect associated with energy (or carbohydrate) intake is possibly duration dependent and is more likely to affect performance during exercise of shorter duration.

In this study, xanthan gum was used to increase the viscosity of the meals in the PLA and CHO trials and enhance the perception of energy intake. Previous research has shown that increasing the viscosity of a liquid/semi-solid meal increases subsequent satiety (Marciani *et al*., 2000, 2001; Fiszman & Varela, 2013). Consistent with these previous findings, it is observed that reduced hunger and increased fullness following the PLA and CHO meals compared to the WAT meal. Whilst there was a small amount of energy (~122 kJ) in the PLA meal, contributed by the ~5.4 g of fibre and the orange squash, it seems unlikely this energy would cause these effects on subjective appetite, a notion that is supported by the results for gut peptides GLP-1, PYY, and ghrelin. GLP-1, and PYY which are reported to exert anorexigenic effects (Batterham *et al*., 2002), were not different between trials, despite greater hunger and lower fullness post-meal in WAT compared to PLA and CHO. Furthermore, ghrelin, reported to exert an orexigenic effect (Cummings & Overduin, 2007), was reduced in the CHO trial only and therefore we observed differences in ghrelin with (i.e. WAT vs. CHO) and without (i.e. PLA vs. CHO) differences in appetite, as well as no difference in ghrelin, despite a difference in appetite (i.e. WAT vs. PLA). These results suggest that, at least in response to a single meal, there can be a discordant response for the subjective and physiological regulators of appetite. Nonetheless, the differential response for ghrelin, as well as glucose and insulin, demonstrates that the CHO breakfast meal induced a physiological response. Interestingly, the differences in hunger/fullness between trials matched the differences in performance. Whether hunger can influence performance is not known and not possible to delineate in the present study.

4.6 Conclusion

In conclusion, the results of the present study demonstrate that performance in 4 sets of back-squat and 4 sets of bench press were similarly enhanced by both placebo and carbohydrate-containing pre-exercise breakfast meals when subjects believed these two meals contained energy. Therefore, the hypothesis 2 stated earlier is rejected because the placebo meal in present study increased back squat performance to a similar degree as the carbohydrate containing meal. This suggests that any performance effects of pre-resistance exercise energy/carbohydrate intake are caused by psychological effects, rather than any physiological/metabolic effects caused by the energy/ carbohydrate content of the meal, at least in otherwise well rested habitual breakfast consumers.

CHAPTER 5: CARBOHYDRATE CONSUMPTION OF A PRE-EXERCISE MEAL INCREASES HIGH-VOLUME EXHAUSTIVE RESISTANCE EXERCISE PERFORMANCE

5.1 Introduction

From Chapter 3, it was found that an ecological breakfast consumption has shown to improve high-intensity resistance exercise performance compared to when it was omitted. However, in Chapter 4, blinded breakfast comparing between maltodextrin contained meal versus colour, texture and taste match placebo, were found negligible on the same mode of exercise. Apart from this placebo effects in Chapter 4, it is stipulated that the small sets number of resistance exercise bout itself might be insignificant (4 sets at 90% 10-RM) to magnify difference in performance following carbohydrate manipulation. Therefore, larger exercise sets which render greater volume might be required to see the ergogenic role of carbohydrate supplementation preceding exercise. Therefore, this chapter attempts to answer whether a greater resistance exercise volume (moderate intensity, longer time duration and larger resistance exercise sets), where multiple bout exercise on one specific isolated muscle group is able to utilise the ergogenic role of pre-exercise carbohydrate ingestion in the morning (i.e. breakfast).

5.2 Literature review

For many athletes/exercisers, resistance exercise is an essential part of their training programme, with performance in training sessions possibly having important implications for maximising resistance training adaptations. As such, if nutritional intake around resistance exercise can alter performance, it might also have the potential to influence the efficacy of training and the resultant adaptive outcomes. With regard to the pre-exercise carbohydrate intake, current recommendations suggest consuming of 1-4 g carbohydrate/kg body mass in the 1-4 h before exercise (Burke *et al*., 2011). To date, the vast majority of studies in this area have examined endurance exercise, with the balance of evidence suggesting that pre-exercise carbohydrate intake can optimise subsequent performance (Clayton *et al*., 2015; Clayton & James, 2015; Ormsbee *et al*., 2014). More recently, some studies have examined the influence of pre-exercise carbohydrate/energy intake on resistance exercise performance (Fairchild *et al*., 2016; Naharudin *et al*., 2019), with less convincing results.

Previous studies isolating the effect of pre-exercise carbohydrate intake on resistance exercise performance have all examined performance in relatively low-volume resistance exercise sessions. Fairchild *et al*. (2016) reported that carbohydrate (provided in a pre-exercise drink) did not affect performance in 3 reps of isokinetic dynamometry for up to 90 min after ingestion. In contrast, Naharudin *et al.* 2019 reported that total repetitions performed in 4 sets of back-squat and 4 sets of bench press were ~15 and ~6% less when breakfast was omitted compared to when an ecologically valid high carbohydrate breakfast was consumed (bread, jam, margarine, cereal, milk and orange juice). Interestingly, in my second study (Chapter 4) suggested that this ergogenic effect of a pre-exercise high carbohydrate meal might be caused by a placebo/nocebo effect since perception of energy intake/consuming a meal was as ergogenic as a high carbohydrate pre-exercise meal. Thus, there is little convincing evidence that carbohydrate intake before resistance exercise influences performance.

Pre-exercise carbohydrate intake, particularly in the morning after an overnight fast, facilitates increases in muscle (Taylor, *et al*., 1993; Chryssanthopoulos *et al*., 2002) and liver (Nilsson & Hultman, 1973) glycogen, which may enhance exercise performance in situations where glycogen availability limits performance (Coyle & Coggan, 1984; Ørtenblad *et al*., 2013; Williams & Rollo, 2015). The low-volume nature of the resistance exercise performed in these previous studies exploring the impact of pre-exercise carbohydrate/energy intake (Fairchild *et al*., 2016; Naharudin *et al*., 2019) means that the glycogen depletion induced was likely to be small (Robergs *et al*., 1991; Tesch *et al*., 1998; Macdougall *et al*., 1999; Haff *et al*., 2000) and insufficient to compromise performance. Indeed, studies examining the effect of carbohydrate intake immediately before and during a bout of resistance have reported performance is enhanced when the volume of an individual exercise is high (Haff *et al*., 1999; Haff *et al*., 2001), but not when it is low (Lambert *et al*., 1991). Whether pre-exercise carbohydrate intake influences performance in bouts of resistance exercise where the volume of work performed is high is unknown.

Therefore, the aim of the present study was to examine the effect of carbohydrate intake at the pre-exercise meal on high volume exhaustive resistance exercise performance (slightly lower intensity but greater number of set), with carbohydrate provided in a double-blind placebo-controlled manner. It was hypothesised that carbohydrate provision in the pre-exercise meal would increase resistance exercise performance, measured as an increase in the number of repetitions and sets of exercise completed.

5.2.1 Objectives of study

For this experiment, it is aimed to observe if performance in very high-volume resistance exercise would be differently affected by placebo or carbohydrate-containing breakfast meals t. The objectives of this study were:

1) Primary objective: to compare the effect of carbohydrate versus placebo breakfast meals on performance of leg extension.
2) Secondary objective: to investigate how subjective appetite sensations and blood glucose concentrations would be affected by placebo and carbohydrate containing breakfast meals.

5.3 Methodology

5.3.1 Experimental approach to the problem and main outcome measures

From the experiment in Chapter 3, we found that an ecological breakfast increased high intensity resistance exercise performance compared to omitting breakfast. In Chapter 4 however, a blinded breakfast meal with very little energy content, on the contrary, was no different compared to a high carbohydrate meal. Apart from the placebo effects on performance, it is stipulated that the volume of resistance exercise itself might be too small (4 sets) to observe changes in performance due to pre-exercise carbohydrate intake. Thus, a further investigation implementing a larger exercise volume, (i.e. more set/work to be done) will allow the true effect of carbohydrate ingestion in the morning (i.e. breakfast) to be examined. The main outcome measure for this study was leg extension number of repetitions and number of sets that subjects could perform to exhaustion.

5.3.2 Subjects

To participate for this study, subjects had to be gym goers, habitually consuming breakfast at least three mornings a week, and who included leg-extension exercise as part of their weekly training regimen at least once a week. Subjects who indicated that they were not habitual breakfast consumers or were not familiar with back squat and bench press were excluded from this study. The sample size for this study was estimated from G*Power 3.0.10 software using an α of 0.05, statistical power of 0.95 and estimated correlation between group of 0.5. The estimated number of 12 subjects would be sufficient to detect a 10% difference in performance between trials. However, considering drop-out rates, 16 subjects were finally recruited.

5.3.3 Study design

All subjects completed 4 visits, consisting of 10 repetition maximum (10-RM) measurement, a familiarisation session and two experimental trials where they consumed carbohydrate (CHO) and placebo (PLA) pre-exercise breakfast meals and performed leg extension to exhaustion ~2 h later. Experimental trial visits were administered in a randomised, counter-balance double-blind manner and separated by ≥ 4 days to allow energy replenishment (Haddock *et al*., 2006). Subjects were informed the purpose of the experiment was to compare two energy-containing breakfast meals of different macronutrient composition. Thus, subjects were unaware that one of the breakfasts consumed was virtually energy-free. Schematic timeline of this study is presented in **Figure 5.1**.

5.3.3.1 Preliminary visit and familiarisation trial

During their first visit, subjects initially warmed up on a cycle ergometer (5 min at 1.5 W/kg body mass; Monark 894E, Vansbro), followed by a period of self-selected stretching. Subjects then completed incremental sets of 10 repetitions of leg extension to determine their 10-RM. After some warm up sets (self-selected), subjects first 10-RM attempt was at a load subjects predicted would be their 10-RM based on their training experience. The load of subsequent attempts was increased until the subject was unable to complete 10 full repetitions. Subjects were given at least 3 min rest between 10-RM attempts. The load of the last completed set was termed the subject's 10-RM and used to determine the load for exercise in the familiarisation and experimental trials, which was ~80% of 10-RM. The second visit was to familiarise subjects with all aspects of the study by completing a trial identical to the CHO trial.

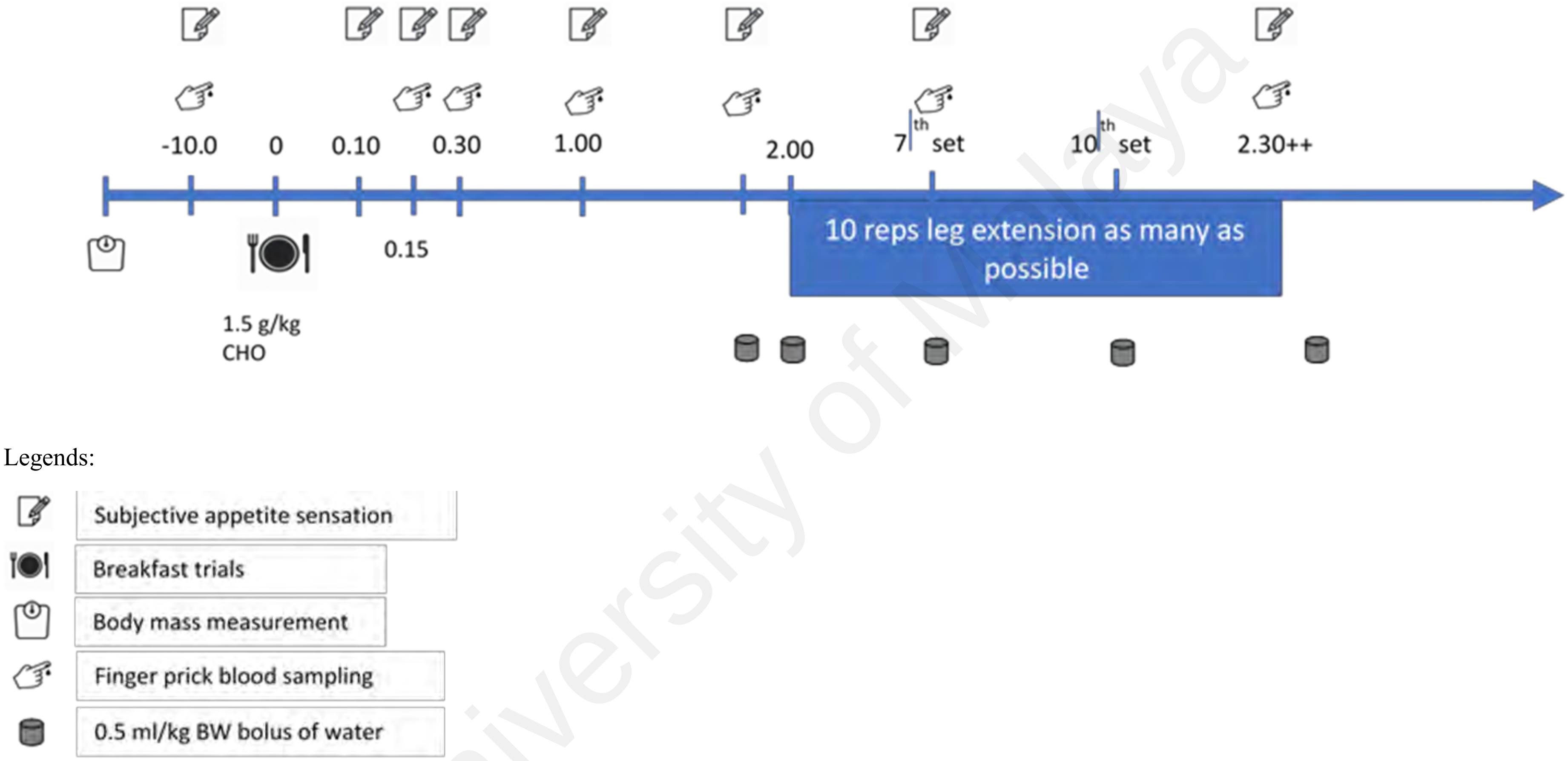


Figure 5.1. Schematic diagram for a typical subject during trial visit.

5.3.3.2 *Pre-trial standardisation*

Subjects recorded their dietary intake on the day before and their habitual physical activities in the two days before their first experimental trial, replicating these patterns in the two days before their second experimental trial. Additionally, subjects were asked not to consume alcohol or perform any strenuous physical activity in the two days before experimental trials.

5.3.3.3 *Experimental trials*

For experimental trials, subjects arrived in the morning after an overnight fast (10-13 h) at a time typical for them to consume breakfast (i.e. 0800-1000) and baseline measurements of post-void body mass, subjective appetite and a finger prick blood sample were collected. Subjects then consumed their allotted breakfast and rested in the laboratory for the next 110 min. Additional appetite questionnaires and finger prick blood samples were collected at 10, 30, 60 and 110 min after breakfast, as well as after every 7^{th} set and after the final set of leg extension.

5.3.3.4 *Breakfast meal*

Breakfasts were semi-solid, served in a standard bowl and eaten with a standard spoon and administered in a double-blind manner. Breakfast meals were 5 mL/kg body mass in volume, consisting of 0.75 mL/kg body mass of low-energy sugar-free orange flavoured squash (Double Strength Orange squash, Tesco, Welwyn Garden City, UK) and 4.25 mL/kg body mass of tap water. To this, 0 g/kg body mass (PLA) or 1.5 g/kg body mass

(CHO) of carbohydrate as maltodextrin (Myprotein, Northwich, UK) was added. A small amount (0.1 g/kg body mass) of xanthan gum (Myprotein, Northwich, UK) was added to thicken the solution and enhance the perception of energy intake (Fiszman & Varela, 2013). Both PLA and CHO breakfast's meals were taste, texture and colour matched and were made the day before trials by a researcher who was not involved in data collection component of the study. Additionally, 3 mL/kg body mass of tap water was consumed as a drink with meals. Macronutrient composition on each trail is presented in **Table 5.1**. All meals were consumed over a 10 min period. At the end of the final trial, both meal contents were revealed to subjects and they were informed of the true aim of the study. Subjects were then asked whether they could identify the breakfasts and if so, to guess which meal was which.

Table 5.1 Macronutrient, energy and water intake during each trial.

	Breakfast meal	
	PLA	**CHO**
Protein (g)	0.7 ± 0.1	0.7 ± 0.1
Carbohydrate (g)	2.0 ± 0.3	100.1 ± 14.6
Fat (g)	0.5 ± 0.1	0.5 ± 0.1
Fibre (g)	4.5 ± 0.7	4.5 ± 0.7
Energy (kJ)	102 ± 15	1742 ± 255
Water (mL)	522.9 ± 76.5	522.9 ± 76.5

Values are presenedt in Mean ± SD, n = 16, PLA, placebo trial; CHO carbohydrate trial.

5.3.3.5 Leg extension exercise performance

Subjects performed a 5 min cycling warm up at 1.5 W/kg body mass, followed by 5 min self-selected standardised warm-up. Subsequently, they performed as many sets of 10 repetitions of leg extension as possible at ~80% 10-RM. Once subjects could no longer complete 10 repetitions in a set they completed as many repetitions as possible for each set until they could no longer successfully complete 8 repetitions. Repetition pace was maintained using a metronome, corresponding to 20 repetitions/minute. Sets were separated by 3 min rest, during which subjects remained seated on the leg extension machine (Nautilus 2ST Leg Extension, USA). Water was provided in a volume of 0.5 mL/kg body mass pre-exercise and every 7th set.

5.3.4 Blood samples

Blood samples were drawn using the finger prick technique and were analysed using a glucose meter (Accutrend Plus, Roche, Germany). All samples were drawn and dispensed by investigators suitable trained in this procedure. Any adverse effects were dealt with using appropriate first aid or medical intervention.

5.3.5 Subjective appetite sensations

Subjects rated their subjective sensations of hunger, fullness, light-headedness, tiredness, alertness and head soreness using visual analogue scales with written anchors of "not at all" /"none at all" and "extremely"/ "a lot" placed 0 and 100 mm, respectively (Flint *et al*., 2000).

5.3.6 Statistical analyses

Data were analysed using SPSS (Version 23.0; IBM Corp., Armonk, NY). Normality of the data was tested using a Shapiro-Wilk test. All data containing two factors were analysed using two-way repeated measure ANOVA followed by Holm-Bonferroni adjusted *t*-tests or Holm-Bonferroni adjusted Wilcoxon sign rank tests, as appropriate. Data containing one factor were analysed using paired sample *t*-test or Wilcoxon sign rank test, as appropriate. Statistical significance was set at $P < 0.05$ and data are presented as mean ± SD.

5.4 Results

5.4.1 Descriptive demographic

Sixteen experienced resistance trained men provided written consent before completing this study, which was approved by the University of Malaya Research Ethics Clearance. Subjects (age 22 ± 1 years, body mass 65.36 ± 9.56 kg, height 170.65 ± 6.31 cm, BMI 22.46 ± 3.35 kg/m^2) had > 6 years' experience of regular resistance exercise and at the time of the study performed resistance exercise 4 ± 1 times/week and leg extension exercise 2 ± 1 times/week. In addition, subjects also habitually consumed breakfast ≥ 6 days/week.

5.4.2 Blood glucose concentration and leg extension performance

For blood glucose, there were time ($P < 0.001$) trial ($P < 0.001$) and interaction ($P < 0.001$) effects. Blood glucose was greater during CHO compared to PLA at all time points post-meal ($P < 0.01$), except at exhaustion ($P = 0.176$). Compared to pre-meal, blood glucose was increased during CHO at all time points post-meal (*P* < 0.01), but only after the 7th set of resistance exercise during PLA (*P* = 0.047). Glucose response is presented in **Figure 5.2**

The total number of repetitions to exhaustion were 8% greater during CHO compared to PLA (CHO 178 ± 33 repetitions; PLA 164 ± 36 repetitions; *P* = 0.046). The number of sets of 10 repetitions completed was greater during CHO compared to PLA (CHO 13.6 ± 3.6 sets; PLA 11.0 ± 4.8 sets; *P* = 0.017), but the total number of sets performed did not quite reach statistical significance between trials (CHO 18.8 ± 3.4 sets; PLA 17.5 ± 3.5 sets; *P* = 0.090). Leg extension performance of number of reps and sets for both trial visit is presented in and **Figure 5.3 A** and **5.3 B** respectively.

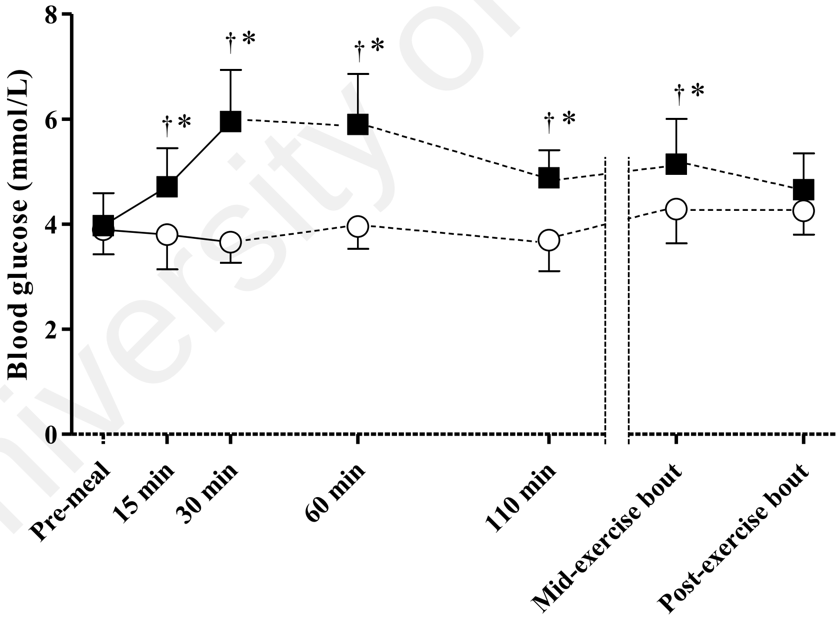


Figure 5.2 Comparison of glucose response between trials. White circle (○) represents the placebo (PLA) and black square (■) represents maltodextrin (CHO) containing meal. Mid-exercise bout appetite sensations were measured at 7th set. Dagger (†) indicates significantly different between PLA and CHO, whilst asterisk (*) indicates significant difference compare to pre-meal (*P* < 0.05).

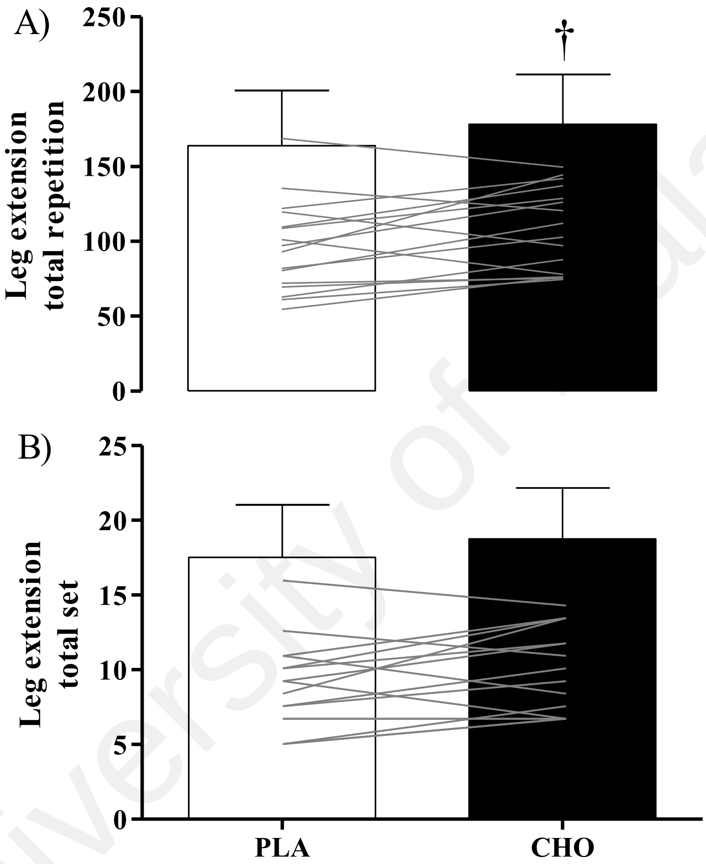


Figure 5.3 Leg extension **(A)** total repetition and **(B)** total sets during placebo (PLA) and maltodextrin (CHO) meals. Bars are mean values, vertical error bars represent SD. Dagger (†) indicates significantly different between PLA and CHO ($P < 0.05$).

5.4.3 Subjective appetite sensation

There was only time effect ($P < 0.001$) with no interaction and trial effect noted, consistently for all subjective appetite responses. It is observed that both CHO and PLA within trial subjective appetite sensations behaving similarly. Compared to the baseline (pre-meal), both trial's sensation of hunger was decreased from 10 to 60 min, but becoming insignificant at 110 min. During exercise, both trial's sensation of hunger was elevated at mid-exercise (7^{th} bout) compared to the baseline and continue to increase until post-exercise. Sensations of fullness, were increased compared to pre-meal from 10 to 60 min in both trials ($P < 0.05$). Whilst during exercise, only CHO trial shows significant elevation at mid-exercise (7^{th}) bout, but at post-exercise bout, both trials demonstrated insignificant compared to the baseline. Subjective appetite sensation for both trials are presented in **Figure 5.4**.

5.4.4 Breakfast perception

Subjects rated the meals were similarly pleasant (PLA: 34 ± 24 mm; CHO: 37 ± 28 mm; $P = 0.391$) and equally filling (PLA: 82 ± 14 mm; CHO: 81 ± 10 mm; $P = 0.831$). Out of sixteen subjects, eight subjects claimed they thought they could detect a difference between PLA and CHO breakfast meals, with 5 of those correctly identifying the trials.

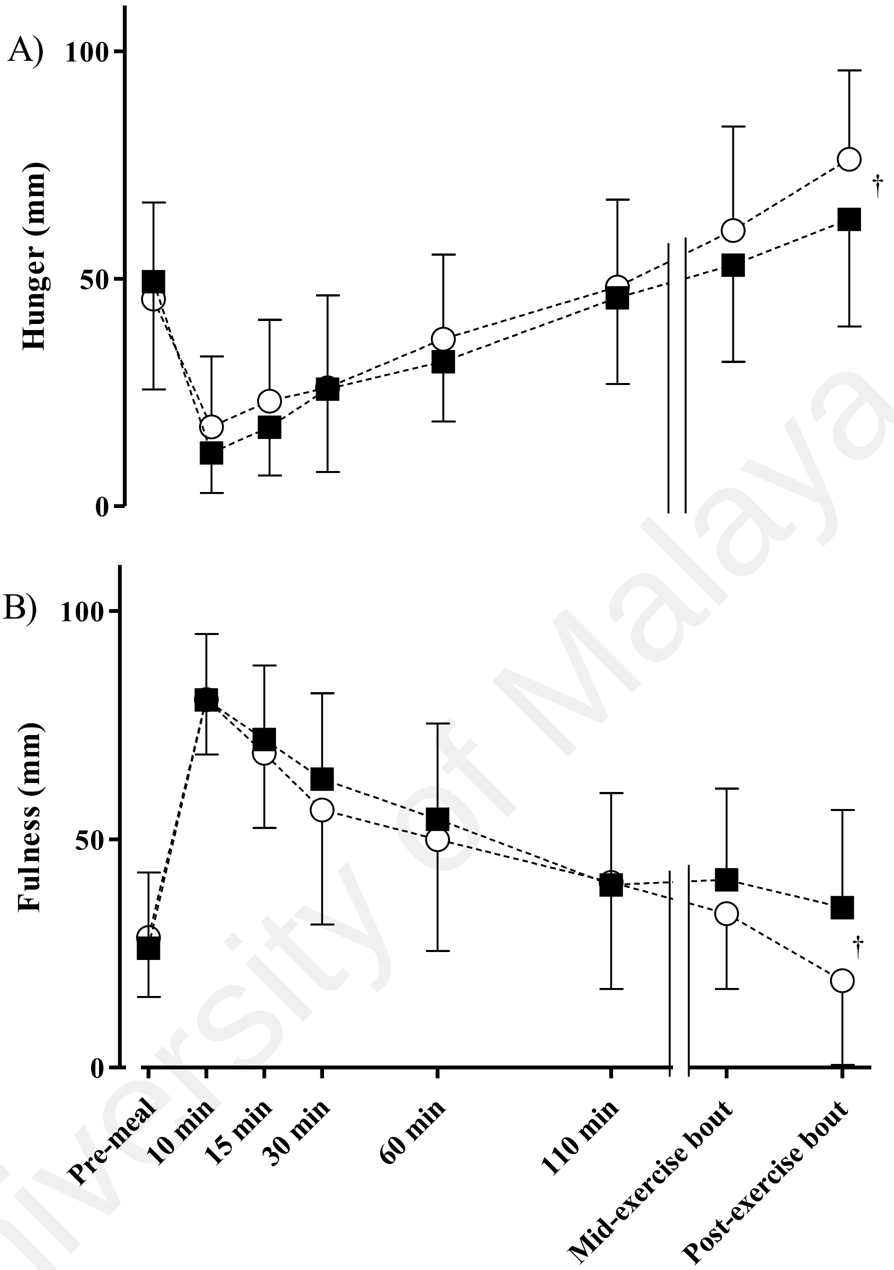


Figure 5.4 Subjective appetite sensations of **(A)** hunger and **(B)** fullness for placebo (PLA) and maltodextrin (CHO) containing meal. White circle (○) represents the PLA and black square (■) represents CHO. Values are presented in Mean ± SD, n = 16. Mid-exercise bout appetite sensations were measured at 7th set. Asterisk (†) indicates significantly different between trials (*P* < 0.05).

5.5 Discussion

The main findings of this experiment were that total leg extension repetitions and the number of sets of 10 repetitions completed were greater ~2 h after consuming a meal containing 1.5 g carbohydrate/kg body mass, compared to a virtually energy-free placebo meal. Given the scarcity of data exploring the effects of pre-exercise energy/carbohydrate intake for resistance exercise performance, these data yield novel and potentially important insight into how to best prepare for exercise of this nature. Pre-exercise carbohydrate intake has consistently been shown to enhance endurance performance in the hours following (Ormsbee *et al*., 2014; Clayton & James, 2015). Additionally, most (Jacobs *et al*., 1981; Leveritt & Abernethy, 1999; Oliver *et al*., 2016), but not all (Mitchell *et al*., 1997) previous studies have reported that starting exercise glycogen depleted impairs resistance exercise performance. However, this study is the first study to demonstrate that pre-exercise carbohydrate intake can enhance performance in resistance exercise. Whilst these effects are likely dependent on the volume of the resistance exercise session performed (Slater & Phillips, 2011), when maximising performance in resistance exercise is desirable (perhaps during critical rehabilitation exercise/key training sessions), commencing the exercise after a high carbohydrate meal might be the prudent approach to optimise performance. It is worth noting that this should be easily achievable by timing resistance exercise training appropriately around normal daily eating patterns.

Interestingly, these results contrast with those of recent studies that have isolated the effect of pre-exercise carbohydrate intake on resistance exercise performance in a blinded manner (Fairchild *et al*., 2016). These divergent results are likely explained by differences between studies in the resistance exercise bouts used to test performance. Fairchild *et al*.

(2016) had subjects perform 3 repetitions of isokinetic knee extension periodically between 5-90 min after ingesting a 300 mL drink containing either 0 g or 75 g glucose, observing no differences in strength performance or electromyography (EMG) between conditions, despite large difference in blood glucose over that time period. Similarly, in Chapter 4, it was observed no difference in performance (total repetitions) during 4 sets of back-squat and 4 sets of bench-press performed ~2 h after consuming semi-solid meals with either 0 g or 1.5 g carbohydrate/kg body mass added. In contrast, in the present study, leg extension exercise continued until exhaustion and resulted in subjects performing ~18 sets, a substantially greater volume of exercise compared to these previous studies. Consistent with this, previous studies examining the effect of carbohydrate intake during resistance exercise have observed performance is enhanced (Haff *et al*., 1999; Haff *et al*., 2001) or tends to be enhanced (Lambert *et al*., 1991) when carbohydrate is ingested during a prolonged exhaustive exercise bout utilising the same exercise. In a similar manner to pre-exercise carbohydrate intake, when lower-volume resistance exercise is performed carbohydrate intake during exercise does not appear to influence performance (Haff *et al*., 2000; Kulik *et al*., 2008).

Whilst the present results demonstrate that carbohydrate intake at a pre-exercise meal enhances subsequent exhaustive resistance exercise performance, it cannot elucidate the mechanisms responsible. The most likely candidate to explain the difference in performance between trials is the differential effects of the pre-exercise meals on endogenous glycogen stores. Muscle glycogen is an important fuel source during resistance exercise, with a single exercise session decreasing stores by up to 40% (Robergs *et al*., 1991; Tesch *et al*., 1998; Macdougall *et al*., 1999; Haff *et al*., 2000). The level of muscle glycogen depletion observed appears to be a function of the amount of work performed (Robergs *et al*., 1991), meaning alterations in pre-exercise endogenous glycogen stores are more likely to influence prolonged resistance exercise sessions utilising the same muscle groups. Since the pre-exercise meal in the present study was consumed after an overnight fast, the ~100 g carbohydrate provided in the CHO trial (compared to the ~2 g in the PLA trial) would likely have increased liver (Nilsson & Hultman, 1973) and to a lesser extent muscle (Chryssanthopoulos *et al*., 2004) glycogen.

Chryssanthopoulos *et al*. (2004) reported that a breakfast of 2.5 g/kg body mass increased muscle glycogen by ~11% 3 h later and in a separate study (Chryssanthopoulos *et al*., 2002) that the same breakfast increases endurance running capacity by ~9%. Interestingly, although the carbohydrate content of the breakfast was slightly smaller in the present study, performance was increased by a relatively similar amount (~8%). Although muscle glycogen was not measured in the present study, the prolonged nature of the resistance exercise in the present study likely meant that muscle glycogen depletion was substantial and may have contributed to fatigue (Lambert *et al*., 1991). Thus, any small difference in starting muscle glycogen between trials could have influenced performance and the possibly greater starting muscle glycogen in the CHO trial might therefore have increased performance in this trial.

Whilst the role of muscle glycogen in fatigue is well established, at least for endurance exercise (Coyle & Coggan, 1984; Ørtenblad, Westerblad, & Nielsen, 2013), the effect of liver glycogen is less well understood (Gonzalez *et al*., 2016). Trials in the present study commenced in the morning after an overnight fast when liver glycogen would be low. Again, whilst liver glycogen stores were not measured, the pre-exercise meal in the CHO trial would likely have facilitated a substantial increase in liver glycogen (Nilsson & Hultman, 1973), which would not have occurred in the PLA trial, producing large differences in liver glycogen content pre-exercise. This may provide another mechanism explaining how performance was enhanced in the CHO trial. Provision of an exogenous carbohydrate source during a standardised bout of resistance exercise, attenuates muscle glycogen depletion (Haff *et al*., 2000) and enhances performance (Lambert *et al*., 1991; Haff *et al*., 1999; Haff *et al*., 2001). Without exogenous carbohydrate supply during exercise, liver glycogenolysis will maintain blood glucose concentrations and, particularly given the 3 min rest between sets, liver glycogenolysis could provide an additional source of carbohydrate for the working muscle, attenuating muscle glycogen depletion and delaying fatigue. Although in the absence of mechanistic data, this hypothesis remains speculative at this time.

Whilst this study is the first to robustly demonstrate that pre-exercise carbohydrate intake can enhance performance in resistance-type exercise, it is not without limitations. The exercise bout utilised is not particularly ecologically valid, as in most resistance training scenarios, current guidelines recommend completing 3-5 sets of an exercise (Ratamess *et al*., 2009), with exercisers typically performing a number of exercises utilising different muscle groups. Indeed, in this scenario it is unlikely that glycogen depletion will be sufficient to impair performance in any one exercise. However, in some training scenarios (e.g. pyramid sets, body mass conditioning exercises, circuit training, certain rehabilitation situations etc.), the training volume of a specific exercise might be sufficient that glycogen availability could limit performance. Therefore, whether or not carbohydrate intake at a pre-exercise meal is a priority is likely to be dictated by the nature of the exercise session planned.

5.6 Conclusion

In conclusion, prolonged multiple-bout leg extension exercise at a moderately-intense load can be improved by pre-exercise carbohydrate intake. Therefore, findings from this experiment accept hypothesis 3 where the ingestion of a high-carbohydrate meal following an overnight fast would enhance exhaustive multiple-bout resistance exercise beyond that of a placebo. In addition, this finding also adds to the knowledge that prolonged exercise by any means, are dependable on the availability of fuel. For a given muscle group, ingesting a considerable amount of carbohydrate may allow sustained performance at a given exercise intensity. As for this study, subjects were able to perform a higher number of repetitions. Practically, this could also extend to any intermittent type of exercise work-out or sports in the morning, although caution should be taken when trying to extend these finding to other types of exercise.

CHAPTER 6: INCREASE IN SENSATION OF FULLNESS FROM A SEMI-SOLID MEAL IMPROVES RESISTANCE EXERCISE PERFORMANCE

6.1 Introduction

In Chapter 3, it was demonstrated that consumption of an ecologically valid pre-exercise breakfast meal increased resistance exercise performance, whilst in Chapter 4 it was demonstrated that this effect was possibly caused by a placebo effect associated with breakfast consumption or a nocebo effect associated with breakfast omission. However, in the experiments in both these chapters, all the 'breakfasts' also suppressed appetite (i.e. decreased hunger and increased fullness) compared to the no breakfast trials. This raises the question of whether it is the perception of eating a meal (i.e. breakfast) or the effect of the meal on sensations of hunger and fullness that influences performance. This chapter attempts to answer this question by manipulating the viscosity of two carbohydrate-containing breakfasts to hopefully effect changes in appetite, with similar carbohydrate provision.

6.2 Literature review

Whilst the ergogenic effects of pre-exercise carbohydrate intake have been well documented for endurance (Clayton *et al*., 2015; Ormsbee *et al*., 2014) and intermittent (Lambert *et al*., 1991) exercise, the effect on resistance-type exercise is less well understood, although some recent work is emerging (Fairchild *et al*. 2016; Chapter 3-5 of this thesis). For endurance and intermittent exercise, it is generally thought that the erogenicity of pre-exercise carbohydrate intake is derived from its effects on endogenous glucose stores (Coyle *et al*., 1986; Taylor *et al*., 1996). After an overnight fast, liver glycogen stores are depleted and ingestion of carbohydrate increases liver glycogen (Nilsson & Hultman, 1973) and to a lesser extent muscle glycogen (Taylor *et al*., 1993; Chryssanthopoulos *et al*., 2004).

During prolonged endurance exercise, where glycogen availability likely plays a role in fatigue development (Coyle *et al*., 1986; Duhamel, Perco & Green, 2006; Ørtednblad *et al*., 2011; Knuiman *et al*., 2015), there is a clear metabolic basis to explain the effects of pre-exercise carbohydrate intake (i.e. increased endogenous glycogen stores). However, during resistance exercise, particularly ecologically valid resistance exercise, it seems unlikely that pre-exercise carbohydrate would act to influence performance via these mechanisms. Current recommendations for resistance exercise training suggest performing 3-5 sets of an exercise, with the number of repetitions (and load) varying depending on training goals (Ratamess *et al*. 2009). Whilst muscle glycogen is utilised during resistance exercise (Roberg *et al*., 1991; Tesch *et al*., 1998; Haff *et al*., 2000), whether the degree of muscle glycogen depletion elicited by exercise of this volume (17-40%) is sufficient to influence performance is unknown.

The previous two chapters suggest that whether provision of carbohydrate ~2 h before resistance exercise influences performance depends on the volume of resistance exercise performed (Chapter 4 and 5). When 4 sets of an exercise were performed, carbohydrate in a pre-exercise meal did not influence performance, but both placebo and carbohydrate meals increased performance compared to a water only control meal (Chapter 4), replicating previous work in high-intensity endurance exercise (Mears *et al*., 2018). It was speculated these findings were explained by a placebo effect (Mears *et al*., 2018; Chapter 4), but equally they could be due to other non-nutrient specific effects. One such factor is the influence of the pre-exercise meal on subjective appetite sensations since the placebo and carbohydrate meals both equally suppressed appetite, meaning the subjects reported greater hunger and reduced fullness in the water-only control trial. Consistent with this, in Chapter 3, the ecologically valid breakfast meal facilitated similar increases in performance and suppression of appetite to those observed in Chapter 4 (~15%).

Although no research has examined the influence of hunger/appetite on exercise performance, there is evidence to suggest that other sensations might influence human exercise performance, including thirst (Goulet 2011), heat (Sawka, 1990) and pain (Mauger 2014). Some have suggested that any factor that influences motivation might influence (endurance) performance (Marcora *et al*. 2009) and as such perceptions of hunger might influence motivation and consequently performance. Therefore, it is possible the results of previous studies reporting a placebo effect of a pre-exercise meal on performance (Mears *et al*., 2018; Chapter 4) might be, at least partially, explained by the effects of the meal on subjective sensations of appetite (i.e. hunger). Therefore, the purpose of this study was to examine the effect of hunger on resistance exercise performance, by providing pre-exercise carbohydrate-containing meals of different viscosity which should elicit differences in subjective hunger (Apolzan *et al*., 2007; Berry *et al*., 2003; Pfeiffer *et al*., 2010; Tieken *et al*., 2007; Martens *et al*., 2012; Chapter 4). It was hypothesised that sensations of hunger would decrease resistance exercise performance.

6.2.1 Objectives of study

For this experiment, it was aimed to observe how different pre-exercise meal viscosity thought to provide similar outcome, would affect appetite sensation and resistance exercise performance. The objectives of this study were:

1) Primary objective: to investigate whether the semi-solid pre-exercise meal would decrease sensations of hunger compared to a liquid pre-exercise meal and consequently increase performance in back squat and bench press exercise.
2) Secondary objective: to investigate how subjective appetite sensations, plasma glucose, insulin, $ghrelin_{total}$, PYY_{total}, would be regulated following the consumption of semi-solid and liquid meal, both with comparable energy content.

6.3 Methodology

6.3.1 Experimental approach and main outcome measures

In Chapter 4, it is found that consuming a semi-solid meal, regardless of the content, was shown to improve performance in back squat, likely via placebo effect. However, it is possible that this increased performance could be due to the concomitant changes in appetite sensations (i.e. decreased hunger and/or increased fullness) caused by the high viscosity meal provided. Thus, a study where sensations of hunger and fullness are manipulated is crucial to answer whether these sensations arising from a meal could influence performance outcomes. Therefore, by giving two isocaloric meals either with (semi-solid) or without (liquid) xanthan gum (liquid) might allow manipulation of appetite whilst largely controlling other nutritional factors. This might then allow examination of whether appetite influences resistance exercise performance and answer this gap of knowledge. The main outcome measures of this study were back squat and bench press number of repetitions following consumption of these meals.

6.3.2 Subjects

To participate in this study, subjects had to be non-smokers, habitually consuming solid/semi-solid breakfast at least four mornings a week and habitually perform resistance exercise training, including at least one session a week of back squat and bench press exercise. Subjects who indicated that they were not habitual breakfast consumers or were not familiar with back squat and bench press were excluded from this study. Suggested number of sample size for this study was computed using G*Power 3.0.10 software using an α of 0.05, statistical power of 0.95 with 2 number of groups. Based on experiment in Chapter 3, it was estimated that 16 subjects would be sufficient to detect a 15% difference between trials.

6.3.3 Study design

This study was primarily designed to examine the effect of hunger on resistance exercise performance, by manipulating the viscosity of a carbohydrate-containing (1.5 g/kg body mass) pre-exercise meal, using a low-energy thickener to decrease hunger (Chapter 4). Secondary aims were to examine the effect of viscosity/fibre intake on appetite regulation measured using subjective appetite and selected gut peptides. Subjects visited the laboratory on 4 separate occasions for: 10 repetition maximum (10-RM) measurement; a familiarisation trial; and two experimental trials (Figure 6.1). During each experimental trial, subjects consumed the allotted pre-exercise meal containing 1.5

g carbohydrate/kg body mass (maltodextrin; My Protein, Northwich, UK) ~2 h before performing 4 sets each of back squat and bench press, with each set performed to failure. The pre-exercise meals were either high viscosity semi-solid (SEM) or low viscosity liquid (LIQ) meals containing 1.5 g/kg body mass as maltodextrin. Trials were assigned in a cross-over randomised, counter-balanced order from coin toss between SEM and LIQ and subsequent counter-balancing, and were separated by ≥ 4 days to allow energy replenishment (Haddock *et al*., 2006). Schematic diagram for this study can be observed in **Figure 6.1.**

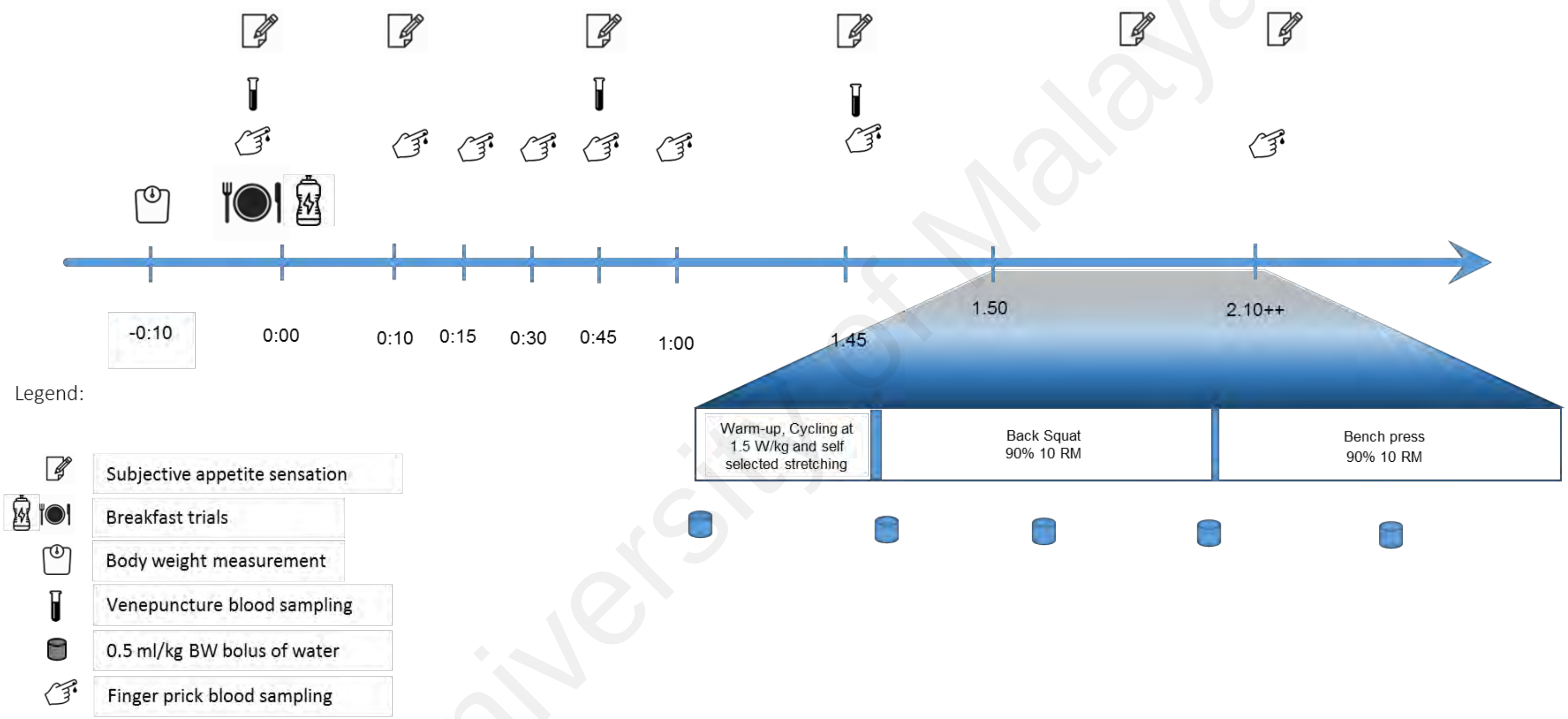


Figure 6.1. Schematic time-line of the experiment.

6.3.3.1 *Preliminary visit and familiarisation trial*

During the first visit, subjects performed a 5 min cycling warm-up at 1.5 W/kg body mass. Subsequently, subjects completed 5 min of self-selected exercise-specific warm-up prior to 10-RM testing for back squat and bench press. After self-selected and standardised warm-up sets, subjects performed their first attempt of each exercise at a weight close to their estimated 10-RM. The load increased until subjects could no longer complete 10 repetitions, with attempt separated by 3 min. The weight of the final completed set of 10 repetitions was termed the subject's 10-RM and was used to determine the load used in subsequent testing sessions (nominally 90% of 10-RM). On a separate visit, subjects were fully familiarised with all procedures that would be expected later in the experimental trials. During this familiarisation, subjects were free to consume their daily habitual breakfast before commencing exercise.

6.3.3.2 *Pre-trial standardisation*

During the familiarisation visit, subjects were given a diet/activity diary and were asked to record their habitual diet and activities for two days before their first experimental trial. Subjects were then asked to replicate these patterns before the second experimental trial. Subjects were also asked not to undertake any strenuous activity or consume alcohol in this 48 h pre-trial period

6.3.3.3 *Experimental trials*

During experiment trials, subjects arrived at the laboratory in the morning (~0800-0900) in a fasted state (10-13 h from their last meal). Baseline measurements of body mass, subjective appetite and blood glucose via finger prick, were collected, then, after 15 min seated rest, a venous blood glucose sample was collected. Subjects then consumed their allotted meal (SEM or LIQ) within 10 min. Additional measures of subjective appetite were taken immediately (10 min), 45 min, 60 min and 105 min post-meal initiation. Additional finger prick blood samples were collected at 15, 30, 45, 60 and 105 min post-meal, as well as after back squat and bench press, whilst additional venous blood samples were drawn at 45 and 105 min post-meal. After the final blood sample was completed, subjects begin the resistance exercise described below.

6.3.3.4 Carbohydrate meals

Both carbohydrate meals were 5 mL/kg body mass, of which 15% (i.e. 0.75 mL/kg body mass) was low-energy orange flavoured squash (Double Strength Orange squash, Tesco, Welwyn Garden City, UK), with the remainder made up with tap water. After the squash and water were mixed together, 1.5 g/kg body mass of maltodextrin was added to the solution (Myprotein, Northwich, UK) and mixed thoroughly. During SEM, 0.1 g/kg body mass of xanthan gum (MyProtein, Northwich, UK) was added and the mixture blended to thicken the solution. For this trial visit, subjects ate the semi-solid meal with a standard spoon from a standard bowl. In LIQ, no thickener was added Subjects were also provided 3 mL/kg body mass water to drink with meals. The nutritional content of the meals is presented in **Table 6.1.**

Subjects were not told the aim or hypothesis of the study. They were informed that the purpose was to test two pre-exercise meals of similar content. Clearly the difference in viscosity of the meals would have been apparent to the subjects, but in an attempt to control expectancy effects, subjects were provided 3 capsules containing ~0.3 g maltodextrin in both trials and were told the ingredients used to thicken the meal in SEM were contained in the capsule in the LIQ trial, so both meals contained identical ingredients.

Table 6.1 Nutritional content of pre-exercise meals.

	Breakfast meal	
	SEM	**LIQ**
Energy (kJ)	1897 ± 249	1837 ± 241
Protein (g)	0.8 ± 0.1	0.5 ± 0.1
Carbohydrate (g)	109.0 ± 14.3	107.9 ± 14.2
Fat (g)	0.5 ± 0.1	0.5 ± 0.1
Fibre (g)	4.9 ± 0.7	0.5 ± 0.1
Total water intake (ml)	573.8 ± 73.2	572.5 ± 73.2

Semi-solid meal trial; SEM, and liquid meal trial; LIQ. Values are presented as mean ± SD, n = 16.

6.3.3.5 Resistance exercise performance

For the resistance exercise test, all subjects initially performed a 5 min warm-up on a cycle ergometer at 1.5 W/kg body mass. Back-squat, followed by bench press testing were then completed, each of which was preceded by 5 min of self-selected stretching and exercise-specific warm up and strength-based warm-up sets of 10 repetitions at 30%

and 60% of 10-RM. Each exercise test required subjects to perform four sets to failure at 90% of 10-RM with 3 min rest in between sets. A standardised lifting technique was used throughout. For back squat, the bar was positioned across the back of subject's shoulders and they started with their knees in a fully extended position. They lowered themselves until their thighs were parallel with the floor, before returning to the starting position. For bench press, subjects started with their elbows fully extended and lowered the bar until it lightly touched their chest, before returning to the starting position. Every repetition was counted by a researcher in silence. Standardised verbal encouragement was also given to the subjects throughout testing. Subjective appetite was additionally measured after the back squat and bench press exercise. Subjects consumed 0.5 mL/kg body mass of water immediately before the cycling warm up, as well as before sets 1 and 3 of back squat and bench press.

6.3.3.6 Subjective appetite sensation

Subjective appetite sensations of hunger and fullness were acquired using visual analogue scales with written anchors of "not at all" and "extremely" placed 0 and 100 mm, respectively (Flint *et al.*, 2000). Additional questions about meal pleasantness and filling using similar visual analogue scales were also measured immediately post-meal (i.e. 10 min).

6.3.4 Blood sampling and analysis

For each venous sample, 7 mL blood was drawn by venepuncture from an antecubital/cephalic vein after 15 min of seated rest. Samples were then transferred into a tube (Sarstedt AG & Co., Nümbrecht, Germany) containing EDTA (1.6 mg/mL), centrifuged (2400 g, 15 min, 4°C) and the resultant plasma was stored at -20°C until analysis. Plasma insulin, ghrelin and peptide tyrosine-tyrosine (PYY) concentrations (All Merck Millipore Ltd, Watford, UK) were determined using commercially available ELISAs kit. Blood glucose concentration was measured on the day of each trial using Accutrend Pluss (Roche Diagnostic, USA) from the finger prick blood sample.

6.3.5 Statistical analyses

Data for this study were analysed using SPSS software (Version 23.0; IBM Corp., Armonk, NY) and reported as mean and standard deviation (M ± SD). Normality of data was checked using a Shapiro-Wilk test. Data containing 2 factors were analysed using 2-way repeated measure ANOVA, with significant effects followed by Holm-Bonferroni adjusted paired *t*-test or Holm-Bonferroni-adjusted Wilcoxon Signed Rank test, as appropriate. Data containing one factor were analysed using paired *t*-test. Statistical significance was set at $P < 0.05$.

6.4 Results

6.4.1 Descriptive demographic

Sixteen men (age 27 ± 3 years, body mass 71.56 ± 9.15 kg, height 1.73 ± 0.05 m, BMI 23 ± 4 kg/m2) provided written consent before completing this study, which was approved by the University of Malaya Research Ethics Clearance. Subjects ate breakfast 6 ± 1 mornings/week, had 5 ± 1 y resistance exercise experience, and at the time of the study were undertaking 4 ± 1 resistance training sessions/week, with 2 ± 1 sessions/week of both back squat and bench press.

6.4.2 Baseline measurement and meals perception between trials

Baseline body mass was not different between trials (SEM = 71.1 ± 8.8 kg; LIQ = 71.4 ± 8.6 kg; $P = 0.307$). Similarly, hunger ($P = 0.428$) and fullness ($P = 0.102$) were not different between trials. For meal perceptions, subjects rated SEM as less pleasant (SEM = 35 ± 22 mm; LIQ = 70 ± 11 mm; $P < 0.001$) and tended to rate SEM as more filling (SEM = 78 ± 13 mm; LIQ = 69 ± 22 mm; $P = 0.092$).

6.4.3 Resistance exercise performance

Total repetitions completed for back squat (**Figure 6.2 A**) were ~10% greater in SEM compared to LIQ (SEM 57 ± 9; LIQ 51 ± 7 reps; $P = 0.001$). For back squat repetitions completed over the 4 sets (**Figure 6.2 B**), there was no interaction effect ($P = 0.549$), but there were effects of trial ($P < 0.02$) and time ($P < 0.001$). Repetitions in all sets were greater in SEM compared to LIQ ($P \leq 0.041$). For bench press (**Figure 6.3 A**), total repetitions were not different between SEM and LIQ (SEM 48 ± 11; LIQ 48 ± 10 reps; $P = 0.621$). Over the 4 working sets (**Figure 6.3 B**), there were no interaction ($P = 0.694$) or trial ($P = 0.621$) effect, but there was a time effect ($P < 0.001$).

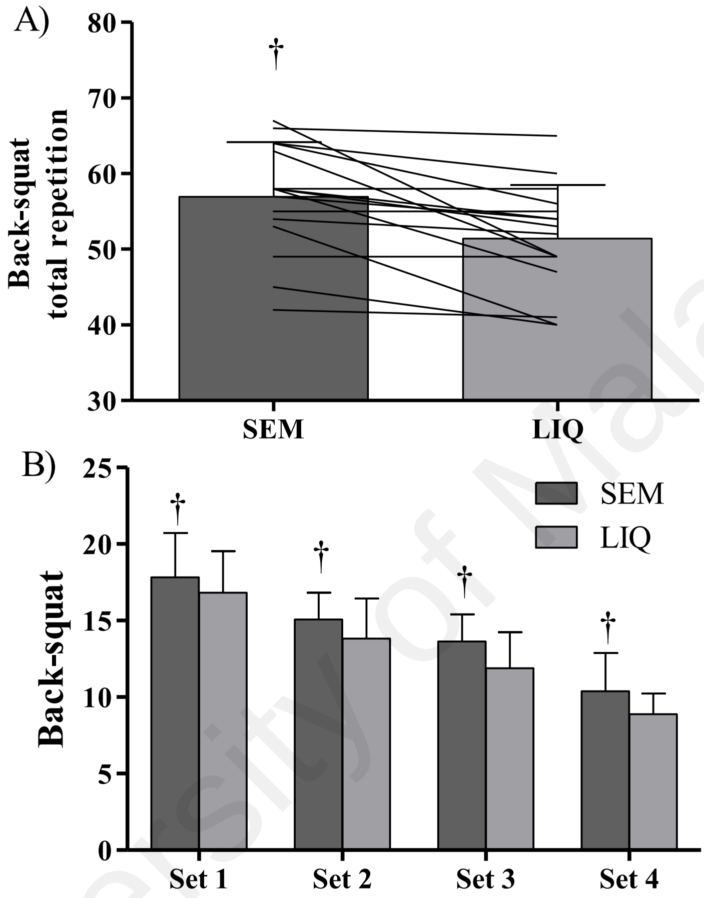


Figure 6.2. (A) Total number of repetitions for back-squat and **(B)** individual set repetitions for back-squat. Semi-solid (SEM) and (LIQ) meal trials. Dagger (†) denotes significant difference between trials (*P* < 0.05). Values are mean ± SD.

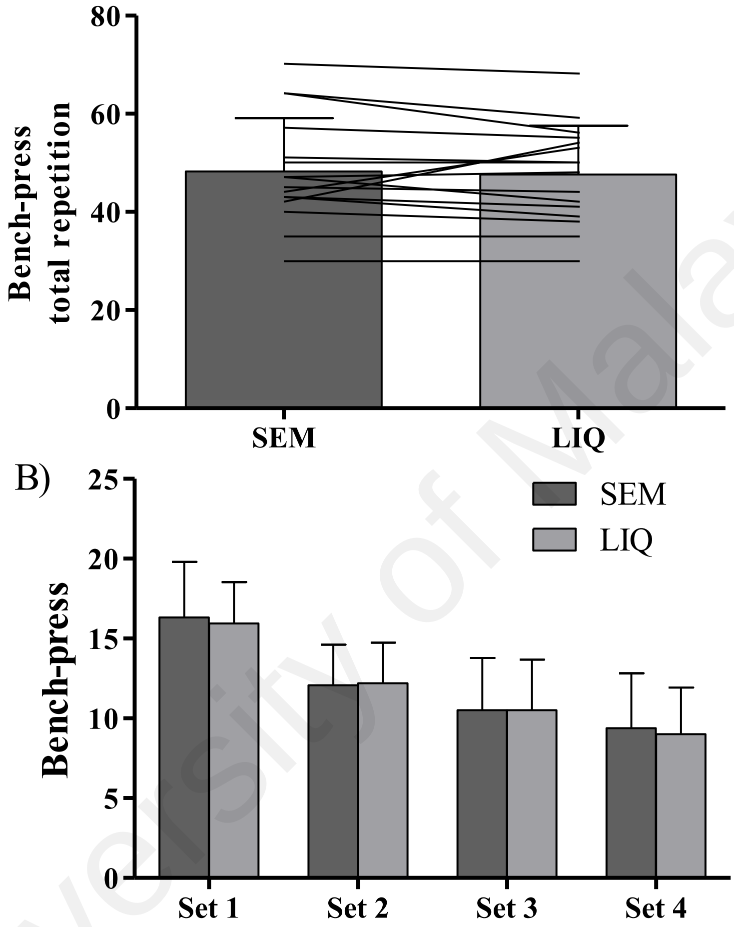


Figure 6.3. (A) Total number of repetitions for bench-press and **(B)** individual set repetitions for bench-press. Semi-solid (SEM) and (LIQ) meal trials. Values are mean ± SD

6.5.3 Subjective appetite sensation

For subjective appetite sensations of hunger and fullness there were trial ($P < 0.001$), time ($P < 0.001$) and interaction ($P \leq 0.01$) effects. Sensations of hunger were lower during SEM compared to LIQ at 105 min, as well as after back squat and bench press ($P \leq 0.027$) and tended to be lower at 10 min ($P = 0.051$) and 45 min ($P = 0.088$). Conversely, sensations of fullness were greater during SEM compared to LIQ at 10 min and 105 min, as well as after back squat and bench press ($P \leq 0.047$; **Figure 6.4**).

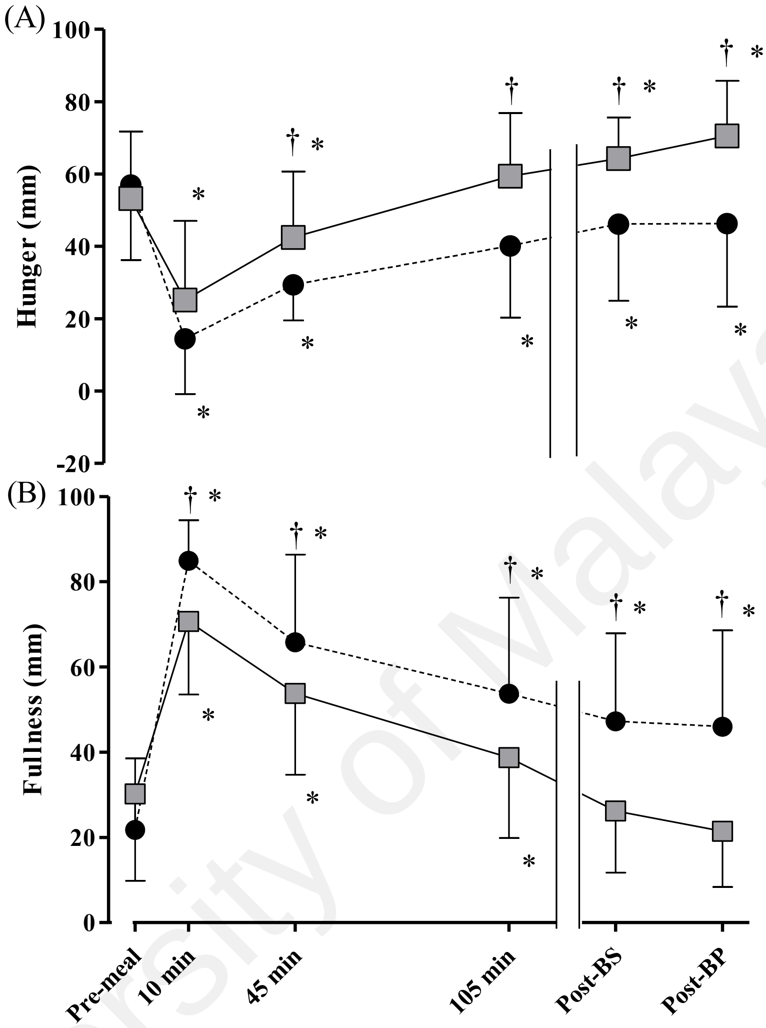


Figure 6.4. Subjective appetite ratings of **(A)** hunger and **(B)** fullness throughout the experimental trials. Black circle (●) represents the semi-solid (SEM), and grey square (■) represents liquid (LIQ) trial. Post-BS (post-back-squat) and Post-BP (post-bench-press) ratings were measured right after both exercise's final set. Dagger (†) denote SEM significantly different to LIQ, whilst asterisk (*) denote significantly different from pre-meal (*P* < 0.05). Values are mean ± SD

6.4.4 Blood analyses

There were time (*P* < 0.001) and interaction (*P* = 0.003) effects, but no trial effect (*P* = 0.067) for blood glucose (**Figure 6.5 B**). Blood glucose concentration was greater during LIQ compared to SEM at 30 min (*P* = 0.005). Compared to pre-meal, blood glucose concentration was increased 15 min until after back squat in both SEM and LIQ (P ≤ 0.007).

For plasma insulin concentration (**Figure 6.5 A**), there were interaction (*P* = 0.002), trial (P < 0.001) and time (P < 0.001) effects. Plasma insulin was greater during LIQ compared to SEM at 45 min (*P* < 0.001) and 105 min (*P* = 0.015). Compared to pre-meal, plasma insulin increased at 45 and 105 min during both SEM and LIQ (*P* < 0.001). For plasma total ghrelin concentration, (**Figure 6.6 A**), there were no interaction (*P* = 0.494) or trial (*P* = 0.210) effects, but there was an effect of time (*P* = 0.001), with lower concentrations at 45 min and 105 min (*P* < 0.024). For plasma total PYY concentration (**Figure 6.6 B**), there were no interaction (*P* = 0.451) or trial (*P* = 0.281) effects, but there was a time effect (*P* < 0.001), with PYY concentrations increased at 45 min compared to pre-meal (*P* = 0.004).

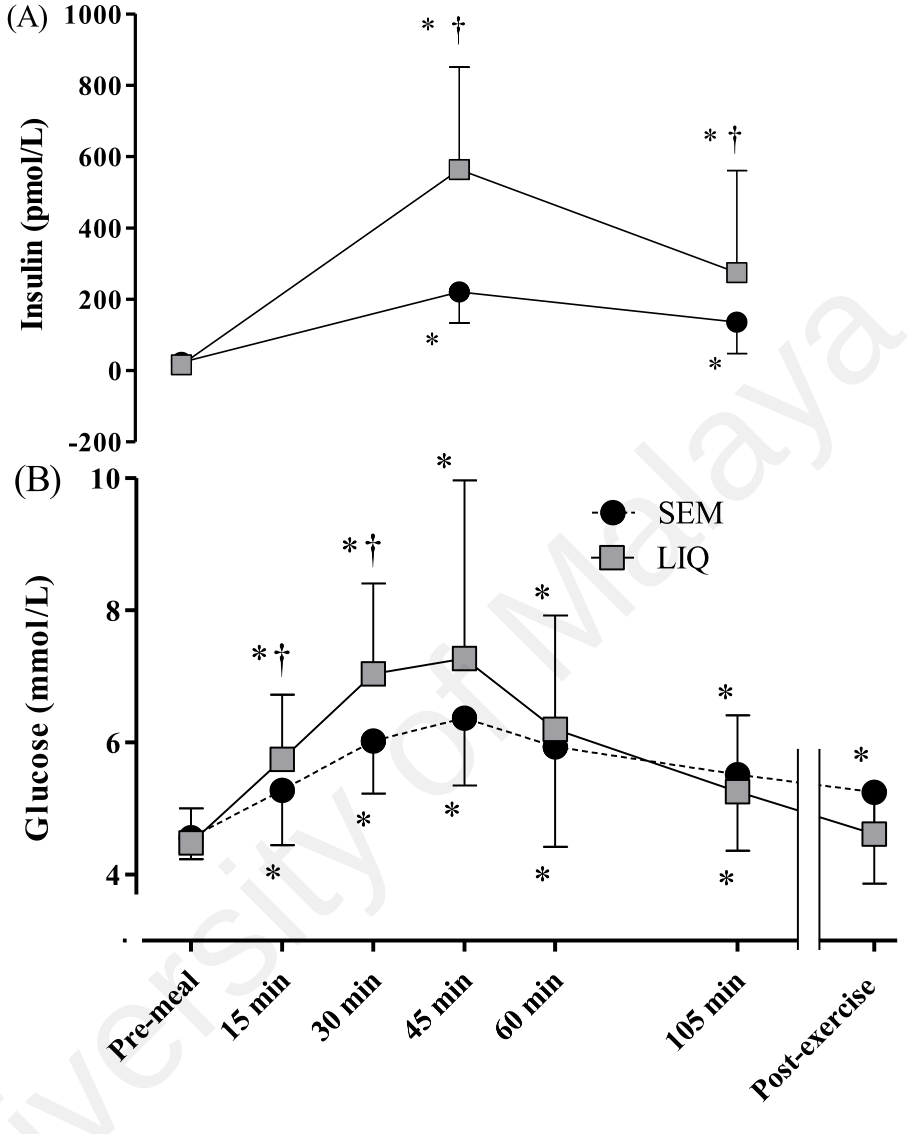


Figure 6.5 (**A**) Plasma insulin and (**B**) blood glucose response measured at specified time points. Black circle (●) represents semi-solid (SEM) and grey square (■) represents liquid meal trial (LIQ). Dagger (†) indicates significantly different between SEM and LIQ at particular time point, whilst asterisk (*) denote significantly different from pre-meal ($P < 0.05$). ($P < 0.05$).

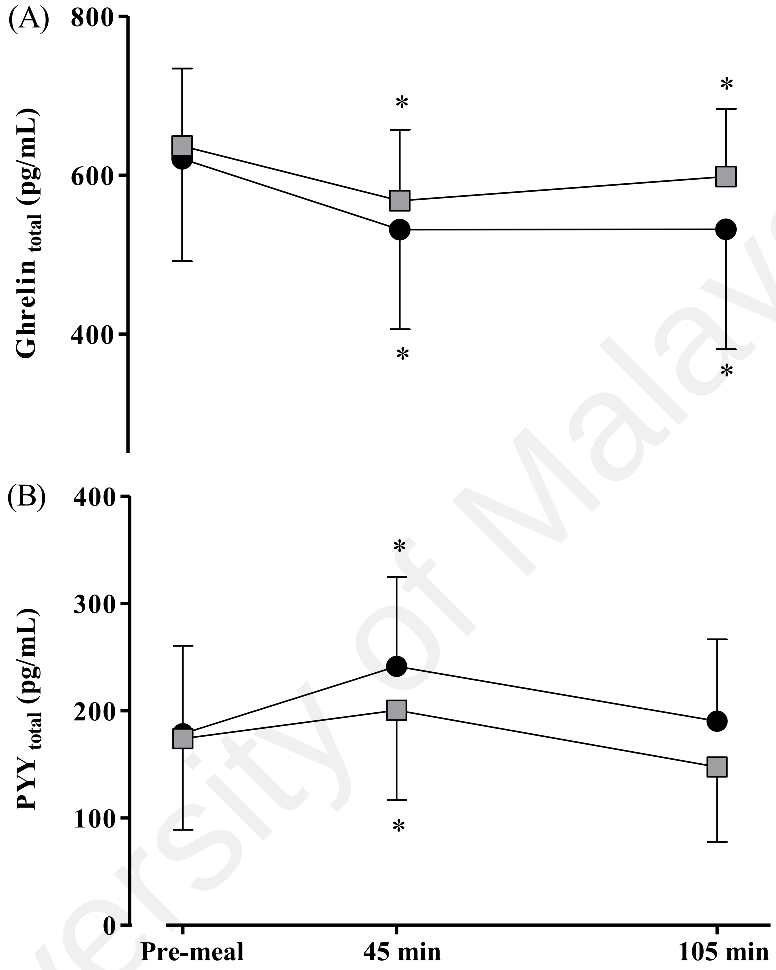


Figure 6.6. Plasma (**A)** Ghrelin$_{total}$ and (**B)** PYY$_{total}$, measured at specified time points before exercise protocol was commenced. Black circle (●) represents the semi-solid (SEM) and grey square (■) represents liquid meal (LIQ). Post-BS (post-back-squat) and Post-BP (post-bench-press). Asterisk (*) denote significantly different from pre-meal (*P* < 0.05). Values are mean ± SD.

6.5 Discussion

The purpose of this study was to investigate the effect of hunger on performance (number of repetitions) in a bout of resistance exercise involving 4 sets of back-squat and 4 sets of bench-press. In an attempt to alter hunger, the viscosity of the pre-exercise meal was manipulated using the xanthan gum (low-energy thickener) to produce a semi-solid meal in one trial and compared with a liquid meal in the other trial. The main findings were two-fold. Firstly, the inclusion of the xanthan was successful in producing the desired effects on appetite, with hunger reduced and fullness increased during SEM compared to LIQ. Secondly, and in line with the hypothesis, subjects completed ~10% more repetitions of back squat exercise during SEM compared to during LIQ (SEM = 57 ± 7 repetitions; LIQ = 51 ± 8 repetitions; $P = 0.001$). Interestingly, there was no difference between trials for the number of repetitions performed during the bench press exercise (SEM 48 ± 11; LIQ 48 ± 10 reps; $P = 0.621$). Therefore, these results suggest, for the first time, that hunger might play a role in how a pre-exercise meal influences performance.

Whilst what accounts for this difference in performance is not known, it is hypothesised that it is the difference in hunger/appetite that accounts for the observed effects. To the best our knowledge, this study is the first to demonstrate that resistance exercise performance, or any aspect of human performance for that matter, may be altered by an individual's perceived hunger. Whilst it cannot be discounted that the small difference in fibre intake between the trials might have influenced performance either directly or indirectly, it seems unlikely. Sensations of hunger arise for various reasons and from numerous sites along the gastrointestinal tract, including signals of endocrine (i.e. hormones secreted by the gastrointestinal tract) and neuronal (i.e. via the vagus nerve) origin. Ultimately, these signals manifest in central responses that effect behaviour (i.e. promote food seeking behaviour/energy intake).

In several different exercise settings, a variety of perceptions have been shown to influence performance. For example, some researchers have suggested that the sensation of thirst explains, at least some of, the decrement in exercise performance reported with dehydration (Sawka & Noakes 2007; Goulet 2011). Indeed, in dehydrated cyclists, the swallowing of a very small amount of water (25 mL water every 5 min during an exercise test lasting ~20 min) increased endurance capacity compared to rinsing the mouth with the same volume of water (Arnoutis *et al*. 2012). This suggests that the swallowing of water/fluid and the consequent activation of oropharyngeal receptors in the throat/stomach might play a role in exercise performance capabilities. The present study suggests that perhaps the act of swallowing/processing a more viscous semi-solid food might act in a similar way to influence performance. Given that the sensation of hunger is distracting, this might consequently mean that an exerciser/athlete is not entirely focussed on the exercise task at hand and thus their performance is lessened. Additionally, a sudden change in someone's habitual diet regimen from a solid meal to liquid, might also contribute sensations appetite, although both meals could be isocaloric. Indeed, hunger might also exert a psychological effect on the exerciser to influence performance. Given that current nutrition recommendations for pre-exercise nutrition suggest exercisers should consume a (high carbohydrate) meal in the pre-exercise period (Burke *et al*. 2011), the sensation of hunger might suggest to the exerciser that they are not appropriately fuelled and thereby cause performance to be impaired via a potential nocebo effect.

The findings of this study therefore suggest that the results of the studies presented in Chapter 3 and 4 might, at least partially, be explained by the effects of the pre-exercise meals provided on subjective appetite. This suggests, for the first time (to our knowledge), that hunger/appetite might mediate some of the effects of pre-exercise nutrition on subsequent performance. Clearly, this is a speculative hypothesis at this time and future studies should seek to confirm these effects, but if these findings are confirmed they provides an alternative mechanism by which nutritional intake might module performance. Interestingly, the results here well reflect those observed in Chapter 4, as effects were apparent for back-squat, but not bench press. Exactly what accounts for this is unknown, but it is interesting to note that the effects on appetite persisted through to the bench press, meaning that the appetitive effects of the pre-exercise meal might be limited to lower-body exercise or that other effects might be playing a role.

Most studies have demonstrated that a solid meal, elicits a stronger satiety response compared to a liquid meal (Apolzan *et al*., 2007; Berry *et al*., 2003; Pfeiffer *et al*., 2010; Tieken *et al*., 2007; Martens *et al*. 2012), although some report no difference (Almiron-Roig *et al*., 2003; DiMeglio & Mattes, 2000). This is consistent with the current study, where the semi-solid meal increased fullness and decreased hunger to a greater extent than the liquid meal. Although fibre was also present in the semi-solid meal, the amount was only small (~4.9 g). A previous study (Flood-Obaggy & Rolls 2009) demonstrated that fibre intake is unlikely to influence sensations of appetite (i.e. hunger and fullness) or indeed subsequent energy intake. In this study, apple juice with (4.8 g fibre) and without fibre elicited similar hunger and fullness responses. However, when solid apple (containing the same amount of fibre) was consumed, appetite and subsequent energy intake were suppressed. This suggests that the state of the meal (i.e. solid vs. liquid) has a stronger effect on appetite than the fibre content. This suggests that factors other than the fibre content likely explain the effects of the meals in the present study on appetite and possibly performance. Whether the type of fibre added is important in this relationship is, to our knowledge, not known. Interestingly, previous work looking at solid and liquid meals does not support the effects observed here for glucose and insulin responses. Studies have shown that glucose and insulin responses are similar between identical solid and liquid meals (Martens *et al*. 2012). Therefore, the reduced glucose and insulin responses seen here after the semi-solid meal are likely caused by the addition of fibre to the meal and have been reported previously (Brennan, 2005).

To our knowledge, no study has compared the effects of solid/ semi-solid versus liquid meals on exercise performance. The closest parallel to this might be studies looking at the effect of glycaemic index (GI) of a meal on exercise performance (Stevenson & Williams, 2005; Ching-Lin & Williams, 2006). Indeed, by design, studies looking at the pre-exercise meal GI, demonstrate reduced postprandial blood glucose concentrations following ingestion of a low GI meal. In some cases, a low GI pre-exercise meal has been shown to enhance (endurance) performance (Stevenson & Williams, 2005; Ching-Lin & Williams, 2006; Durkalec-Michalski *et al*., 2018), with the suggested mechanism the stability of postprandial glucose levels during exercise (Wee *et al*., 2004; Ching-Lin & Williams, 2006), compared to rapid decrease in blood glucose concentration after 10 to 20 min of exercise (Karamanolis *et al*., 2011). Whether these mechanisms played a role in the present study is unknown, but it seems unlikely that the reduced postprandial glucose concentrations explain the performance effects. Firstly, whilst some studies show effects of meal GI on exercise performance, a recent systematic review and meta-analysis (Burdon *et al*. 2017) reported no consistent effect for low GI meals on performance. Secondly, whilst the divergent postprandial glycaemic responses might invoke small differences in glucose metabolism and storage as glycogen in muscle and liver, these would pale in comparison to the difference that would have been observed in Chapter 4, where either 0 or 1.5 g/kg body mass was consumed. In Chapter 4, these large differences in meal carbohydrate intake altered the metabolic response (i.e. glucose, insulin and ghrelin concentrations) and presumably altered glycogen levels (at least in liver), but did not affect performance. This suggests that the relatively small differences in postprandial glucose responses, and possibly glycogen storage, in the present study would be unlikely to influence the performance response. Indicating it is likely that the effects on appetite explain the findings.

Concerning the hormonal response to differences in meal form, the semi-solid meal was likely to slow gastric emptying rate (Berry *et al*., 2003). Thus, compared to LIQ, it is possible that the lower glucose response observed during the SEM trial may be due to the fibre content of the SEM meal that produced a slower rate of digestion. As previously discussed, although the SEM meal increased fullness and decreased hunger, there were no differences in hormonal mediators of appetite (ghrelin and PYY). Ghrelin and PYY are orexigenic and anorexigenic hormones, respectively, responding to nutrient ingestion typically in a dose-dependent manner to the energy content of a meal (Batterham, *et al*., 2010; Sakata *et al*., 2010). Although some macronutrient-specific effects have been previously reported (Foster-Schubert *et al*., 2008; Chowdhury *et al*., 2015). In the present study, the postprandial suppression of ghrelin and elevation in PYY was similar between conditions, which is interesting given that these hormones have been implicated in appetite regulation and clear differences in hunger and fullness where observed between trials. This is consistent with the results reported in Chapter 4, where there was also an uncoupling of subjective and hormonal appetite regulation. Either way, these results suggest that changes in endocrine appetite markers secreted from the gastrointestinal tract (at least for ghrelin and PYY) do not explain the effects on performance observed.

6.6 Conclusion

In conclusion, the results of the present study demonstrate that performance in 4 sets of back squat exercise was enhanced by a high viscosity semi-solid breakfast meal compared to a liquid meal. Results from this study suggest that any performance effects of pre-resistance exercise energy/carbohydrate intake are likely caused by psychological effects of consuming a semi-solid form of meal, rather than physiological/metabolic effects, at least among well rested habitual breakfast consumers. Findings from this study suggest that resistance exercise at high intensity, can be influenced by appetite sensations. At a given exercise intensity, energy/carbohydrate intake may not be a factor influencing performance, but rather the perception of having a meal might be. As for this study, subjects were able to perform a greater number of repetitions with a meal form that more closely resembled to their habitual regimen. Practically, this could also extend to any intermittent type of exercise in the morning.

CHAPTER 7: GENERAL DISCUSSION AND CONCLUSION

With the trend to omit breakfast increasing (Haines *et al*., 1996), especially among exercisers, the effect of breakfast omission on subsequent exercise performance is important to understand. Although a number of studies have investigated the effect of consuming/omitting breakfast on endurance exercise, its impact on short term resistance exercise performance, as well as the mechanisms explaining any observed effects remain unclear. The aim of this thesis was to fill the gap of knowledge as to if and how pre-exercise carbohydrate intake in the morning effects subsequent resistance exercise performance. Besides, this thesis also examined the ambiguous relationship between subjective sensation of appetite (i.e. hunger/fullness) and metabolism, as both of these factor could independently influence resistance exercise performance. This chapter presents a summary of the main findings in each study within this thesis and how they contribute to understanding the relationship between breakfast omission, appetite sensations and metabolic regulation on resistance exercise performance.

7.1 Effects of a pre-exercise carbohydrate rich breakfast on resistance exercise performance

Breakfast, which typically contains a high percentage of carbohydrate, might be important to ensure sustainability of muscular effort during exercise in the morning. It offsets the depletion of liver glycogen and at the same time alleviates sensations of hunger following an overnight fasting. Although consumption of a carbohydrate containing breakfast could increase liver glycogen and improve physical performance, for resistance exercise which is typically intense and intermittent in nature, its effects are not well documented. In Chapter 3, it was found that resistance exercise of back squat and bench press at 90% from 10-RM for 4 sets to exhaustion were improved by ~6-15% after an ecological high-carbohydrate meal (i.e. cereal, jam sandwich, milk, orange juice) was consumed, compared when breakfast was omitted.

Given that subjects knew they ate a breakfast meal pre-exercise (or not as the case may be), this might have a psychologically influence exerting a nocebo effect on performance. Therefore, Chapter 4 sought to determine whether giving a blinded meal, with the intention to isolate pre-exercise carbohydrate consumption, would exert similar results on resistance exercise performance. Interestingly, a placebo/nocebo effect was evident where exercise performance was improved due to subjects perceiving they had eaten 'breakfast' before performing exercise. As such, resistance exercise performance improved by ~15% and ~16% for both placebo and carbohydrate containing breakfast, respectively, compared to when subjects omitted it. Interestingly, the improvement was comparable to the earlier experiment, suggesting any sort of pre-exercise breakfast consumption could benefit subsequent resistance exercise performance, irrespective of its energy content. It seems likely that the placebo effect was able to exert an effect on performance because of the mode of exercise studied (i.e. high intensity small volume exercise). It would be interesting to know if any such effects related to the pre-exercise meal are apparent with prolonged exercise. One study explored the placebo effect of carbohydrate intake during 3 h of exercise, reporting that a placebo carbohydrate drink produced no better performance than water (Hulston *et al*., 2009). The number of sets of each exercise performed in the present study was chosen to reflect current guidelines for those engaged in resistance training programmes, typically 3-5 sets per exercise (Ratamess *et al*., 2009).

Only when higher volume and more prolonged resistance exercise was studied in Chapter 5, was an ergogenic role of carbohydrate, above that of a placebo, observed. In Chapter 5, multiple bout leg extension exercise was performed at ~80% from 10-RM was increaserd after consumption of a meal containing carbohydrate, compared a placebo meal. This finding is consistent with the literature where low intensity (55 - 85% from 1 - 10-RM) resistance exercise to exhaustion was increased carbohydrate supplementation during exercise (Haff *et al.*, 1999; Haff *et al*., 2001; Oliver *et al*., 2016). Thus, when performing very high-volume resistance exercise (e.g. pyramid sets, body mass conditioning exercises, circuit training, certain rehabilitation situations etc.), consuming a high carbohydrate pre-exercise meal might be the prudent approach to optimise performance (Slater & Phillips, 2011).

Collectively, the findings from Chapter 3 and 4 suggest that, resistance exercise performance of 4 sets to exhaustion seem not to be of benefited by the metabolic effects of a pre-exercise carbohydrate breakfast. Rather, psychological factors related to a person's perception of having had a pre-exercise meal, or the meal's consequent effects on sensations of fullness (alleviate hunger), seem to be potential factors influencing performance outcomes. However, when more prolonged high-volume resistance exercise (~18 sets) was carried out in Chapter 5, the ergogenic role of pre-exercise carbohydrate intake may become apparent. This response could be explained by a study by Spriet *et al*. (1992) which investigated the estimated energy contributions of anaerobic glycolysis, PCr and aerobic metabolism during 3 bouts of maximal isokinetic cycling for 30 s, with 4 min rest between bouts. In this study, Spriet *et al*. suggested that the anaerobic contribution to the total amount of work declines, whilst relative, contributions from aerobic metabolism increase with the increase number of exercise bout (Spriet *et al*., 1992). Metabolically, aerobic metabolism utilises substantial amounts of stored carbohydrate via glycolysis and then oxidative phosphorylation, meaning that aerobic exercise is far more likely to be influenced by small differences in endogenous carbohydrate stores (Burke *et al*., 2011). Although the exercise implemented in Chapter 5, which involved prolonged multiple bout leg extension to exhaustion, is far from ecologically valid for most resistance training scenarios, the findings could apply to some prolonged high volume training session such as pyramid sets, body mass conditioning exercises, circuit training, or certain rehabilitation situations. Therefore, adequate carbohydrate intake at the pre-exercise meal might be crucial for performance in this type of exercise.

7.2 Mechanism by which pre-exercise carbohydrate meal effects resistance exercise

Many researchers have demonstrated that resistance exercise utilises muscle glycogen as fuel source, with a single exercise session decreases muscle glycogen by up to 40% (Robergs *et al*., 1991; Tesch *et al*., 1998; MacDougall *et al*., 1999; Haff *et al*., 2000). Since the carbohydrate containing pre-exercise breakfasts provided in Chapters 3, 4 and 5 were consumed after an overnight fast, the ~100 g carbohydrate would likely have increased liver glycogen compared to the ~2 g in no breakfast/placebo trial (Nilsson & Hultman, 1973) and to a lesser extent muscle glycogen (Chryssanthopoulos *et al*., 2004). Hypothetically, any small difference in starting muscle glycogen due to carbohydrate consumed at a pre-exercise meal intake could have influenced performance. However, the work in Chapter 4, confirms that carbohydrate intake pre-exercise does not exert an ergogenic effect during 4 sets of high intensity resistance exercise. Similarly, other previous work using double-blind and placebo-controlled designs have all shown no ergogenic effects of carbohydrate supplementation when the number of sets is small (up to 6 sets) and exercise is high intensity in nature (Mitchell *et al.*, 1997; Dalton *et al.*, 1999; Kulik *et al.*, 2008; Raposo, 2011; Fairchild *et al.*, 2016).

Although muscle glycogen was not measured in any of experiment described in this thesis, it is believed that the level of muscle glycogen depletion appears to be a function of the amount of work performed (Robergs *et al.*, 1991). Thus, manipulating carbohydrate intake in a pre-exercise meal following an overnight fasting, is more likely to influence prolonged high volume resistance exercise. As evidenced in Chapter 5, a pre-exercise carbohydrate meal was shown to improve multiple bout leg extension number of repetition. Similarly, many previous studies reported the ergogenic effects of carbohydrate appear to become apparent in prolonged high intensity resistance exercise of 10 to 16 sets (Haff *et al.*, 1999; Haff *et al.*, 2001; Lambert & Flynn, 2002; Jagim *et al.*, 2016; Oliver *et al.*, 2016). Thus, it seems likely the 8% increase in performance after the carbohydrate compared to the placebo meal in Chapter 5 was caused by the glucose ingested through the meal increasing liver and muscle glycogen and prolonging exercise capabilities. Indeed, carbohydrate intake after an overnight fast has been shown to increase liver (Bawden *et al.*, 2014) and to a lesser extent muscle (Chryssanthopoulos *et al.*, 2004) glycogen stores, suggesting that augmentation of these stores could assists high volume resistance exercise performance.

Although the energy content in the placebo meals in Chapters 4 and 5 was negligible, it was observed that the sensations of hunger and fullness comparably to after consumption of the carbohydrate containing meal. Indeed, the small amount of energy in the placebo meals, which was mainly contributed by the fibre and the orange squash, seems unlikely to affect subjective appetite. Similarly, in Chapter 6, the decrease in sensations of hunger and increase in sensations of fullness after consuming a semi-solid compared to liquid meal seems unlikely due to the small difference in energy content (~60 kJ) contributed by the ~4.5 g of fibre. Thus, the increased satiety responses (increased sensations of fullness and decreased sensations of hunger) in all semi-solid meal of Chapter 4, 5 and 6, is likely caused by the xanthan gum or its effects on meal viscosity (Marciani *et al*., 2000, 2001; Fiszman & Varela, 2013). However, interestingly, the reported subjective sensations of hunger and fullness during placebo trials did not correspond with changes in metabolic/hormonal markers of appetite status. Specifically, sensations of fullness remained elevated and hunger decreased, despite no change in plasma glucose and insulin, metabolic effects that were apparent after consumption of the carbohydrate meal. Furthermore, ghrelin which is an orexigenic hormone (Cummings & Overduin, 2007), was suppressed in all carbohydrate containing meals in Chapter 4 and 6, whilst PYY and GLP-1, which are anorexigenic hormones (Batterham *et al*., 2002), showed no effect between meal trials. This suggests that, at least in response to a single breakfast, there can be a discordant response for the subjective and physiological regulators of appetite. From this, it seems likely that the improved performance could be due to psychological factors related to placebo/nocebo effects or due to the alleviation of sensations of hunger/fullness, rather than related to metabolic effects.

The contribution of subjective appetite effects to pre-exercise meal-induced changes in resistance exercise performance was confirmed in Chapter 6. To the authors' knowledge, this is the first experiment comparing of human performance is effected by sensation of appetite (i.e. hunger and fullness). Interestingly, the number of repetitions of back squat was greater in semi-solid meal, which provided greater sensations of fullness and reduced sensations of hunger, compared to when a macronutrient and energy-matched liquid meal was consumed. It is therefore seems likely that, the performance responses observed in Chapters 3, 4, and 6 were unlikely due to metabolic factors. It seems likely that some of this effect might be caused by the fact that all subjects used in this thesis were habitual breakfast consumers. It would certainly be interesting to know if similar effects are apparent in those that do not habitually consume breakfast.

The most plausible explanation for how sensations of appetite might be linked to performance is related to perceptual factors that feed into self-regulation of exercise, as described by Noakes *et al*. (2012) for other perceptual factors. According to Central Governor Model (CGM) of exercise regulation, it is suggested that the brain acts as a centre that regulates exercise performance by continuously modifying the number of motor units recruited at a given time. The brain uses unpleasant, sometimes illusory, sensations to ensure exercise performance is always within the exerciser's capacity (Noakes *et al*., 2012). It is suggested that one of many of CGM factors that could modify performance outcomes includes placebo effects from any brain stimulant (i.e. caffeine, cytokine inyterleukin-6, amphetamine etc.; Del *et al*., 2008; Swart *et al*., 2009), emotional states (Renfree *et al*., 2011) and the level of motivation and habitual experience of the exerciser (Corbett *et al*., 2009; Foster *et al*., 2009). Therefore, any activities prior to or during exercise testing that are uncommon, could lead the brain (via afferent sensory feedback) to downregulate physical performance (Lander *et al*., 2009).

As mentioned previously, after consuming a semi-solid breakfast meal in Chapter 6, subjects reported to be less hungry before exercise testing was commenced. It is possible, that for this reason, the number of repetitions in all 4 sets of back squat were significantly higher following the semi-solid meal than after the liquid pre-exercise meal. Moreover, the subjective sensation scale of hunger (~40 mm) and fullness (~54 mm) for a semi-solid meal in Chapter 6, were comparable to subjective sensation scale of hunger (~45 mm) fullness (~45 mm) for an ecological breakfast meal given in Chapter 3. This suggests that the subjective appetite response to this rather contrived lab-based breakfast designed to allow blinding of energy/carbohydrate intake whilst also providing subjects a 'meal' to consume, rather than a liquid breakfast appears to be similar to that of a more realistic meal. Therefore, it is suggested that psychobiological factors arising from changes in appetite sensation of fullness contributes about 10% to the improvement of back-squat exercise performance conducted in these series of experiments.

In Chapters 3, 4 and 6, resistance exercise testing for back squat always preceded bench press for every subject. Since subjects in the present study had to push themselves to complete 4 sets of back squats to failure at an intensity of 90% from 10-RM, presumably, subjects would have commenced the bench-press exercise with some residual level of mental and physical fatigue. Indeed, engagement in mentally demanding activities is a psychobiological state that could influence physical performance (Boksem & Tops, 2008; Marcora *et al*., 2009). Supporting this assertion, a previous study (Johnson *et al*, 2014) observed that severely high intensity arm cycling resulted in a substantial reduction in subsequent leg cycling power output (Johnson *et al*., 2014). This shows fatigue (mental/physical) and possibly metabolites that arise from one muscle group can contribute to reductions in physical performance in another muscle group (Johnson, *et al*., 2014). This might explain why there were no difference in bench-press between trials, as the prior fatiguing back squat exercise might have interacted with the subjects abilities to perform maximally and overridden any possibly less powerful effects of appetite sensations.

7.3 Limitation and suggestion for future studies

The major limitation of the work in this thesis is that no muscle or liver glycogen measures were made in any of the studies presented in this thesis. This means that expected changes in body glycogen content are presumed from similar previous work reported in the scientific literature. Although these studies demonstrate important outcomes related to how a pre-exercise meal influences resistance exercise performance in the morning, an inherent limitation with all studies presented in this thesis is that they only document the acute effects to a single exposure. Thus, future studies should seek to investigate the long-term effects of manipulating pre-exercise feeding strategies on performance and training responses.

7.4 Conclusion

In conclusion, consumption of carbohydrate at a pre-exercise meal (i.e. breakfast) does not appear to enhance resistance exercise performance above and beyond the effects of a placebo meal when exercise involves 4 sets of an exercise. However, perception of energy intake and/ or hunger might influence performance, at least among habitual breakfast consumers. The results of the studies presented here demonstrate that performance in 4 sets of back squat exercise was enhanced by a semi-solid compared to a liquid pre-exercise breakfast meal, an effect that seems likely to be related to the effects of the meal on sensations of appetite. That is increased hunger impaired performance. Therefore, in exercise settings where the metabolic effects of the carbohydrate intake before exercise are unlikely to influence performance (such as resistance exercise), consumption of meals that decrease sensations of hunger might be a simple strategy to enhance performance via a placebo/nocebo effect or effects on subjective appetite. However, caution should be taken when interpreting these results since subjects in this thesis were well rested (48 h rest before trials). In situations where the time between training sessions is short, it is likely that consumption of a high carbohydrate pre-exercise meal could make an important contribution to total daily carbohydrate intake, as well as performance in a subsequent bout of exercise if pre-meal muscle glycogen stores were sub-optimal.

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LIST OF PUBLICATIONS AND PRESENTED PAPERS

Published Original Article

Naharudin, M. N., & Yusof, A. (2018). The effect of 10 days of intermittent fasting on Wingate anaerobic power and prolonged high-intensity time-to-exhaustion cycling performance. *European Journal of Sport Science*, *18*, 667–676.

Naharudin, M. N., Yusof, A., Shaw, H., Stockton, M., Clayton, D., James, L. J. (2019). Breakfast omission reduces subsequent resistance exercise performance. *Journal of Strength and Conditioning Research*, *00*, 1–7.

Manuscript Under Review

Naharudin, M. N., Adams, J., Richardson, H., Thompson, T., Oxinou, C., Marshall, C., Clayton, D. J., Mears, S. A., Yusof, A., Hulston, C. J., & James, L. J. (2019). A pre-exercise meal increases resistance exercise performance via a placebo effect. *British Journal of Nutrition*, (In Press).

Papers Presented (Oral)

Naharudin, M. N., Adams, J., Richardson, H., Thompson, T., Oxinou, C., Marshall, C., Clayton, D. J., Mears, S. A., Yusof, A., Hulston, C. J., & James, L. J. (2018). Perception of breakfast rather than carbohydrate/energy intake improves morning resistance exercise performance, 23rd Annual Congress of the European College of Sport Science, 4 - 7 July 2018 in Dublin – Ireland (International).

Yusof, A., & Naharudin, M. N. (2018). Chronological changes during 10-day intermitent fasting with low energy intake on high-intensity aerobic performance and lipid constituents. The 1st Conference on Interdiciplinary Approach in Sports of Faculty of Sports Science, Universitas Negeri Yokyakarta, 26 – 27 October 2018 in Yokyakarta – Indonesia (International).

Paper Presented (Poster)

Naharudin, M. N., & Yusof, A. (2015). The Effect Of 10-Day Continuous Fasting On Fuel Utilization Cross-Over During High Intensity Aerobic Performance, 1st Asian Sports Medicine Conference of Malaysian Association of Sports Medicine, 28 – 29 November 2015 in Kuala Lumpur – Malaysia, (International).