Acute carbohydrate strategies for resistance training performance

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Abstract

Carbohydrate (CHO) is critical for moderate-to-high-intensity exercise; however, its relevance to resistance training (RT) performance is unclear due to inconsistent findings, limited mechanistic evidence, and overreliance on endurance-based nutritional guidelines. This thesis elucidates the role of CHO ingestion and mouth rinsing (CMR) as potential ergogenic aids for RT performance by integrating systematic evaluation and update of the literature (Chapters 2 - 4); characterisation of applied nutrition practices in RT-centric athletes (Chapters 5 & 6); and experimental cross-over trials (Chapters 7 & 8), including preliminary evidence of acute CHO ingestion's influence on subcellular glycogen utilisation during RT (Chapter 8).

A systematic review and meta-analysis were conducted to quantify the acute effects of CHO on RT performance and identify ergogenic response moderators (Chapter 2). Across studies with varying designs, CHO produced small improvements in total session volume when pre-exercise fasts exceeded 8 hours, and large improvements when session durations exceeded 45 minutes. An updated meta-analysis (Chapter 3) incorporating recently published trials and corrected data extractions refined these estimates as a small effect across the same sub-groups.

A network meta-analysis was subsequently conducted to rigorously synthesise CMR data for acute RT outcomes (Chapter 4). The network structure allowed for the simultaneous modelling of multiple active comparators (e.g., CMR with maltodextrin, glucose, or maltose) and non-active comparators (e.g., taste matched placebo and water only rinses, or no-rinse control). Relative to placebo, CMR did not improve maximal dynamic strength but produced moderate and small effects on peak force and total session volume, respectively.

Two international surveys characterised the general and peri-workout nutrition practices of drug-tested powerlifters (Chapters 5 & 6). Athletes periodised their nutrition across training phases and reported peri-workout nutrition strategies broadly aligned with sport nutrition guidelines. Pre-training nutrition was prioritised, with many athletes consuming CHO-containing meals before RT, with general and peri-workout CHO practices varying by sex, weight class, age class, and competitive calibre.

To test whether CHO ingestion, independent of energy provision, enhances RT performance, a double-blind, isoenergetic, cross-over trial compared high-CHO (1.2 g/kg), low-CHO (0.3 g/kg), and calorie-less placebo breakfasts before a ~90-min, high-volume RT session (Chapter 7). Volume performance did not differ between conditions, indicating performance may not be sensitive to CHO dose when EI and expectancy are controlled.

Finally, a case series examined the effects of acute CHO ingestion versus an energy-matched placebo on high-volume lower-body RT volume and total and subcellular glycogen compartments (Chapter 8). Preliminary data suggest an ergogenic effect of CHO on volume performance. Total muscle glycogen decreased by approximately 50 - 77% from pre- to post-exercise, representing a substantially greater depletion than previously reported in the literature. Subcellular glycogen depots exhibited similarly large pre- to post-exercise reductions, and neither total nor subcellular glycogen measures demonstrated consistent differences between high- and low-carbohydrate conditions.

Collectively, this thesis clarifies the contextual role of CHO ingestion and CMR as potential RT ergogenic aids, advances their mechanistic understanding through novel subcellular analyses, and provides applied insights informing RT-specific sport nutrition guidelines.

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List of commonly used abbreviations

1-RM: 1-repetition maximum

10-RM: 10-repetition maximum

AS: Artificially sweetened

BG: Blood glucose

BL: Blood lactate

BM: Body mass

CHO: Carbohydrate

CI: Confidence interval

CMR: Carbohydrate mouth rinse

CMJ: Counter movement jump

EI: Energy intake

FA: Felt arousal

FFM: Fat free mass

HCHO: high carbohydrate

HR: Heart rate

IIFYM: If It Fits Your Macros

IPF: International Powerlifting Federation

LCHO: Low carbohydrate

MVIC: Maximum voluntary isometric contraction

MVC: Maximum voluntary contraction

PI: Prediction interval

RPE: Rating of Perceived Exertion

RT: Resistance training

SMD: Standardised mean difference

STF: Sets to failure

Attestation of authorship

"I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor used artificial intelligence tools or generative artificial intelligence tools (unless it is clearly stated and referenced, along with the purpose of use), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning."

Andrew King

Co-authored works

This thesis includes research papers that were jointly co-authored and have either been published or are currently under peer review. Andrew King is the principal author of all research papers included in this thesis. Each research paper is listed below with AUT's co-authorship contributions template (full document is in Appendix A). The role of all co-authors is specified in accordance with the Contributor Role Taxonomy (CRediT).

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Raw I'ma give it to ya, with no trivia, raw like cocaine straight from Bolivia.

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- 8 June 2022 AUTEC reference number 20/312 (Chapters 5, 6, and 7)
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Chapter 1: Introduction

1.1 Background and rationale

Dietary CHO and fat constitute the primary fuel sources during exercise lasting several minutes to several hours, with the relative contribution of each determined largely by exercise intensity and duration [1]. At moderate-to-high intensities, CHO becomes increasingly important [2], as glycogen stored in the liver and skeletal muscle – alongside phosphocreatine – plays a central role in supporting high-intensity efforts [3]. RT is typically performed intermittently and at high intensity by athletes seeking strength, power, and hypertrophy outcomes [4], and is traditionally considered less glycogen-demanding than endurance exercise. Accordingly, although contemporary sport nutrition guidelines recommend a daily CHO intake of 4–7 g/kg for RT-centric athletes [5] and advocate CHO ingestion before and after RT to support glycogen restoration [5, 6], the necessity of CHO provision for acute RT performance has been questioned [7]. Nonetheless, overall dietary provision of CHO may be a key consideration for various strength sport athletes (e.g., throwers, weightlifters, bodybuilders) [5] and phase-specific modulation of CHO intake is documented in bodybuilders [8, 9].

The nutrition practices of endurance exercise athletes [10-12] and the effect of CHO feeding on endurance exercise performance are well established with general recommendations for ingestion in the pre-, intra-, and post-exercise periods [13-15]. In comparison, at the commencement of this doctoral work, the role of acute CHO feeding in RT remained comparatively understudied and marked by conflicting findings [16]. Throughout this thesis, acute CHO feeding is operationally defined as CHO provision occurring on the day of exercise, either within 4 h before exercise and/or during the exercise bout itself [17]. The stressors and energetic demands of RT differ from endurance training [18, 19], and given the high-intensity nature of RT, CHO ingestion needs to be considered with specificity to the unique stimuli and demands of RT. Standard volumes of RT result in decreases of total muscle glycogen stores of 24 – 40% [20-23], with greater volumes producing greater depletion [24]. Importantly, glycogen is compartmentalised within skeletal muscle into intramyofibrillar, intermyofibrillar, and subsarcolemmal stores, each potentially fulfilling different metabolic roles not fully elucidated [25]. Intramyofibrillar glycogen, situated near sites critical for Ca^{2+} release from the sarcoplasmic reticulum, is implicated in excitation–contraction coupling [26-28]. Hokken et al. [29] observed that lower-body RT not only produced ~38% reductions in total vastus lateralis glycogen but also resulted in near-complete intramyofibrillar depletion in approximately half of type II fibres. Such depot-specific reductions may impair contractile function and contribute to fatigue, in concert with and beyond the reductions in total glycogen.

Although muscle glycogen is minimally affected by an overnight fast, hepatic glycogen is substantially reduced [30-32]. Nevertheless, ingestion of a medium-to-high CHO mixed meal after an overnight fast increases muscle glycogen stores by 12–42% in rested individuals [33-36]. Alongside the potential for preserving muscle glycogen during RT, CHO feeding may improve performance by sustaining blood glucose (BG) availability [37, 38] or by activating oropharyngeal receptors sensitive to CHO that relay signals to regions of the brain implicated in motivation, reward, and motor output [39, 40]. These central and metabolic pathways provide plausible mechanisms through which CHO ingestion could enhance RT performance.

At the commencement of this thesis, the evidence base evaluating acute CHO ingestion and RT performance was equivocal. Though narrative summaries existed [16], systematic methods had not been applied. CHO ingestion did not seem to enhance peak power [41], maximal strength [42], or peak isokinetic force or torque [43-46]. However, CHO ingestion often improved RT performance indices such as total isokinetic work completed [44] and total number of sets and repetitions completed to failure [47, 48], especially during longer (>45 mins) RT sessions [41, 44, 47, 48]. Yet these findings were inconsistent, with several longer-duration protocols reporting null effects [49, 50]. Likewise, for shorter duration training sessions (<45 mins), no ergogenic effect of CHO ingestion was reported on lower body sets or repetitions to failure [51, 52], nor did CHO supplementation improve lower and/or upper body isokinetic total and average work in pre- vs post-RT session comparisons [43, 46]. Some shorter protocols nonetheless demonstrated ergogenic effects of CHO ingestion [53-55]. Overall, while session duration appeared to moderate the likelihood of CHO ergogenicity, the evidence was inconsistent and often contradictory.

CMR represents an alternative approach targeting central mechanisms without ingestion [39], and the RT-specific CMR literature also offered equivocal findings. The only meta-analysis available at the start of this doctoral work concluded that CMR had no effect on RT performance [56], but this analysis included only two relevant studies and pooled heterogeneous outcomes. Subsequent studies expanded this literature markedly [57-69]. While CMR does not appear to influence maximal strength [57, 59, 61, 70, 71], an ergogenic effect of CMR has been reported for muscular endurance [65, 67], although most studies report a null effect [57, 59, 61, 66, 71]. Further, several studies also reported an ergogenic effect of CMR on indices of total session training volume or work [60, 63, 64, 68, 72], although this is also an inconsistent finding [62]. In RT protocols, fasting duration, CHO concentration, rinse frequency, and participant characteristics likely contributed to these disparate outcomes. No systematic or quantitative synthesis had yet consolidated this expanding evidence base.

Given these gaps, a rigorous systematic review and meta-analysis of acute CHO ingestion and CMR was required to clarify conditions under which CHO feeding may influence RT performance and provide

the first comprehensive quantitative estimates of these effects. Additionally, despite recent experimental work examining pre-exercise CHO feeding [73-75], it remained unclear whether performance responses reflected CHO-specific metabolic effects or the broader influence of energy provision. Further, no study investigated how acute CHO ingestion influenced total muscle glycogen and its subcellular compartments before and after RT – a key mechanistic gap given the potential role of intramyofibrillar depletion in RT-induced fatigue.

1.2 Purpose of the research

The overarching purpose of this research was to elucidate the role of acute CHO ingestion as a potential ergogenic aid for RT performance by integrating evidence across three complementary domains: (1) systematic evaluation of the literature, (2) examination of applied nutrition practices among RT-centric athletes, and (3) rigorously controlled experimental research. This structure was designed to address conceptual, methodological, and applied gaps in the current evidence and generate practically relevant findings for athletes, coaches, sport nutrition practitioners, and researchers.

The specific objectives of this thesis were to:

1. Qualitatively and quantitatively synthesise the existing evidence on how acute CHO feeding and CMR affect RT performance.
2. Characterise the general and peri-workout nutrition practices of RT-centric athletes.
3. Experimentally evaluate the effects of acute CHO ingestion on RT performance using a cross-over design.
4. Provide novel evidence on the effects of acute CHO feeding with RT on total glycogen and its subcellular components.

1.3 Significance of the thesis

At the commencement of this thesis, most RT CHO feeding recommendations were extrapolated from sport nutrition guidelines developed primarily for endurance exercise. These recommendations do not account for the unique demands of RT or specific adaptations sought by RT-centric athletes. As a result, acute CHO provision was often emphasised despite an incomplete understanding of its relevance, dose–response characteristics, or mechanistic justification within RT-specific contexts.

This thesis provides the first comprehensive synthesis of the acute effects of CHO ingestion and CMR on RT performance by integrating systematic and meta-analytical methods, applied survey research, and trial-based experiments with preliminary mechanistic insights. Collectively, the studies address gaps that previously limited both theoretical interpretation and practical recommendations. The systematic

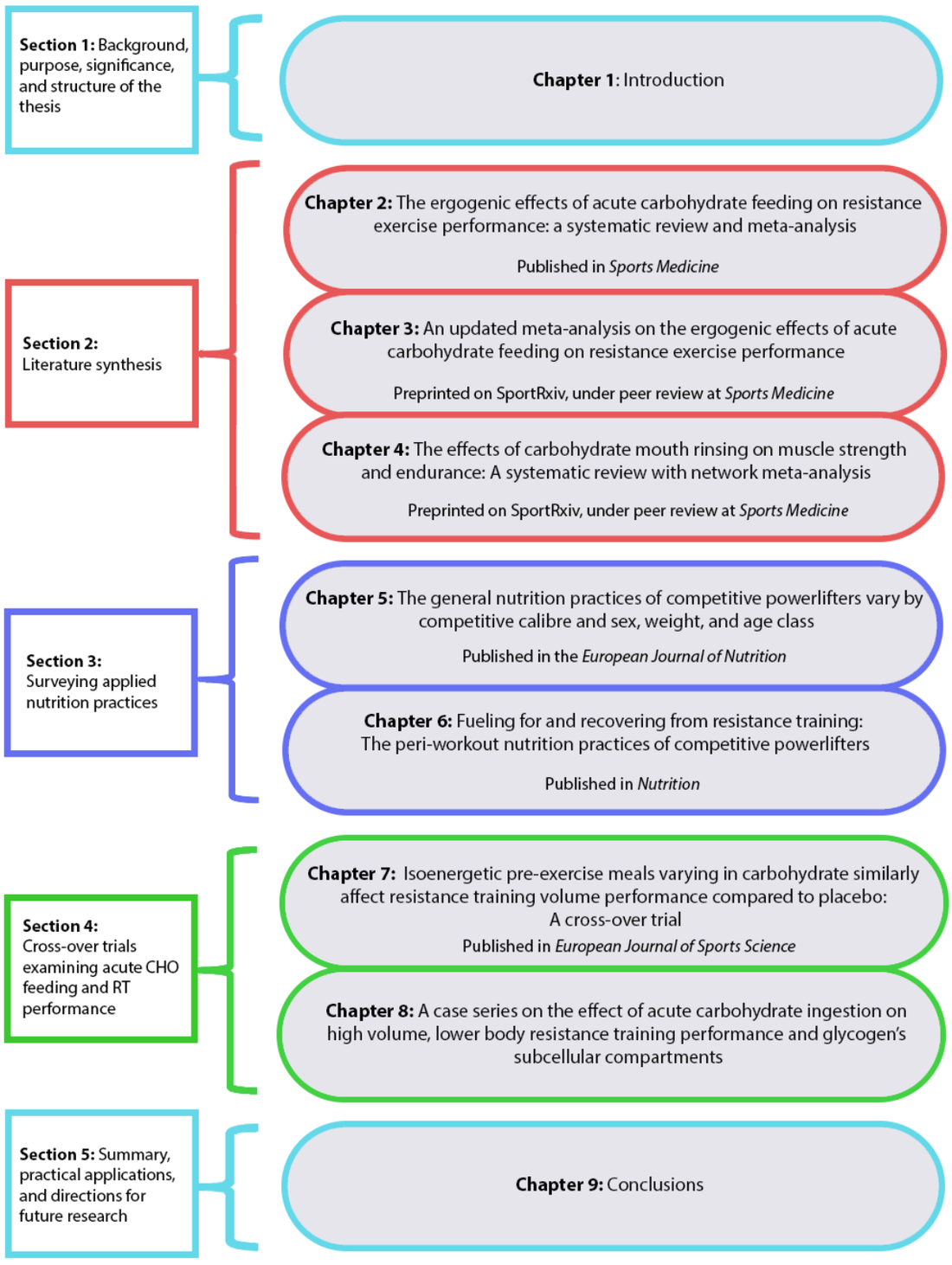
reviews and meta-analyses establish, for the first time, the conditions under which CHO strategies may exert ergogenic effects and quantify the certainty of the available evidence. The survey studies characterise the applied nutrition practices of RT-centric athletes. The experimental trials contribute to the literature by incorporating isoenergetic comparators and preliminary assessments of total and subcellular muscle glycogen utilisation before and after RT with acute CHO feeding.

Together, these contributions hold theoretical and applied significance. They refine our understanding of how acute CHO availability interacts with RT demands, inform RT-specific sport nutrition guidelines, and provide actionable insights for athletes, coaches, nutrition practitioners, and sports scientists. In doing so, this thesis advances both the scientific foundation and practical implementation of nutritional strategies to optimise RT performance.

1.4 Structure of the thesis

This thesis comprises five sections and follows Auckland University of Technology's Format 2 – Thesis by Publication structure. Accordingly, all research chapters are presented in the format of published or publishable journal articles with the exception of Chapter 1 (Introduction), which provides the background and conceptual framework; Chapter 8, which reports preliminary case series data from an acute CHO feeding trial; and Chapter 9 (Discussion), which summarises the findings across all chapters and directs future research. The intervening chapters (Chapters 2 – 7) are presented as stand-alone manuscripts that collectively address the overarching research aims while building a coherent narrative on the role of acute CHO availability in RT performance.

Figure 1-1: Thesis structure



Chapter 2: The ergogenic effects of acute carbohydrate feeding on resistance exercise performance: a systematic review and meta-analysis

This chapter has been published in Sports Medicine, 52(11), 2691-2712. https://doi.org/10.1007/s40279-022-01716-w

2.1 Preface

This chapter provides the first quantitative synthesis of the acute effects of CHO ingestion on RT performance and metabolic responses, establishing the empirical foundation for the remainder of the thesis. Building on the conceptual framework outlined in Chapter 1, this systematic review and meta-analysis clarifies when, and to what extent, acute CHO provision enhances RT volume, with particular attention to the moderating effects of session duration, pre-exercise fasting duration, the number of maximal-effort sets, the CHO dose, and load (%1-RM). By incorporating risk of bias and GRADE assessments, this chapter also appraises the certainty of the available evidence and highlights its key methodological limitations.

The findings of this synthesis provide the necessary rationale for the subsequent research directions of this doctoral work. Specifically, the emphasis on acute CHO availability, delivery mode, and mechanistic pathways motivates the subsequent focus on CMR (Chapter 4) as an alternative strategy and potential mechanistic explanation for any RT ergogenic benefit of CHO ingestion. Finally, recognising the contextual dependence of any ergogenic effect, this chapter provides the rationale for examining applied nutrition practices in powerlifters (Chapters 5 and 6) and conducting controlled experimental work on the influence of pre-exercise CHO feeding on RT performance (Chapters 7 and 8).

2.2 Abstract

2.2.1 Background

CHO ingestion has an ergogenic effect on endurance training performance. Less is known about the effect of acute CHO ingestion on RT performance and equivocal results are reported in the literature.

2.2.2 Objective

The current systematic review and meta-analysis sought to determine if and to what degree CHO ingestion influences RT performance.

2.2.3 Methods

PubMed, MEDLINE, SportDiscus, Scopus, and CINAHL databases were searched for peer-reviewed articles written in English that used a cross-over design to assess the acute effect of CHO ingestion on RT performance outcomes (e.g., muscle strength, power, and endurance) in healthy human participants compared to a placebo or water only conditions. The Cochrane Collaboration's risk of bias tool and GRADE approach were used to assess risk of bias and certainty of evidence, respectively. Random effects meta-analyses were performed for total training session volume and post-exercise BL and BG. Sub-group meta-analysis and meta-regression were performed for categorical (session and fast durations) and continuous (total number of maximal effort sets, load used, and CHO dose) covariates, respectively.

2.2.4 Results

Twenty-one studies met the inclusion criteria (n = 222 participants). Pooled results revealed a significant benefit of CHO ingestion in comparison to a placebo or control for total session training volume (standardised mean difference [SMD] = 0.61). Sub-group analysis revealed a significant benefit of CHO ingestion during sessions longer than 45 mins (SMD = 1.02) and after a fast duration of eight hours or longer (SMD = 0.39). Pooled results revealed elevated post-exercise BL (SMD = 0.58) and BG (SMD = 2.36) with CHO ingestion. Meta-regression indicated that the number of maximal effort sets, but not CHO dose or load used, moderates the effect of CHO ingestion on RT performance (beta co-efficient [b] = 0.11). CHO dose does not moderate post-exercise lactate accumulation and maximal effort sets completed, load used, and CHO dose do not moderate the effect of CHO ingestion on post-exercise BG.

2.2.5 Conclusions

CHO ingestion has an ergogenic effect on RT performance by enhancing volume performance, which is more likely to occur when sessions exceed 45 mins and where the fast duration is eight hours or longer. Further, the effect is moderated by the number of maximal effort sets completed, but not the load

used or CHO dose. Post-exercise BL is elevated following CHO ingestion but may come at the expense of an extended time-course of recovery due to the additional training volume performed. Post-exercise BG is elevated when CHO is ingested during RT, but it is presently unclear if it has an impact on RT performance.

2.2.6 Protocol Registration

The original protocol was prospectively registered on the Open Science Framework (Project identifier: DOI 10.17605/OSF.IO/HJFBW).

2.3 Introduction

Dietary CHO and fat are the two main fuel sources during exercise, but the relative contribution of each depends on the intensity and duration of exercise [1], with CHO making a greater relative contribution to energy production where exercise is of moderate-to-high intensity [2]. Dietary CHO is stored in the liver and skeletal muscle as glycogen and is generally considered important for fuelling high-intensity exercise [3]. RT is often performed intermittently and at high intensity by athletes seeking strength, power, and hypertrophy adaptations [4]. While the role of CHO in endurance exercise performance has received thorough study with general recommendations for ingestion in the pre-, intra-, and post-exercise periods [13-15], the role of CHO feeding on RT performance is less clear due to conflicting findings in a relatively smaller body of literature [16]. The stressors and energetic demands of RT differ from endurance training [18, 19], and given the high-intensity nature of RT, CHO ingestion needs to be considered with specificity to the unique stimuli and demands of RT.

Standard volumes of RT result in decreases of total muscle glycogen stores of 24 – 40% [20-23], with greater training volumes resulting in greater decrements [24]. Muscle glycogen is compartmentalised to several distinct locations within skeletal muscle, including stores that are intramyofibrillar (i.e., within the myofibril), intermyofibrillar (i.e., between myofibrils), and subsarcolemmal (i.e., between the outermost myofibres and the sarcolemma) [25]. While the exact metabolic role of these muscle glycogen compartments requires further elucidation, intramyofibrillar stores of glycogen are purported to be located such that they are readily available to fuel Ca^{2+} release from the sarcoplasmic reticula [26-28]. Recently, Hokken et al. [29] reported that in addition to modest decreases in total glycogen stores of the *m. vastus lateralis* (38%) after a lower body RT session, approximately half of type II fibres exhibited near total depletion of intramyofibrillar stores of glycogen. Thus, the reductions in total muscle glycogen and the selective depletion of intramyofibrillar glycogen incurred during RT could impair the contractile ability of muscle and play a role in fatigue.

Glycogenolysis occurs during strenuous exercise such as RT, but also during periods of fasting, such as the overnight fast. Overnight fasting significantly decreases hepatic stores of glycogen but has a negligible effect on muscle glycogen [30-32]. Despite overnight fasting's minimal effect on muscle glycogen stores, the ingestion of a mixed, medium-high CHO meal after an overnight fast in rested individuals increases muscle glycogen stores by 12-42% [33-36]. Thus, the duration of fast before RT likely influences CHO availability during training, which could be attenuated with CHO ingestion. In addition to offsetting exercise and fasting induced decrements to glycogen content, CHO feeding may also enhance RT performance by maintaining/increasing BG concentration as a readily available fuel source [37, 38], or by activating oropharyngeal receptors sensitive to CHO presence that relay signals to regions of the brain

involved in motivation, reward, and motor output [39, 40]. Taken together, several metabolic and central mechanisms related to CHO feeding could potentially improve RT performance.

The literature investigating the effects of acute CHO feeding on RT performance is equivocal. CHO ingestion does not seem to enhance peak power [41], maximal strength [42], or peak isokinetic force or torque [43-46]. However, CHO ingestion often improves RT performance indices such as total isokinetic work completed [44] and total number of sets and repetitions completed to failure [47, 48] especially during longer (>45 mins) RT sessions [41, 44, 47, 48]. With that said, not all studies agree, as some have reported null findings during longer RT protocols with CHO ingestion for similar RT performance indices such as total repetitions to failure [49, 50]. Likewise, for shorter duration training sessions (<45 mins), no ergogenic effect of CHO ingestion was reported on lower body sets or repetitions to failure [51, 52], nor was CHO supplementation reported to improve lower and/or upper body isokinetic total and average work in pre- vs post-RT session comparisons [43, 46]. But once again, exceptions exist as some shorter duration studies do report an ergogenic effect of CHO ingestion on RT performance [53-55]. Thus, while there seems to be a general trend for CHO ergogenicity dependant on RT session duration, these findings are not consistent and are at times contradictory. Recently, a systematic review by Henselmans et al. [76] concluded that while the majority of studies investigating the acute effects of CHO ingestion on RT performance did not find a positive effect, there was a trend where studies with longer pre-exercise fast durations and RT protocols of greater than 10 sets completed reported an ergogenic effect of CHO ingestion. However, it is important to note that a quantitative analysis of specific RT outcomes was not conducted.

These inconsistencies and gaps in the literature establish a need for a comprehensive review and quantitative synthesis of the available literature on CHO ingestion's effect on RT performance. Thus, we conducted a systematic review and meta-analysis on the effects of acute CHO ingestion on RT performance to understand if and to what degree CHO feeding influences RT performance, assess the certainty of evidence presented in the literature, and identify gaps in knowledge for future investigations. Such evidence is necessary to guide RT fuelling recommendations for athletes, coaches, and nutrition practitioners.

2.4 Methods

2.4.1 Registration of Systematic Review Protocol

A systematic review was performed in accordance with the *Cochrane Handbook for Systematic Reviews* (version 5.1.0) and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [77]. The original protocol was prospectively registered on the Open Science Framework

(Project identifier: DOI 10.17605/OSF.IO/HJFBW). The protocol registration occurred after pilot searches but before any formal systematic searches were conducted.

2.4.2 Literature Search

A patient/population, intervention, comparison, and outcomes (PICO) strategy was developed using the Word Frequency Analyser Tool (https://sr-accelerator.com/#/help/wordfreq) to suggest search terms for electronic databases. PubMed, MEDLINE, SPORTDiscus, Scopus, and CINAHL electronic databases were searched from inception to 26th of June 2021. The MEDLINE, SportDiscus, and CINAHL strategies were run simultaneously as a multi-file search in EBSCOhost and the records yielded from this search were automatically deduplicated by EBSCOhost. Free-text terms were chosen based on word frequency analysis using the Researcher Refiner tool (https://ielab-sysrev2.uqcloud.net/) and pilot searches to achieve a balance between sensitivity and precision. Only terms related to or describing the intervention were used in the search. The following keywords were used to search the PubMed/MEDLINE database and were applied to the title, abstract, and keyword search fields: “carbohydrate” OR “glucose” OR “maltodextrin” AND “resistance training” OR “resistance exercise” OR “strength training” OR “weight training”. The full search strategy for each respective electronic database is available in the Appendix B Ch. 2 Supplementary File I. Secondary searches included (a) forward citation tracking of included studies using Google Scholar and (b) setting up search alerts of the electronic databases included in this systematic review up to the 8th of January 2022. No year or any other restrictions were applied in the search.

2.4.3 Text Screening

Search records were imported into Endnote (version X8.2, Clarivate Analytics, Philadelphia, PA, USA) and duplicates were removed using automated and manual methods. The remaining records were uploaded to the systematic review tool Rayyan (https://rayyan.ai/). Records were independently screened by title and abstract by two investigators (AK and IJ) to determine initial eligibility. The full texts of the remaining records were then retrieved and assessed by the same investigators for inclusion in the review. Disagreements between investigator’s decisions were resolved via discussion and consensus or in consultation with a third reviewer (EH) where required.

2.4.4 Inclusion and Exclusion Criteria

All studies included in this systematic review met the following inclusion criteria: (1) the study was a peer-reviewed research article; (2) was written in the English language; (3) included healthy human participants with no musculoskeletal injury; (4) used a cross-over study design to assess the acute effect of

CHO ingestion in the pre- and/or intra-exercise period on outcomes of muscle force production (e.g., maximal strength and power) and/or muscle endurance; and (5) used a low to zero-caloric placebo (≤ 25 total kilocalories) or water only comparator condition. Performance indices considered for inclusion were those related to muscle force production (e.g., 1 repetition-maximum [1-RM], isokinetic/isometric force production, power) and endurance (e.g., repetitions completed per set or exercise, total session work or volume, session duration). Perceptual measures (e.g., perceived exertion) and metabolic markers (e.g., BL and BG) were considered secondary outcomes of interest. Review articles, unpublished abstracts, theses, and dissertations were excluded.

2.4.5 Study Coding and Data Extraction

From the included studies, the following data was extracted: (1) study design descriptors including information about blinding and the number of periods and sequences; (2) the number of participants in the study and characteristics such as age, sex, BM, height, and training experience; (3) pre-trial diet standardisation including length and method of dietary tracking; (4) pre-testing fast duration; (5) the dose, timing, and type of CHO used; (6) description of the comparator placebo and/or control condition/s; (7) the RT protocol including intensity, volume, rest periods, exercise selection, and session duration; and (8) means and standard deviations of the relevant performance, perceptual, and metabolic indices. Means and standard deviations for all primary and secondary outcomes were collated into a single spreadsheet and sorted by outcome. Where insufficient information was reported, the corresponding author of the study was contacted via email. All data extraction was completed independently by two authors (AK and IJ). Coding files were cross-checked between the two authors and differences were resolved via discussion and consensus.

2.4.6 Risk of Bias

Risk of bias was assessed using the Cochrane Collaboration's risk of bias tool for randomised trials (RoB 2) [78] with online resources for cross-over trial designs (https://www.riskofbias.info/welcome/rob-2-0-tool/rob-2-for-crossover-trials). Risk of bias was assessed using the information provided in the published article. Rating and grading were completed independently by two investigators (AK and IJ). Decisions were made using the Cochrane Collaboration's most recent online guiding document for cross-over trial designs (March 2021). Risk of bias related to blinding was considered important in this review since risk of bias is highest when affected by subjective expectations and that blinding would be conceivably easy to apply [79]. Signalling question 4.2 of the guidance document was adjusted to consider the risk of bias arising from diet standardisation and the time of day at which trials were conducted. Inconsistent diet

standardisation could affect CHO availability before the RT testing protocol which could influence performance [17], and exercise performance is known to be affected by the time of day at which it is performed [80]. Differences in risk of bias assessment were resolved via discussion and agreement before merging the scores into a single spreadsheet.

The Grading of Recommendations Assessment, Development and Evaluation (GRADE) system was used to evaluate the certainty of evidence for the studies included in the quantitative synthesis [81], in a similar manner to previous reviews evaluating exercise physiology and performance outcomes [82-84]. Specifically, a study was rated high and downgraded one point to moderate, low, or very low for each of the following limitations: imprecision, inconsistency, and risk of bias. For imprecision, a study was downgraded if the conclusion about the effect magnitude (i.e., point estimate) would be altered based on the lower or upper boundary of the confidence interval. For example, if the mean effect was moderate and the lower bound of the 95% confidence interval crossed the threshold for a small effect size (i.e., $g < 0.5$), the precision was insufficient to support a strong recommendation of the conclusion because the lower bound of the confidence interval could include a small effect. For inconsistency, a study was downgraded if high statistical heterogeneity was observed ($I^2 > 50\%$), and for risk of bias if >50% of the studies had >1 risk of bias item assessed as high risk.

2.4.7 Statistical Analysis

A random-effects meta-analysis was performed for each separate outcome when reported by at least two studies in the review. Meta-analysis was performed in R language and environment for statistical computing (version 4.0.5, The R foundation for Statistical Computing, Vienna, Austria) [85], using the *Meta* and *Metafor* statistical packages [86, 87]. The restricted maximum-likelihood method was used to calculate model parameters, and the inverse variance method was used to pool a weighted estimation of the standardised mean differences across the studies included in the quantitative synthesis [88]. The Knapp-Hartung small-sample correction was also used as it provides a more adequate accounting of uncertainty when pooling treatment effects from a small number of heterogeneous studies [89, 90]. Three outcomes of interest were sufficiently reported by the included studies to enable meta-analysis, these were: total training volume, BL, and BG. For total training volume, repetitions completed to failure were most reported and was preferentially used in the meta-analysis.

SMDs with Hedge's g correction and 95% CIs (95% CI: [lower bound, upper bound]) were calculated between CHO and placebo/control condition trials using the means and standard deviations of RT performance and metabolic outcomes, the correlation between the trials, and the number of participants [91]. Since no studies reported correlations, corresponding authors were contacted via email to request this

data. The requested studies were either too old and the data had been destroyed/lost or no reply was received, so correlations were calculated using unpublished data (n = 5) from our laboratory for the outcomes of interest. These calculations yielded values of 0.78, 0.74, and 0.26 for training volume, BL, and BG, respectively. Sensitivity analyses were performed using correlation values of 0.3 and 0.5 for training volume and BL, and 0.5 and 0.7 for BG, to check the robustness of the results. SMD magnitude was interpreted as: small (0.20-0.49), moderate (0.50-0.79), and large (>0.80) [92]. All hypothesis tests were conducted with significance set at $\alpha = 0.05$. The number of studies is denoted by *k*. Where multiple observations of an outcome were reported (e.g., separate effects were reported for repetitions to failure per exercise, rather than total session repetitions completed), the observations were combined into a single, composite effect using methods outlined by Borenstein et al. [91] for dependent continuous outcomes. This ensured that double counting individuals from those studies included in the meta-analysis was avoided.

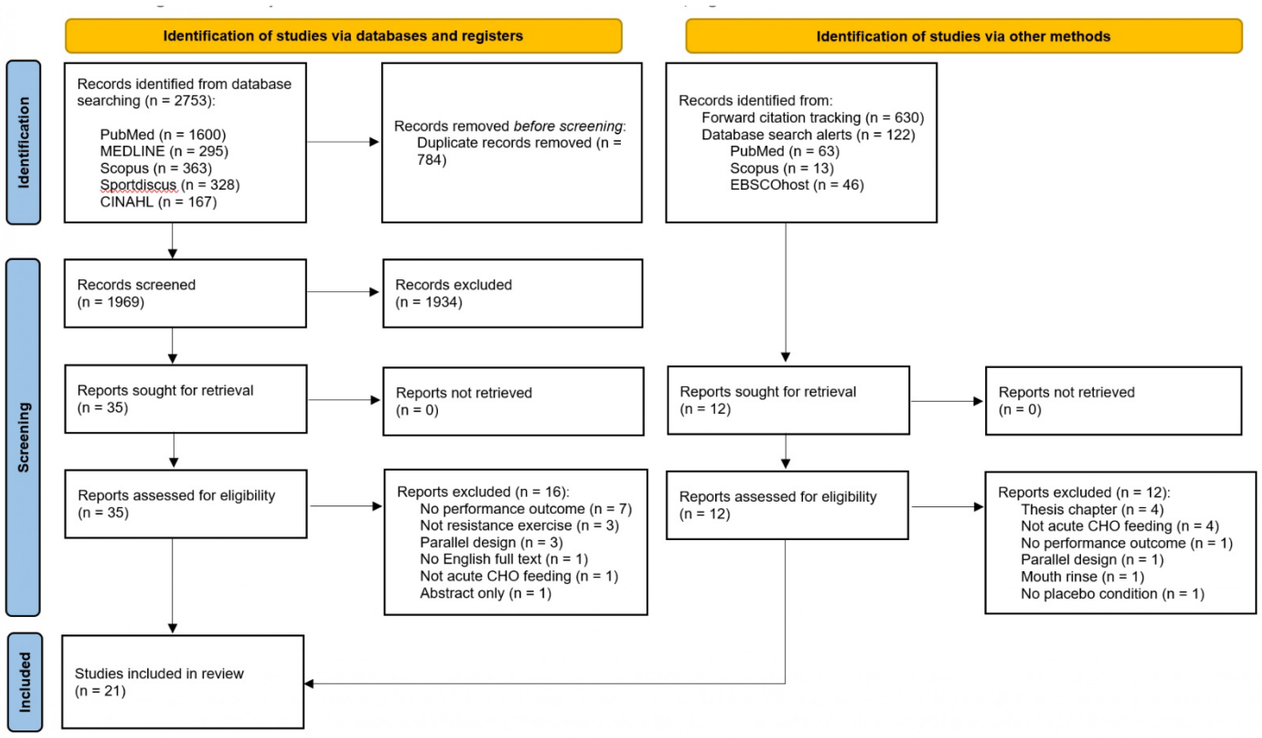
Meta-regressions based on CHO dose (g/kg body mass), load used (%1-RM), and total number of maximal effort sets, were performed when at least six effects were reported for each outcome [93] and are presented as unstandardised regression co-efficient *b*. The statistical heterogeneity of the trials included in the meta-analysis was assessed by the I^2 statistic, where I^2 was considered small (I^2<25%), moderate (I^2=25-49%), or high (I^2>50%) [94]. Publication bias was assessed by examining funnel plot asymmetry and using Egger's regression test [95] for primary outcomes with more than 10 studies, as recommended in the *Cochrane Handbook for Systematic Review Interventions* [96]. Additional information concerning (a) decisions on indices to be included in the total session volume meta-analysis, (b) composite effect calculations, (c) decisions on meta-regression calculations, and (d) decisions on publication bias analysis are detailed in Appendix B Ch. 2 Supplementary File II.

2.5 Results

2.5.1 Search Results

The initial search yielded 2753 records, of which 1969 were screened by title and abstract after duplicates were removed. Title and abstract screening yielded 35 potential inclusions that were screened by full text, of which 19 studies met the full inclusion criteria. Monitoring newly published articles with search alerts did not yield any additional inclusions. Forward citation tracking yielded two additional studies that met the inclusion criteria, resulting in 21 studies included in this review. The stages of this search and the study selection process are presented in Figure 2-1.

Figure 2-1: Literature search flowchart



2.5.2 Study Characteristics

2.5.2.1 Participants

There were 228 participants pooled across all studies in this review. However, two studies [53, 54] used the same participant data for the analysis, reducing the total participants to 222. Of the 222 pooled total participants, 210 were male and 12 were female. Of the 21 studies in this review, 19 included a male only sample, one study included only females [42], and one study recruited a mixed sex cohort [45]. All studies were conducted in young adult populations, with the mean age falling between 20 – 30 years. Participants in sixteen studies were described as resistance trained or as athletes in sports involving RT. There was a range of RT experience with some studies requiring a minimum 2 - 6 months of training experience [50, 51, 97]; whereas others reported participant cohorts with more than 5 years RT experience [43, 44, 47, 53, 54]. Participants in four studies were recreationally trained or physically active [42, 45, 98, 99] and one study did not report any information regarding training history [100]. A comprehensive description of participant characteristics can be found in Table 2-1.

Table 2-1: Participant characteristics of individual study samples.

Study	Participants	Sex: M/F	Age (years)	Mass (kg)	Training history (subjective description, RT experience (years), relative strength (1-RM/BM)
Aoki et al. [42]	CHO = 6; PLA = 6	0/6	22.4 ± 3.8	64.9 ± 7.2	Physically active; at least 2 years; unclear
Ballard et al. [99]	CHO = 21; PLA = 21	21/0	20 ± 1.8	82.3 ± 13.6	Recreationally trained; unclear; unclear
Battazza et al. [100]	CHO = 20; PLA = 20	20/0	25.1 ± 4.4	76.3 ± 7.6	Unclear; unclear; unclear
Bin Naharudin et al. [73]	CHO = 16; PLA = 16	16/0	23 ± 4	77.56 ± 7.13	Resistance trained; at least 2 years; unclear
Bird et al. [101]	CHO = 15; PLA = 15	15/0	21.7 ± 0.8	85.7 ± 1.9	Resistance trained field and court athletes; 3.1 ± 0.3; back squat = 1.55, bench press = 1.1
dos Santos et al. [98]	CHO = 8; PLA = 8	8/0	21.3 ± 2.7	73.1 ± 6.1	Recreationally trained; at least 1 year; relative bench press 1-RM = 0.91
Fairchild et al. [45]	CHO = 17; PLA = 17	11/6	22.1 ± 3.9	69.5 ± 9.6	Recreationally active; at least 0.5 years; unclear
Haff et al. [47]	CHO = 6; PLA = 6	6/0	24.3 ± 2.1	82.6 ± 2.6	Resistance trained; 6.2 ± 0.4 years; able to squat 1.5x BM
Haff et al. [43]	CHO = 8; PLA = 8	8/0	24.3 ± 1.1	85.7 ± 3.5	Resistance trained; 9.9 ± 2.0 years; able to squat 1.75x BM
Haff et al. [44]	CHO = 8; PLA = 8	8/0	23.7 ± 1.3	94.9 ± 4.9	Resistance trained; 8.1 ± 0.9; unclear
Krings et al. [49]	CHO = 7; PLA = 7	7/0	21.9 ± 1.6	91.6 ± 9.7	Resistance trained; at least 1 year; unclear
Kulik et al. [51]	CHO = 8; PLA = 8	8/0	23.8 ± 1.8	92.9 ± 11.4	Resistance trained; at least 0.5 years; back squat = 1.8 ± 0.2
Lambert et al. [48]	CHO = 7; PLA = 7	7/0	22.8 ± 1.3	82.8 ± 7.7	Resistance trained; at least 2 years; unclear
Laurenson et al. [41]	CHO = 10; PLA = 10	10/0	25.3 ± 6.1	83.6 ± 13.1	Resistance trained; unclear; back squat = 1.63, bench press = 1.28
Naharudin et al. [74]	CHO = 22; PLA = 22; CON = 22	22/0	23 ± 3	77.9 ± 8.1	Resistance trained; 4.7 ± 1.5 years; unclear
Oliver et al. [55]	CHO = 16; PLA = 16	16/0	23 ± 3	88.2 ± 8.6	Resistance trained; at least 2 years; able to squat 1.5x BM
Rountree et al. [97]	CHO = 8; PLA = 8	8/0	22 ± 1.8	81.3 ± 7.2	CrossFit athletes; at least 0.5 years; unclear
Smith et al. [50]	CHO = 13; PLA = 13	13/0	23 ± 3.8	82.1 ± 11	Resistance trained; at least 2 months; bench press = 1.4 ± 0.2
Wax et al. [53] & Wax et al. [54]	CHO = 6; PLA = 6	6/0	29.1 ± 4.4	102.4 ± 20.6	Elite competitive bodybuilders and powerlifters; at least 5 years; unclear
Wilburn et al. [52]	CHO = 10; PLA = 10	10/0	21.6 ± 2.27	90 ± 18.2	Resistance trained; at least 1 year; leg press = 5.98 ± 1.55

Values are expressed as means ± standard deviations. *M* male, *F* female, *RT* resistance training, *1-RM* 1-repetition maximum, *BM* body mass, *CHO* carbohydrate, *PLA* placebo, *CON* control.

2.5.2.2 Resistance Exercise Protocol

An exercise protocol including free-weight, isotonic RT was used in 16 studies, with seven studies including only lower body exercises [42, 43, 47, 48, 52, 55, 101], one study using upper body only [98], and seven studies using the upper and lower body [41, 49, 50, 73, 74, 97, 99]. The most common exercise was the back squat, which was used in seven studies [41, 43, 47, 51, 55, 73, 101], followed by a barbell/dumbbell chest press in six studies [41, 49, 50, 73, 98, 99], and leg press in five studies [42, 48, 52, 99, 101]. There was a variety of loading schemes from 10 to 100% of 1-RM, and the total number of sets (including submaximal) completed per session ranged from three to 34. Four studies included isokinetic exercise, of which one was knee extension [45] and three were knee extension and flexion [43, 44, 100]. One study [43] included isokinetic contractions in addition to a lower body free-weight RT session. Two studies [53, 54] used a static isometric quadriceps contraction with intermittent bouts of superimposed electrical stimulus. A comprehensive description of each resistance exercise protocol is shown in Table 2-2.

Table 2-2: Resistance training protocol characteristics of the studies included in the systematic review

Study	Exercises	Exercise protocol (sets x repetitions x load, rest)	Duration (mins)	Outcomes
Aoki et al. [42]	Leg press	1 x 1 x 100%1-RM; 2 x failure x 70%1-RM, 1.5-min interset	Unclear	1-RM load lifted vs. pre-exercise Repetitions completed per set
Ballard et al. [99]	Mix of upper and lower body strength/hypertrophy exercises	3 x 10 x 70%1-RM; 1 x failure x 55%1-RM, 2-min interset and 3-min inter-exercise	80	Volume load per exercise Total session volume load
Battazza et al. [100]	Isokinetic knee extension/flexion	10 x 8 x maximal effort, unclear	29	Pre- vs. post-exercise isometric peak torque Rate of torque development
Bin Naharudin et al. [73]	Back squat, bench press	4 x failure x 90%10-RM, 3-min interset	Unclear	Total repetitions completed per set and exercise
Bird et al. [101]	Mix of lower body strength/hypertrophy exercises	4 x failure x 8-15RM, 1.5-min interset and 3-min inter-exercise	Unclear	Total session volume CMJ lower body peak power
dos Santos et al. [98]	Bench press	1 x failure x 70%1-RM, unclear	Unclear	Repetitions completed
Fairchild et al. [45]	Isokinetic leg extension	8 x 3 x maximal effort, 5–15-min interset	90	Peak and mean repetition force
Haff et al. [47]	Back squat	Failure x 10 x 55%1-RM, 3-min interset	CHO: 77.7 ± 19.4 PLA: 46.1 ± 8.9	Total session repetitions and sets Training session duration
Haff et al. [43]	Back squat, speed squat, 1-legged squat	3 x 10 x 10-65%1-RM, 3-min interset	38.9 ± 0.3	Total and average isokinetic work (pre- vs post-RT) Total and average torque (pre- vs post-RT)
Haff et al. [44]	Isokinetic knee flexion/extension	16 x 10 x maximal effort, 3-min interset	CHO: 56.9 ± 0.2 PLA: 57.1 ± 0.4	Total work per set and session Average and peak torque per set
Krings et al. [49]	Upper and lower body power & strength/hypertrophy exercises	2-6 x 2-failure x 45-90%1-RM, 0.5–3-min interset	71.3 ± 2.9	Repetitions to failure in final set of upper body exercises Total session repetitions to failure
Kulik et al. [51]	Back squat	Failure x 5 x 85%1-RM, 3-min interset	CHO: 29.7 ± 3.6 PLA: 28.5 ± 3.0	Total session repetitions, sets, work, duration, and volume load
Lambert et al. [48]	Leg extension	Failure x 7-10 x 80%10-RM, 3-min interset	Unclear	Total session repetitions and sets
Laurenson et al. [41]	Back squat, bench press	6 x 7-15 x 60%1-RM, 2-5-min interset	Unclear	Volume and power during last set of each exercise
Naharudin et al. [74]	Back squat, bench press	4 x failure x 90%10-RM, 3-min interset	Unclear	Total repetitions completed per set and exercise
Oliver et al. [55]	Smith machine back squat	5 x 10 x 75%1-RM, 3-min interset	Unclear	Average power, velocity, and force per set and session
Rountree et al. [97]	Wall throw, sumo deadlift high pull, push press	5 x repetitions per min x 9-34kg, 1-min interset	30	Total repetitions completed per set and session
Smith et al. [50]	Mixture of upper body strength/hypertrophy exercises	5 x failure x 65%1-RM, 2-min interset	59.8 ± 2.3	Total repetitions completed per exercise and session
Wax et al. [53] & Wax et al. [54]	Static quadriceps isometric contraction	Failure x 20secs x 50% MVF; 4-7 x 3 secs x 100% MVC + ES, 40-sec interset	CHO = 29 ± 13.1 PLA = 16.0 ± 8.1	Time to exhaustion Total force during 50%MVC and 100%MVC + ES
Wilburn et al. [52]	Leg press	4 x failure x 70%1-RM, 45-secs interset	Unclear	Total repetitions completed per set and session

Values are expressed as means ± standard deviations. *1-RM* 1-repetition maximum, *10-RM* 10-repetition maximum, *CMJ* counter movement jump, *RT* resistance training, *MVC* maximum voluntary contraction, *ES* electrostimulation, *CHO* carbohydrate, *PLA* placebo.

2.5.2.3 Nutrition Protocol

Of the 21 studies included in this review, 19 delivered CHO as a liquid beverage, one used a viscous semi-solid meal [74], and one used CHO containing food items served as a meal [73]. All studies that delivered CHO as a liquid beverage or semi-solid meal used a simple, powdered CHO source such as maltodextrin, dextrose/glucose, or fructose. For the comparator condition, 18 studies reported using a low/non-caloric placebo; however, two studies did not explicitly provide information regarding the caloric content of the placebo beverage [42, 100]. One study used a water-only control condition [73] and one study used both a placebo and water only control as comparator conditions [74]. There was a range of pre-trial fasting durations from 2 - 12hrs. These pre-trial fasting durations clustered at each end of the range with nine studies using a 2 - 4 or 10 - 12hr fast duration, respectively. The fast duration of two studies was unclear [98, 100]. A comprehensive description of nutrition protocols of all studies is shown in Table 2-3.

Table 2-3: Nutrition protocol characteristics of the studies included in the systematic review.

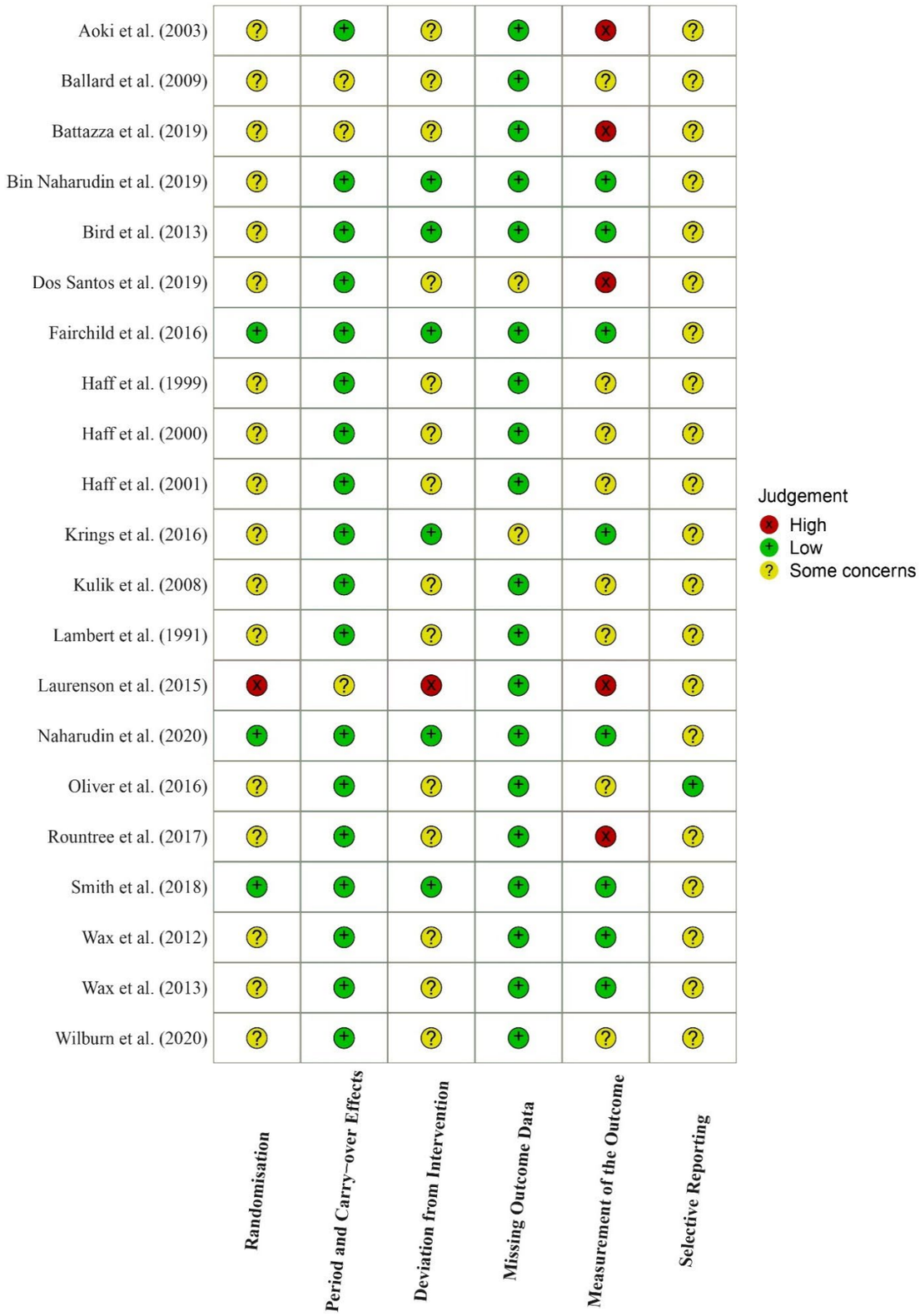
Study	Pre-trial diet	Pre-trial fast (hrs)	CHO protocol (dose unit in g/kg body mass unless stated)		Placebo/control description
			CHO dose	Timing around training session	
Aoki et al. [42]	24-hr prescribed diet (70% CHO, 15 fats, 15% protein)	2	60g	1-hour before (30g) and ~10 mins before (30g)	AS beverage
Ballard et al. [99]	24-hr prescribed diet (65% CHO, 20% fat, 15% protein)	2.5	65g	Five mins before and during (32 servings total)	AS non-caloric beverage
Battazza et al. [100]	24-hr record of normal dietary habits	Unclear	60g	1-hour before	Unclear
Bin Naharudin et al. [73]	24-hr record of normal dietary habits	10	1.5	2-hours before	*Ad-libitum* water only
Bird et al. [101]	3-day record of normal dietary habits (~3.8 g/kg/day CHO)	4	25.2g	Fifteen mins before (5.5g) and after each set (19.7g)	AS non-caloric beverage
dos Santos et al. [98]	None	Unclear	20g	1-hour before	Non-caloric beverage
Fairchild et al. [45]	24-hr record of normal dietary habits	12	75g	Immediately after first set of exercise	AS non-caloric beverage
Haff et al. [47]	3-day record with recommended diet (55% CHO, 20% protein, 25% fat)	2.5	0.3	After every second set to failure	AS non-caloric beverage
Haff et al. [43]	3-day record with recommended diet (55% CHO, 20% protein, 25% fat)	3	0.3 – 1.0	Ten mins before (1.0g/kg) and every 10 mins during (0.3g/kg)	AS non-caloric beverage
Haff et al. [44]	3-day record with recommended diet (55% CHO, 20% protein, 25% fat)	3	0.51 – 1.0	Immediately before (1.0 g/kg) and after sets 1, 6, and 11 (0.51 g/kg)	AS non-caloric beverage
Krings et al. [49]	Instructed to maintain normal dietary habits	10	15, 30 and 60 g/h	Immediately before and every 15 mins during	Low caloric amino acid-electrolyte beverage (~20kcal)
Kulik et al. [51]	3-day record with recommended diet (55% CHO, 20% protein, 25% fat)	3	0.3	Immediately before and after every second set	AS non-caloric beverage
Lambert et al. [48]	2-day record of normal dietary habits	4	0.17 – 1.0	Immediately before (1.0 g/kg) and after set 5, 10, and 15 (0.17 g/kg)	Non-caloric beverage
Laurenson et al. [41]	3-day record of normal dietary habits	8	36g	At twelve and 26 minutes during (18g)	AS non-caloric beverage
Naharudin et al. [74]	2-day record of normal dietary habits	10-13	1.5	2-hours before	PLA: Semi-solid, low caloric CON: *Ad-libitum* water only
Oliver et al. [55]	24-hr record of normal dietary habits	12	1.2	2-hours before	AS non-caloric beverage
Rountree et al. [97]	Instructed to maintain normal dietary habits 3-days prior	10-12	16g	Immediately before and after every round	AS non-caloric beverage
Smith et al. [50]	24-hr record of normal dietary habits	10	36g	Immediately before and after the last set of each exercise	AS non-caloric beverage
Wax et al. [53] & Wax et al. [54]	3-day record with recommended diet (55% CHO, 20% protein, 25% fat)	10	0.17 – 1.0	Thirty mins before (1.0 g/kg) and every 6 minutes during (0.17 g/kg)	AS non-caloric beverage
Wilburn et al. [52]	2-day record of normal dietary habits	3	2.0	30-mins before	AS non-caloric beverage

CHO carbohydrate, *AS* artificially sweetened, *PLA* placebo, *CON* control

2.5.3 Risk of Bias Assessment

One study was rated a high risk of bias related to the randomisation process [41]. Three studies [45, 50, 74] reported a randomisation method and information that would suggest allocation sequences were concealed (e.g., a researcher uninvolved in data collection handled randomisation and sequence allocation) and were awarded a low risk of bias. The remaining studies stated the trial was randomised but did not report a randomisation method or information regarding allocation concealment and were rated with some concerns. In the domain assessing risk of bias related to period and carry over effects, three studies [41, 99, 100] did not report the wash-out length and were rated some concerns. The remaining studies reported a sufficient wash-out period (at least 72 hrs) and were rated as low risk of bias. Regarding bias arising from the intervention assignment, 14 studies were rated some concerns due to a lack of reported information as to whether participants and personnel delivering the intervention were aware of the intervention assigned. A high risk of bias was awarded to one study [41] due to a lack of blinding whereas six studies presented information that suggested the participants and personnel delivering the intervention were not aware of the intervention assigned and were rated low risk of bias [45, 49, 50, 73, 74, 101]. Relating to bias from missing outcome data, two studies were rated some concerns due to missing data points on presented figures [98] and due to no provided reason for participant drop-outs that could have arisen due to the intervention [49]. The rest of the studies were rated low risk of bias. Relating to risk of bias in the measurement of the outcome, five studies [41, 42, 97, 98, 100] were rated high risk of bias for a lack of information on outcome assessor blinding, diet standardisation, or time of testing. Eight studies were rated some concerns for a lack of information to indicate outcome assessor blinding [43, 44, 47, 48, 51, 52, 55, 99]. The remaining studies were awarded a low risk of bias for this domain, of which five provided sufficient information to indicate assessor blinding [45, 49, 50, 74, 101], one was not able to blind assessors due to trial context [73], and two did not include sufficient information to judge assessor blinding but the outcomes were not likely affected by blinding [53, 54]. Regarding bias related to the selection of the reported result, all studies reported results in agreement with what was outlined in their methods sections. One study [55] pre-registered the trial protocol with a publicly available register and was rated low risk of bias. The rest of the studies were not pre-registered and were rated some concerns. Risk of bias assessment is illustrated in the traffic light format in Figure 2-2.

Figure 2-2: Risk of bias assessment for all included studies.



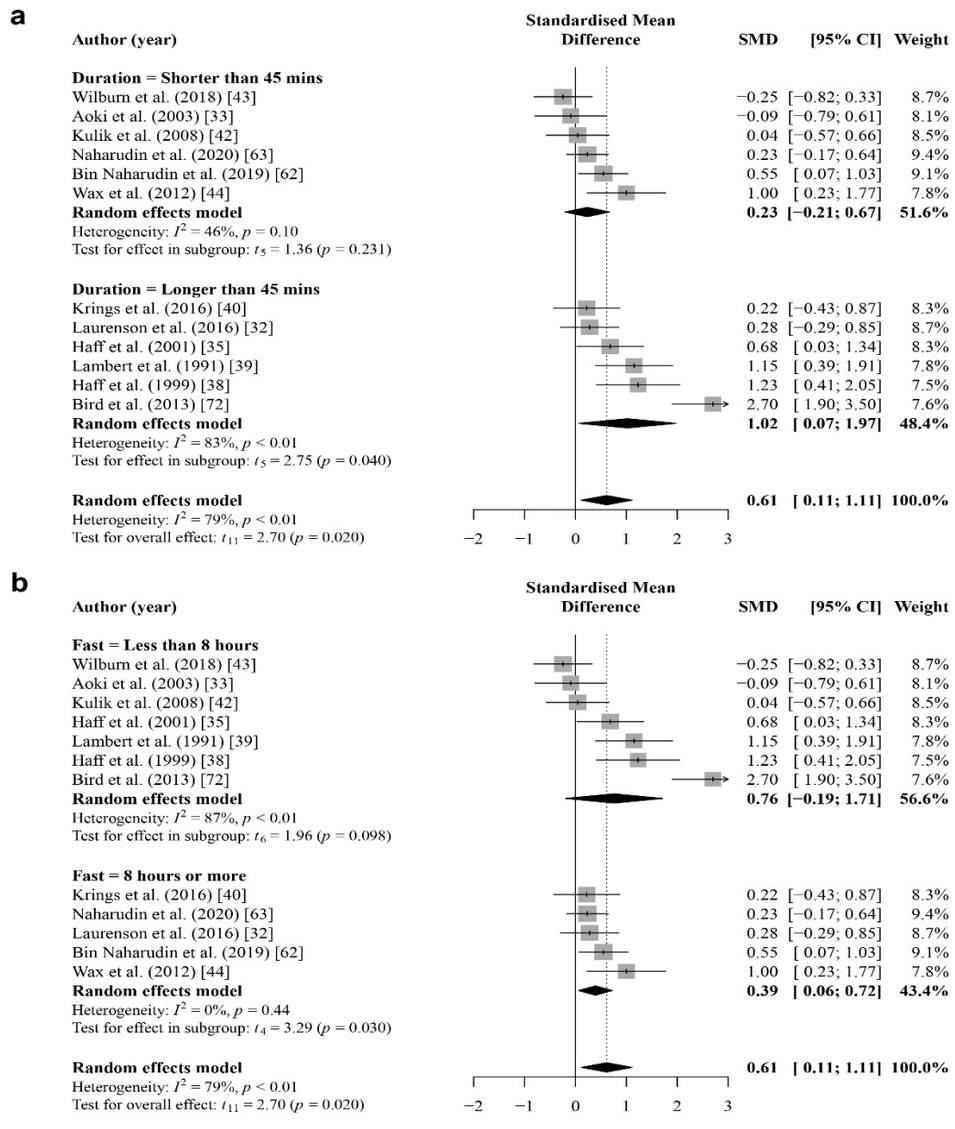
2.5.4 Total Session Training Volume

Pooled meta-analysis identified a significant benefit of CHO ingestion in comparison to a placebo or control for total session training volume (SMD = 0.61, [95% CI: 0.11, 1.11]; p = 0.020; I2 = 79%; k = 12; Figure 2-3). The meta-analysis for total session training volume provided low GRADE quality of evidence (Table 2-4). There was no evidence of publication bias for the training volume outcome (b = 5.26; [95% CI: 0.21, 10.3]; t = 2.04; p = 0.069).

Sub-group analysis revealed a significant effect of CHO ingestion for session durations longer than 45 mins (SMD = 1.02 [95% CI: 0.07, 1.97]; p = 0.040; I2 = 83%; k = 6; Figure 2-3). For session durations shorter than 45 mins, CHO ingestion did not have a statistically significant effect on training volume (SMD = 0.23 [95% CI: -0.21, 0.67]; p = 0.231; I2 = 46%; k = 6; Figure 2-3). These sub-group analyses provided low and moderate GRADE quality of evidence for longer and shorter than 45 mins, respectively (Table 2-4).

Sub-group analysis revealed a significant effect of CHO ingestion for fasting periods 8 hours or more (SMD = 0.39 [95% CI: 0.06, 0.72]; p = 0.030; I2 = 0%; k = 5; Figure 2-3). For fasting durations less than 8 hours, CHO ingestion did not have a significant effect on training volume (SMD = 0.76 [95% CI: -0.19, 1.71]; p = 0.09; I2 = 87%; k = 7; Figure 2-3). These results provided moderate and low-GRADE quality of evidence for fasting durations ≥ 8 hours or < 8 hours, respectively (Table 2-4).

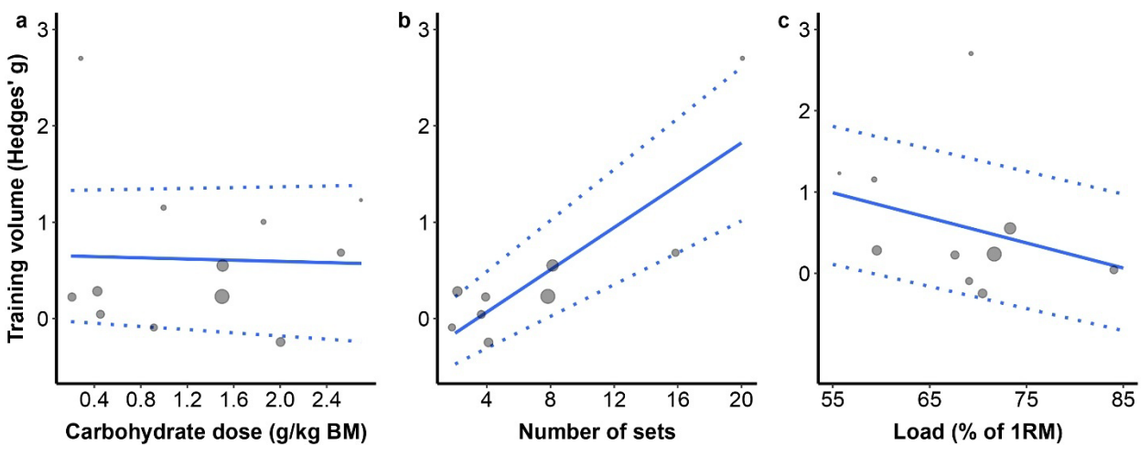
Figure 2-3: Random-effects meta-analysis of the effect of acute CHO ingestion on total training session volume compared to a placebo or water only. Sub-group analysis based on session (a) and fast (b) duration separately.



CHO carbohydrate*, CI* confidence interval*, SMD* standardised mean difference

The total number of maximal effort sets (b = 0.11 [95% CI: 0.05, 0.17]; p = 0.005) was a significant moderator of the SMD for training volume. CHO dose (b = -0.03 [95% CI: -0.68, 0.62]; p = 0.917) and load used (b = -0.03 [95% CI: (-0.11, 0.05); p = 0.400) were not significant moderators of the SMD for training volume (Figure 2-4).

Figure 2-4: Mixed-effects meta-regression of the effect of acute CHO ingestion on RT volume performance compared to a placebo or water only while controlling for the effects of CHO dose (a), maximal effort sets completed (b), and load used (c). Larger data points received greater weighting than smaller data points. Solid lines represent the estimated relationship, and dotted lines represent the upper and lower 95% confidence intervals.



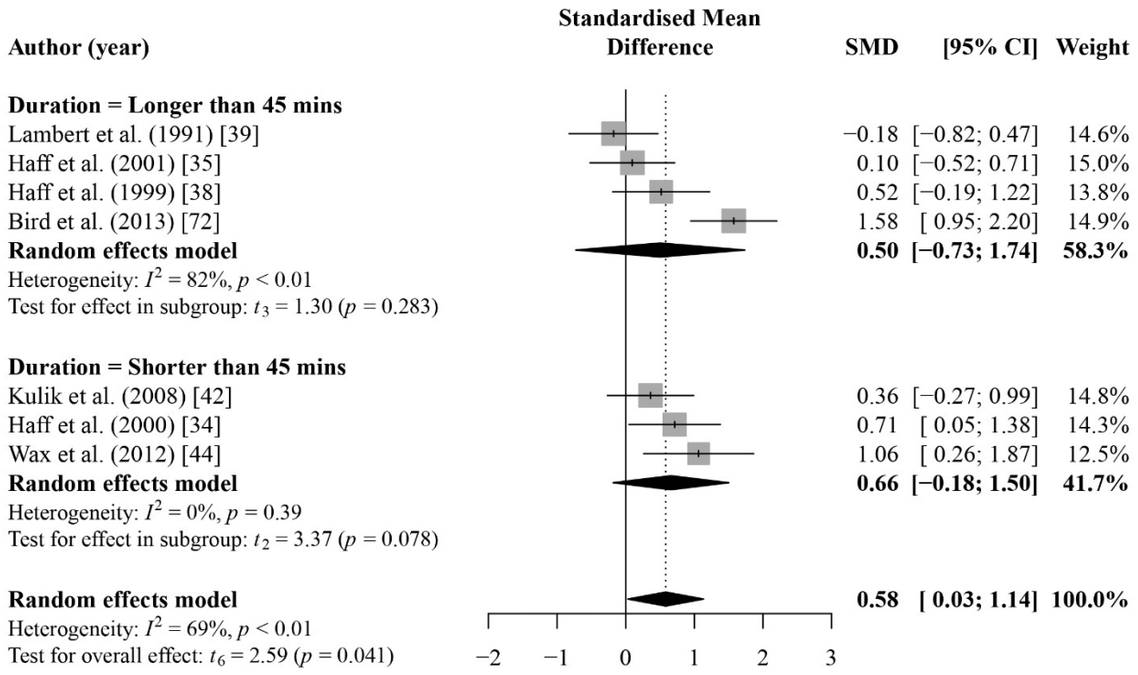
BM body mass, *IRM* 1-repetition maximum

2.5.5 Blood lactate

Pooled meta-analysis for post-exercise BL identified significantly higher concentrations with CHO ingestion than a placebo or control (SMD = 0.58 [95% CI: 0.03, 1.14]; p = 0.041; I2 = 69%; k = 7; Figure 2-5) with a low GRADE quality of evidence (Table 2-4).

Sub-group analysis indicated that post-exercise BL concentrations were not significantly different for session durations longer than 45 mins (SMD = 0.50 [95% CI: -0.73, 1.74]; p = 0.283; I2 = 82%; k = 4; Figure 2-5) or shorter than 45 mins (SMD = 0.66 [95% CI: -0.18, 1.50]; p = 0.078 I2 = 0%; k = 3; Figure 2-5). These results provided low and moderate GRADE quality of evidence, respectively (Table 2-4).

Figure 2-5: Random-effects meta-analysis of the effect of acute CHO ingestion on post-exercise blood lactate accumulation compared to a placebo or water only. Sub-group analysis based on session duration and postexercise lactate.



CHO carbohydrate*, CI* confidence interval

CHO dose was not a significant moderator of post-exercise BL (b = -0.24 [95% CI: -0.93, 0.45]; p = 0.418; Figure 2-7). The total number of maximal effort sets and load used were not meta-regressed for post-exercise BL due to insufficient data.

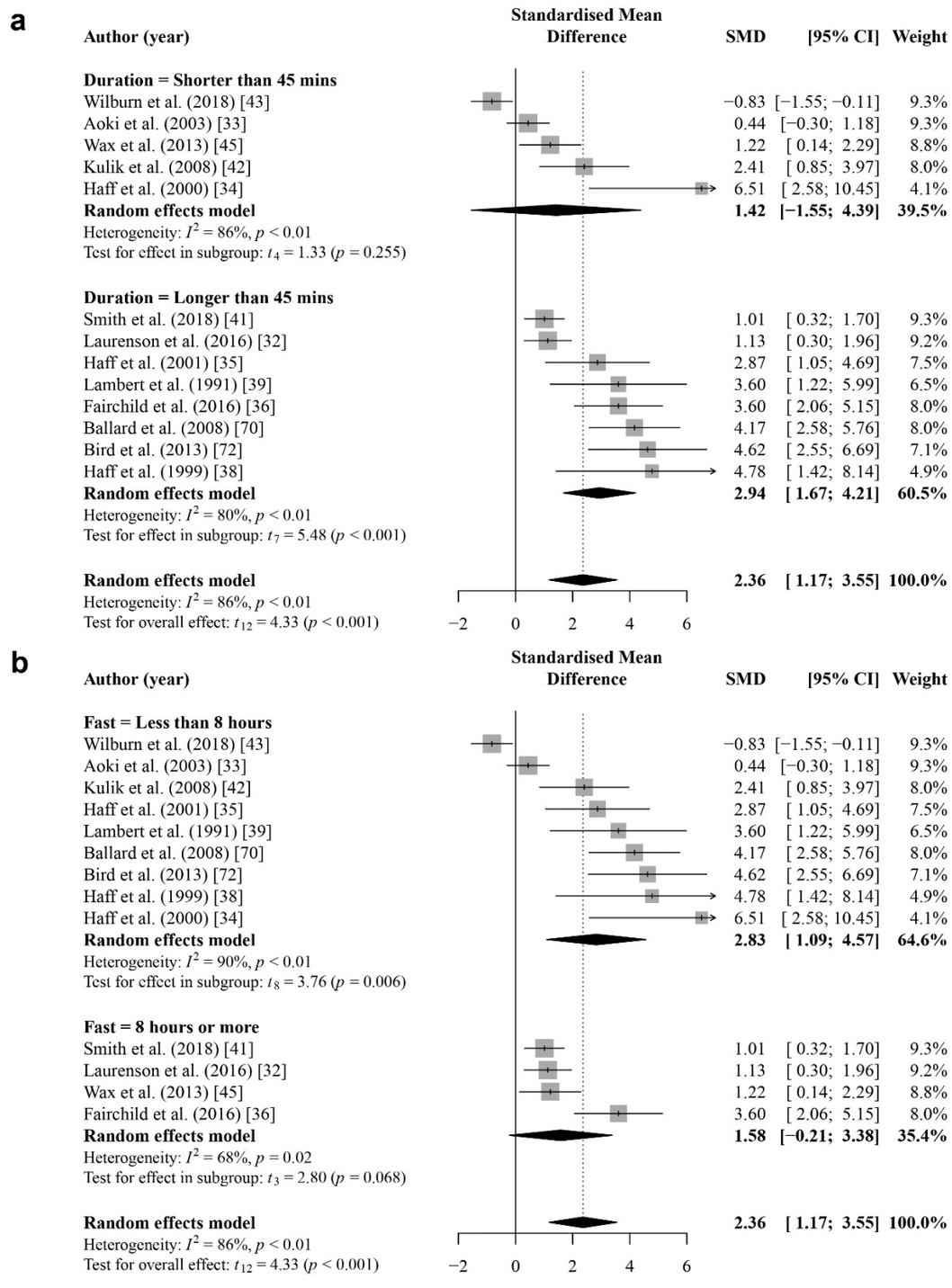
2.5.6 Blood glucose

Pooled meta-analysis for post-exercise BG identified significantly higher concentrations with CHO ingestion than a placebo or control (SMD = 2.36 [95% CI: 1.17, 3.55]; p < 0.001; I^2 = 86%; k = 13; Figure 2-6) with a moderate GRADE quality of evidence (Table 2-4).

Sub-group analysis indicated that post-exercise BG concentration was significantly higher for CHO ingestion in session durations longer than 45 mins (SMD = 2.94 [95% CI: 1.67, 4.21]; p = 0.001; I^2 = 80%; k = 8; Figure 2-6). Post-exercise BG concentration was not significantly different for session durations shorter than 45 mins (SMD = 1.42 [95% CI: -1.55, 4.39]; p = 0.255; I^2 = 86%; k = 5; Figure 2-6). The session duration sub-group analysis provided moderate and low-GRADE quality of evidence for longer and shorter than 45 mins, respectively (Table 2-4).

Sub-group analysis indicated that post-exercise BG concentration was not significantly higher for CHO ingestion following fasting durations ≥ 8 hours (SMD = 1.58 [95% CI: -0.021, 3.38]; p = 0.068; I^2 = 68%; k = 4; Figure 2-6), whereas post-exercise BG was significantly higher for CHO ingestion following a fasting duration of < 8 hours (SMD = 2.83 [95% CI: 1.09, 4.57]; p = 0.006; I^2 = 90%; k = 9; Figure 2-6). The fasting duration sub-group analysis provided low and moderate GRADE quality of evidence for ≥ 8 hours or < 8, respectively (Table 2-4).

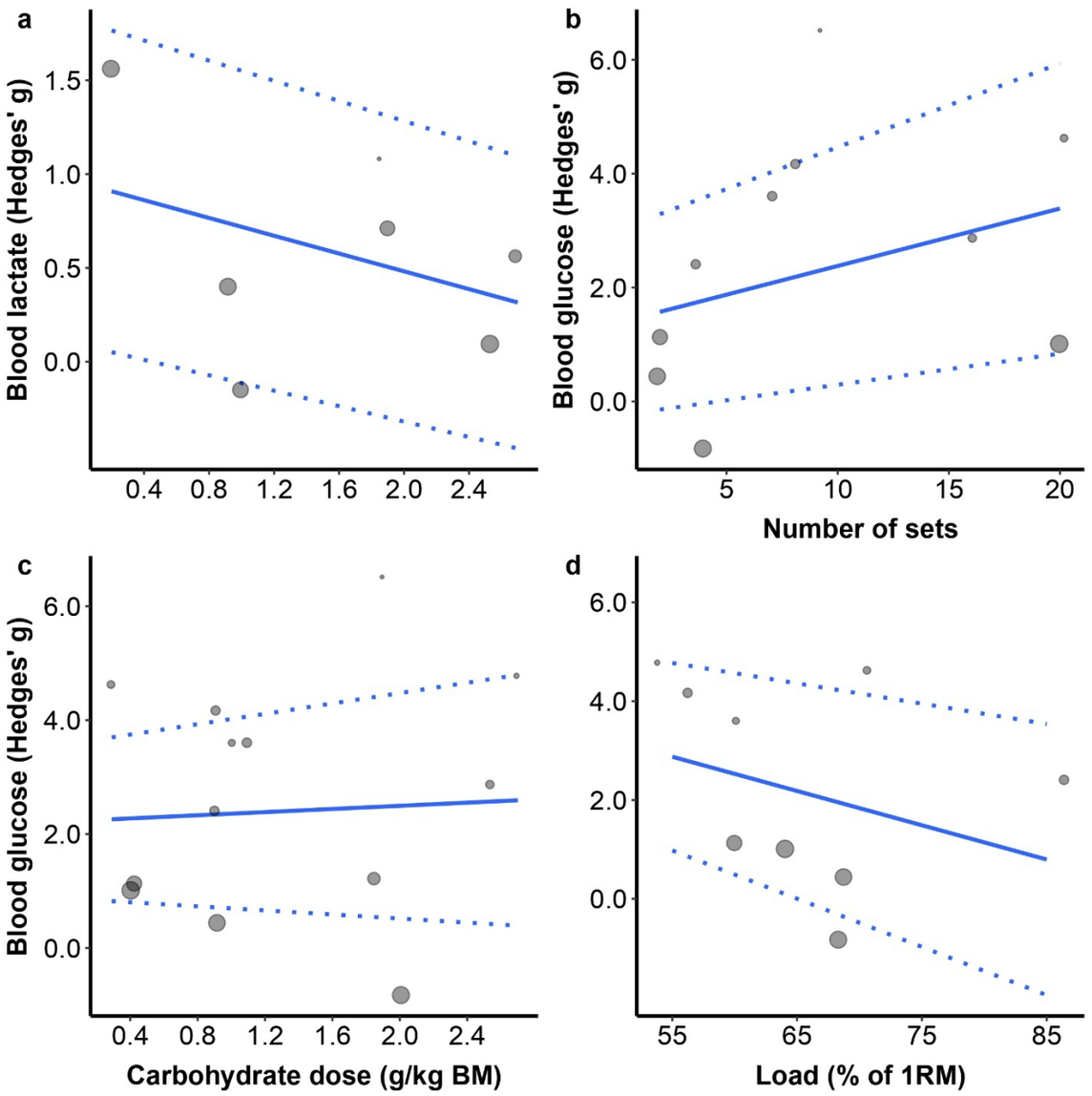
Figure 2-6: Random-effects meta-analysis of the effect of acute CHO ingestion on post-exercise blood glucose concentration compared to a placebo or water only. Sub-group analysis based on session (a) and fast (b) duration separately.



CHO carbohydrate, *CI* confidence interval

CHO dose (b = 0.14 [95% CI: -1.54, 1.82]; p = 0.859), number of maximal effort sets (b = 0.10 [95% CI: -0.12, 0.32]; p = 0.319), and load used (b = -0.07 [95% CI: -0.25, 0.11]; p = 0.400) were not significant moderators of post-exercise BG concentration (Figure 2-7).

Figure 2-7: Mixed-effects meta-regression of the effect of acute CHO ingestion on post-exercise blood lactate and glucose compared to a placebo or water only while controlling for the effects of CHO dose on post-exercise lactate (a) and total number of maximal effort sets (b), CHO dose (c), and load used (d) on post-exercise blood glucose. Larger data points received greater weighting than smaller data points. Solid lines represent the estimated relationship, and dotted lines represent the upper and lower 95% confidence intervals.



BM body mass, *CHO* carbohydrate, *CI* confidence interval, *IRM* 1-repetition maximum, *SMD* standardised mean difference

Table 2-4: Summary of meta-analysis findings and quality of evidence synthesis

Outcome	**Summary of findings**				**Quality of evidence synthesis (GRADE)**			
	k	*n*	*Effect (95% CI)*	*Direction of the effect compared to placebo*	*Imprecision*	*Inconsistency*	*Risk of bias*	*Overall quality*
Total session volume								
Longer than 45 mins session duration	6	68	1.02 (0.07, 1.97)	↑	-1	-1	None	Low
Shorter than 45 mins session duration	6	53	0.23 (-0.21, 0.67)	↔	-1	None	None	Moderate
8-hr fast or more	5	61	0.39 (0.06, 0.72)	↑	-1	None	None	Moderate
Less than 8-hr fast	7	60	0.76 (-0.19, 1.71)	↔	-1	-1	None	Low
All	12	121	0.61 (0.11, 1.11)	↑	-1	-1	None	Low
Blood lactate								
Higher than 45 mins	4	36	0.50 (-0.73, 1.74)	↔	-1	-1	None	Low
Lower than 45 mins	3	22	0.66 (-0.18, 1.50)	↔	-1	None	None	Moderate
All	7	58	0.58 (0.03, 1.14)	↑	-1	-1	None	Low
Blood glucose								
Longer than 45 mins session duration	8	97	2.94 (1.67, 4.21)	↑	None	-1	None	Moderate
Shorter than 45 mins session duration	5	48	1.42 (-1.55, 4.39)	↔	-1	-1	None	Low
8-hr fast or more	4	46	1.58 (-0.21, 3.38)	↔	-1	-1	None	Low
Less than 8-hr fast	9	89	2.83 (1.09, 4.57)	↑	None	-1	None	Moderate
All	13	135	2.36 (1.17, 3.55)	↑	None	-1	None	Moderate

CI confidence interval, *GRADE* Grading of Recommendations Assessment, Development and Evaluation; *k* number of studies, *n* number of participants

Only outcomes with $k > 1$ are included in this table

2.5.7 Sensitivity Analyses

Sensitivity analyses indicated that the pooled and sub-group training volume and post-exercise lactate meta-analyses were robust when imputing a within-study correlation of 0.3 and 0.5. Similarly, the post-exercise BG meta-analyses for longer and shorter session duration and fasting sub-groups were robust when imputing a within-study correlation of 0.5 and 0.7. For the 8 hours or more fast sub-group, imputing with a 0.5 within-study correlation provided robust results ($p > 0.05$), but when imputing a correlation of 0.7, the result changed from non-significant (SMD = 1.58 [95% CI: -0.21, 3.38]; p = 0.068; I2 = 68%; k = 4) to significant (SMD = 1.51 [95% CI: 0.14, 2.89]; p = 0.039; I2 = 77%; k = 4). A comprehensive report of the sensitivity analyses is provided in Appendix B Ch. 2 Supplementary File III.

2.6 Discussion

The present systematic review and meta-analysis is the first to synthesise the evidence regarding the efficacy of CHO ingestion on RT performance and metabolic markers while also assessing potentially relevant moderators such as session duration, fasting duration, CHO dose, number of maximal effort sets, and load used. The main findings indicate that (1) CHO ingestion allows for greater RT volume to be completed, (2) CHO ingestion is effective for session durations longer than 45 mins and fasting durations at least eight hours or more, (3) CHO ingestion elevates post-exercise BL and glucose in comparison to a placebo or control, (4) the number of maximal effort sets moderates the effect of CHO ingestion on RT volume performance and post-exercise BL, but not BG, and (5) the load used and CHO dose do not moderate the effect of CHO ingestion on RT volume performance, post-exercise BL, or post-exercise BG.

2.6.1 Total Training Session Volume

The present meta-analysis indicates that CHO ingestion results in a moderate effect size (SMD = 0.61 [95% CI: 0.11, 1.11]) volume enhancement compared to a placebo or control. Given the novelty of the present review in quantitatively evaluating feeding strategies for RT performance, direct comparisons of this treatment effect with other CHO interventions are difficult. However, similar magnitudes of effect were reported for the effect of CHO feeding on mean power during cycling (SMD = 0.40 - 0.46) [102], and time to exhaustion (SMD = 0.47) and time trial performance in endurance exercise modalities (SMD = 0.53) [103]. In contrast, other acute ergogenic aids, such as caffeine (SMD = 0.20) [104] and citrulline malate (SMD = 0.30) [105] supplementation, have comparatively smaller magnitudes of effect on maximal strength performance.

Statistical heterogeneity in the present meta-analysis was high (I^2 = 79%), indicating considerable variability in the effect size estimates across studies. Several studies reported large effect sizes with CHO

ingestion [44, 47, 48, 53, 101]. All five of these studies used a training protocol consisting of only lower body training [44, 47, 48, 53, 101]. Conversely, studies including exercises of the upper body only or a mixture of upper and lower body exercise completed to failure, reported a non-significant effect of CHO ingestion on training volume performance [41, 49, 74]. For example, Bird et al. [101] reported a comparatively large effect size to the rest of the studies in the meta-analysis, in which participants completed 20 sets of lower body RT to failure. Lower body training recruits more total muscle mass, producing more total work, and subsequently, results in greater metabolic fatigue compared to upper body training [106-108]. However, this explanation is speculative, and may not be a lower body specific effect *per se* given that none of the studies included in this review included more than four sets of maximal effort upper body RT. Therefore, it is possible that if higher volumes of upper body RT are completed, CHO ingestion may also enhance volume for upper body RT similarly to lower body RT. There are also several exceptions where volume was not enhanced for lower body RT. Specifically, Aoki et al. [42], Kulik et al. [51], and Wilburn et al. [52] all reported no improvement in total repetitions to failure during two to four sets of lower body RT. Therefore, it is likely that two to four sets of lower body exercise to failure was insufficient total volume to observe an ergogenic effect of CHO ingestion. This contention is supported by the results of our meta-regression analysis showing that the total number of sets performed with maximal effort is a significant moderator of the magnitude of ergogenic effects of CHO ingestion on RT performance. Overall, while CHO ingestion does have an ergogenic effect on RT performance, the magnitude of this effect is sensitive to the total amount of volume completed, with greater RT volumes (e.g., > 4 sets) benefitting more from CHO ingestion then lower RT volumes (e.g., ≤ 4 sets), and possibly lower body exercise selection.

The results of our sub-group analyses indicate that session duration is important when considering the ergogenic effect of CHO, as volume was enhanced for session durations longer than 45 mins (SMD = 1.02 [95% CI: 0.07, 1.97]), but not shorter. There was high statistical heterogeneity observed among the studies in these sub-groups, indicating substantial variability in the results. Again, the discrepancies in findings can likely be attributed to differences in the RT protocols and is highlighted by our meta-regression, which found that total sets completed with maximal effort (which directly influences session duration) is a significant moderator of the ergogenic effect of CHO on volume performance. Indeed, the decreases in muscle glycogen stores during RT are dependent on total training volume [24]. Unfortunately, muscle glycogen was only directly measured by one study included in the quantitative synthesis [52]. However, it could be hypothesised that without CHO ingestion, decreases in muscle glycogen stores influence fatigue in a time (and volume) dependant manner when the session duration exceeds 45 mins, potentially constraining RT performance. Additionally, it could be hypothesised that CHO ingestion immediately before and during RT could supply BG to the working musculature, and due to the intermittent

nature of RT, be taken up by muscle during rest periods to aid in the partial replenishment of muscle glycogen. However, these notions are speculative, and future research is needed to substantiate them. Nevertheless, the findings of this sub-group analysis indicate that CHO ingestion enhances training volume for RT sessions lasting greater than 45 mins.

The fasting duration before RT is also an important consideration for the ergogenic effect of CHO ingestion, as the sub-group analysis indicates that CHO ingestion only enhances training volume after an 8-hour or longer fast (SMD = 0.39 [95% CI: 0.06, 0.72]). Extended periods of fasting inevitably lead to a decreased CHO availability, and exogeneous CHO may then be needed to 'rescue' performance. For instance, glycogen stores of the liver deplete during periods of fasting [30, 31], such as the overnight fast. The specialised glycogen stores of skeletal muscle are spared for high-intensity efforts and are thought to remain comparatively unaffected by periods of fasting [109]. However, acute feeding studies suggest that muscle glycogen stores can be partially depleted after an extended period of fasting, as muscle glycogen stores can increase 10-42% in the 3-4 hours after a high CHO breakfast (approx. 2 – 3 g/kg BM) [33, 34, 36], with a post-prandial period of at least 1-2 hours necessary to achieve net gain in muscle glycogen stores [35]. The two studies with the largest effects for CHO ingestion in the 8 hours fast or longer sub-group provided CHO dose of 1.0-1.5 g/kg in the 0.5 – 2 hours before RT [53, 73]; whereas, no volume enhancement was reported when CHO was ingested immediately before and during RT [41, 49]. Therefore, CHO ingestion in the hours before RT may be of importance for augmenting muscle glycogen stores and enhancing RT performance. In comparison to this finding, CHO ingestion after a fast of less than 8 hours did not enhance volume performance. In this sub-group, a small, CHO containing breakfast was ingested 3-4 hrs before RT, which in addition to a moderate dietary CHO intake, was likely sufficient to preserve performance. It is also worth noting that there was high statistical heterogeneity in the results of the less than 8 hrs fast sub-group (I^2 = 87%), which again could be attributed to differences in the RT protocol (i.e., higher training volumes and lower body exercises). Overall, the findings of this sub-group analysis indicate that CHO ingestion attenuates the negative effect of extended fasting periods (8 hrs or more) on CHO availability, enhancing RT volume performance when compared to a control or placebo.

Our findings contrast and agree with the findings of a recent systematic review by Henselmans et al. [76] which found that the majority of studies assessing the effects of acute CHO ingestion on RT performance reported no ergogenic effect. There are differences in study inclusion criteria and outcomes of interest that may explain the differences in our findings. Specifically, the current review exclusively included cross-over trials comparing CHO ingestion to a zero to low kcal (≤ 25 total kilocalories) placebo or water only control; whereas, the review by Henselmans et al. [76] additionally included parallel trials, and isocaloric comparator conditions. It is important to note that the analysis by Henselmans et al. [76]

broadly and qualitatively assessed the effects of CHO ingestion on various RT outcomes, whereas we have used meta-analysis to specifically quantify the magnitude of the effects of CHO on RT volume performance. We have also conducted various sub-group and meta-regression analyses to control for potential confounders. Nonetheless, there is some agreement in results, as Henselmans et al. [76] note that CHO ingestion may be beneficial in some circumstances such as fasted training and higher training volumes (<10 sets per muscle group). This finding by Henselmans et al. [76] agrees with the findings of our current meta-analysis in which CHO ingestion improves RT volume performance for longer session durations (>45 mins) and fast durations (8 hrs or longer).

2.6.2 Blood Lactate

CHO ingestion results in significantly higher post-exercise BL accumulation (due to the greater work completed) in comparison to a placebo, with a moderate effect size (SMD = 0.58 [95% CI: 0.03, 1.14]). Additionally, the duration of RT did not significantly affect post-exercise lactate accumulation. These findings are consistent with previous evidence that demonstrated less lactate accumulation with acute dietary CHO restriction during high-intensity exercise, when compared to a high dietary CHO intake [110]. Lactate is an important CHO fuel source during high-intensity exercise, and while lactate accumulation in blood is unlikely to be a central cause of fatigue during RT [111], post-exercise BL is strongly correlated with metabolic and neuromuscular fatigue during high-intensity exercise [112, 113] and serves as a useful marker for fatigue evaluation. In the present meta-analysis, several studies reported significant increases in post-exercise BL accumulation and reported large effect sizes for volume enhancement [53, 101]. On the other hand, Kulik et al. [51] reported similar post-exercise lactate between conditions and no volume enhancement. These findings suggest that the increased post-exercise lactate accumulation with CHO ingestion does not constrain RT performance and may even be necessary for improved performance. However, increased accumulation of post-exercise lactate with CHO ingestion suggests that total fatigue incurred from RT may increase due to the additional training volume performed. Therefore, a trade-off may exist where the cost of the ergogenic effect of CHO ingestion on RT volume induces additional metabolic stress and could influence time-course of recovery.

2.6.3 Blood Glucose

CHO ingestion increases post-exercise BG concentration with a large effect size (SMD = 2.36 [95% CI: 1.17, 3.55]). In addition, CHO ingestion significantly increased post-exercise BG for fasting durations less than 8 hours (SMD = 2.83 [95% CI: 1.09, 4.57]) and session durations longer than 45 mins (SMD = 2.94 [95% CI: 1.67, 4.21]). There was high heterogeneity across the post-exercise glucose findings, which could potentially be explained by the differences in participant cohorts amongst studies (e.g., training status,

sex) (Table 2-1) and CHO dosages and timings (Table 2-3). There was consistently higher post-exercise glucose in studies that supplemented a rapidly digestible liquid CHO source during RT [43, 44, 47, 48, 51, 99, 101], whereas studies providing CHO in the 10 – 60 mins before RT reported no increase in post-exercise BG with CHO ingestion [42, 52]. These findings suggest that CHO ingestion increases BG during RT and to maximise BG availability, CHO ingestion should occur consistently during the RT session.

Several of the studies finding increased post-exercise BG with CHO ingestion also reported improved training volume performance [44, 47, 48, 101]. However, it is presently unclear whether readily available BG is necessary to improve RT performance under specific circumstances. A hypoglycaemic effect of RT training was not reported in any of the placebo conditions of the studies included in this review and BG is maintained or increased after standard volumes of RT [24, 114]. Therefore, if BG were to play a role in RT performance it would likely be a result of maintaining or elevating BG concentration as a readily available substrate for glycolysis or to partially replenish muscle glycogen during inter-set rest [37, 115]. Haff et al. [43] observed a significantly smaller decrease in muscle glycogen stores compared to resting values after RT with CHO ingestion (27%) when compared to a placebo (40%). Given that muscle glycogen stores are preferentially used to fuel specific processes during contraction, it is conceivable that at least some of this glycogen-sparing effect of CHO ingestion was a result of glycogenesis. Nevertheless, since it is presently unclear whether readily available BG is necessary to improve RT performance, future studies should elucidate the effects of BG on RT performance by manipulating pre-exercise CHO status and supplementing CHO during RT.

2.6.4 Limitations and Considerations

There are several limitations to the current systematic review and meta-analysis that should be acknowledged. We opted to include only peer-reviewed, published literature in our review; the exclusion of grey literature could have biased the findings [116]. However, we note that funnel plot asymmetry examination and the results of the Egger's regression test did not find publication bias to be present in the current review. While we contacted authors to request the data necessary for the analysis (e.g., correlations necessary for the calculation of the effect size variance), we were unable to acquire it. Therefore, we imputed correlations using unpublished data from our laboratory in our meta-analyses for all outcomes of interest. While this is a limitation to the current meta-analysis, sensitivity analyses with a range of other realistic correlations indicated that our results were largely robust to correlation imputations. Additionally, the data for two studies [50, 99] were originally intended to be used in the quantitative synthesis, but due to the data reporting and because we were unable to obtain the data from the authors before the analysis, they were ultimately omitted from the meta-analysis. Both investigations included upper body RT exercise completed to failure and could have contributed to an under-representation of upper body RT in the current

meta-analysis. Finally, the GRADE quality of evidence presented in the current review was generally low to moderate. These ratings constrain the certainty of the results presented, but we have offered potential explanations for the heterogeneity and imprecision of the results to aid in interpretation. Additionally, given that CHO ingestion is unlikely to negatively affect performance and that the CIs of the present meta-analysis suggest at least a trivial ergogenic effect for volume enhancement, our overall recommendations reflect the position that CHO ingestion is an efficacious nutrition strategy for enhancing volume.

Several study characteristics warrant investigation in future research. Participants in the current review were generally consuming moderate amounts of dietary CHO in the 1-3 days preceding RT, it is possible that varying amounts of dietary CHO could influence the ergogenic effect of acute CHO ingestion. Eight of twelve studies in the current meta-analysis used an exclusively lower body RT protocol; more research is needed to quantify the overall effect of CHO ingestion on upper body only RT, or a mixture of upper and lower body exercises. Regarding the generalisability of our results, only twelve of 222 (5.4%) participants included in this review were females. More research with female participants is therefore necessary to determine if sex-specific recommendations for CHO ingestion are needed, and what they should be. Additionally, we only identified one performance outcome that had sufficient data to enable meta-analysis. More research is needed on other outcomes such as expressions of muscle force production (e.g., maximal strength and power), muscle endurance, and time course of recovery to fully understand how CHO ingestion affects other RT performance indices. Finally, several recent investigations suggested that RT performance may be influenced by the psychological effects of, or the hunger and satiety cues associated with feeding [74, 75], a notion that is somewhat supported by our meta-regression finding that CHO dose was not a moderator of the ergogenic effect of CHO ingestion on RT performance. Future research should seek to fully elucidate the role of psychology and hunger/satiety on RT performance.

Several reporting and methodological issues were identified in the risk of bias analysis (Figure 2-2). It was often unclear from the full texts what randomisation method was used, how allocation concealment was achieved, and how double blinding was achieved, and whether it was successful. An assessment of blinding efficacy may be informative in some circumstances, such as where participants can be blinded to their performance. We have not discussed blinding efficacy in the current review as participants are generally not able to be blinded to training volume completion. Moreover, the most recent Cochrane guidance note that successful intervention guesses could simply reflect a good outcome of an active intervention (e.g., greater training volume performed could be attributed to CHO ingestion), and that deducing the intervention received does not inherently lead to a risk of bias (https://www.riskofbias.info/welcome/rob-2-0-tool/current-version-of-rob-2). Additionally, only one study included in the current review pre-registered their protocol and statistical reporting was often incomplete

(e.g., missing means, standard deviation of the difference scores etc.). The quality of reporting seems to be improving with the recent publications being the only studies to report these methodological aspects in full, but this is not a consistent trend. To strengthen the quality of research on this topic, and to support open and transparent science, we encourage authors of future research to report methods and results in sufficient detail [117], readily provide study data to other researchers upon reasonable request, and to consider publicly pre-registering their investigations.

2.6.5 Implications for Practice

The findings of the current review have several implications for practice:

(1) For RT session durations greater than 45 mins and consisting of at least 8-10 sets, CHO ingestion can be expected to improve performance.

(2) When RT occurs after an eight or more hour fast, such as the overnight fast, CHO ingestion may improve performance relative to a control or placebo.

(3) The number of sets completed with maximal effort seems to influence the ergogenic effect CHO ingestion. Therefore, as session training volume increases, the importance of CHO ingestion for performance also increases.

(4) CHO ingestion seems to have a greater benefit for lower body RT protocols, suggesting that CHO ingestion before and during lower body RT sessions may be of importance.

(5) CHO dose does not seem to influence the ergogenic effect of CHO ingestion, so ingesting an amount of CHO that the trainee perceives as adequate fuelling for the training session and staves off sensations of hunger may be of importance.

(6) CHO ingestion enhances volume which increases post-exercise BL. While this increased lactate accumulation may be necessary for improved RT performance, there may be a trade-off where the additional fatigue incurred from greater training volume with CHO ingestion may influence the time-course of recovery.

(7) BG may influence training volume as a readily available fuel source. To increase BG during RT, it appears that readily digestible sources of CHO (e.g., a sports drink) during RT consistently and robustly increase BG concentration.

2.7 Conclusion

This systematic review and meta-analysis found that the ingestion of CHO provides an ergogenic effect on RT volume performance, when compared to a placebo or control. CHO ingestion has ergogenic effects on RT performance where session duration was longer than 45 mins and the fast duration was eight hours or more. Conversely, CHO ingestion did not significantly affect performance when session durations were shorter than 45 mins or fast durations less than eight hours. Post-exercise BL is significantly higher with CHO ingestion compared to a placebo. Lactate itself is an important fuel source for training, but also strongly correlates with metabolic fatigue, suggesting that the additional lactate accumulation with CHO ingestion is necessary for RT performance, but the increased volume of training may incur additional fatigue. Post-exercise BG was elevated with CHO ingestion, where readily digestible sources ingested during training seem to increase BG the most. Meta-regression analysis revealed that sets completed with maximal effort was a significant moderator of the effect magnitude of CHO ingestion on RT performance and lactate, but not BG. Load used and CHO dose were not significant moderators of the effect magnitude of CHO ingestion. Collectively, the findings of the current review demonstrate an ergogenic effect of CHO ingestion for enhancing volume performance during RT

Chapter 3: An Updated Meta-analysis on The Ergogenic Effects of Acute Carbohydrate Feeding on Resistance Exercise Performance

This chapter has been pre-printed on SportRXiv (https://doi.org/10.51224/SRXIV.696) and is currently under peer review at Sports Medicine.

3.1 Preface

This chapter builds on the quantitative synthesis presented in Chapter 2 by utilising a refined methodological framework to provide an updated meta-analytic estimate of the ergogenic effects of acute CHO ingestion on RT performance. By incorporating newly published trials (including the published crossover in Chapter 7 of the present thesis), correcting data extraction errors, and applying contemporary GRADE and heterogeneity guidance, this chapter provides a more precise and conservative estimate of the effect of acute CHO ingestion on RT volume, post-exercise BG, and BL. In doing so, this chapter advances the inquiry from establishing that an effect exists to defining its precise magnitude, contextual boundaries (e.g., session duration, fasting status), and the degree of underlying evidence certainty.

These refined analyses enable a more nuanced appraisal of potential moderators and mechanistic candidates, including substrate availability and central effects, strengthening the conceptual link to the CMR literature addressed in Chapter 4. Likewise, the smaller, more reliable effects emphasise the importance of context and trial design, providing an evidential platform for the subsequent examination of nutrition practices among powerlifters (Chapters 5 and 6) and the targeted experimental investigations of pre-exercise CHO feeding and RT performance in Chapters 7 and 8.

3.2 Abstract

3.2.1 Background

A previous meta-analysis reported a moderate ergogenic effect of carbohydrate (CHO) ingestion on resistance training (RT) performance, particularly where the session duration and pre-exercise fasting duration were longer (> 45 mins and ≥ 8 h, respectively). Methodological limitations in the prior meta-analysis (i.e., data extraction errors and a potentially confounded comparison) may have overestimated previous estimates.

3.2.2 Objective

Incorporate recently published studies and correct identified data extraction errors to provide an updated meta-analytic estimate on the effect of acute CHO on RT performance.

3.2.3 Methods

PubMed, MEDLINE, SportDiscus, Scopus, and CINAHL databases were searched using the original strategy, with dates restricted from January 2022 to 15 November 2025, alongside forward citation tracking and search alerts. Peer-reviewed English-language studies using cross-over designs and comparing acute CHO ingestion to placebo/control during RT were eligible. Random effects meta-analyses were performed for total session volume and post-exercise blood lactate and glucose. Sub-group meta-analysis and meta-regression were performed for categorical (session duration; fast duration) and continuous (total sets, load, and CHO dose) covariates. Risk of bias was assessed with RoB 2 and certainty of evidence was evaluated using GRADE. Sensitivity analyses were conducted by excluding a study in which the CHO condition included caffeine.

3.2.4 Results

Six additional studies met inclusion, of which three were included in the quantitative synthesis. With high certainty, pooled results revealed a small, statistically significant benefit of CHO ingestion versus placebo/control for total session training volume (SMD [standardised mean difference] = 0.28

[95% CI: 0.13, 0.44]; [95% PI: 0.05, 0.51]; p = 0.002). With high certainty of evidence, sub-group analyses revealed a statistically significant effect for sessions longer than 45 min (SMD = 0.38 [95% CI: 0.20, 0.56]; [95% PI: 0.10, 0.65]; p = 0.002) and after fasting durations ≥ 8 h (SMD = 0.27 [95% CI: 0.06, 0.48]; [95% PI: 0.06, 0.48]; p = 0.02). Total sets, CHO dose, and load used were not statistically significant moderators of the CHO effect on training volume. In sensitivity analysis, the pooled effect remained high certainty and statistically significant (SMD = 0.25, [95% CI: 0.09, 0.40]; [95%PI: 0.09, 0.40]; p = 0.004). With very low certainty, pooled results revealed elevated post-exercise blood glucose (SMD = 0.93, [95% CI: 0.44, 1.42]; [95% PI: -0.67, 2.53]; p = 0.001) with CHO ingestion. With high certainty, pooled results revealed elevated post-exercise blood lactate (SMD = 0.24, [95% CI: 0.04, 0.44]; [95% PI: 0.03, 0.45]; p = 0.02) with CHO ingestion.

3.2.5 Conclusions

Acute CHO ingestion has a small but robust, high certainty ergogenic effect on total session volume and sub-groups suggest greater benefits during longer sessions (> 45 min) and after pre-exercise fasting (≥ 8 h), though interaction tests were not statistically significant. Post-exercise blood glucose is elevated following acute CHO ingestion – particularly when ingested during exercise. Post-exercise blood lactate is modestly elevated with CHO ingestion, likely reflecting greater work performed rather than detrimental metabolic consequences.

3.3 Introduction

King et al., [118] published a 2022 systematic review with meta-analysis on the effects of acute CHO ingestion on RT volume performance. The results suggested that acute CHO ingestion has an ergogenic effect on RT by enhancing total session volume performance, which is more likely to occur when sessions exceed 45 min, where the fast duration is ≥ 8 h, and as higher set volumes are performed.

Since the original publication, several new studies (e.g., [119, 120]) have been added to the literature that may meet the full inclusion criteria. In the original review [118], the certainty of evidence for total session volume was downgraded due to imprecision, based on effect size thresholds and the width of the corresponding 95% CIs. Incorporating recent trials may reduce imprecision and strengthen the overall certainty of evidence by narrowing these intervals. Additionally, *standard errors* – rather than *standard deviations* – were erroneously extracted from one study [101] included in the original review [118]. Extracting standard errors rather than standard deviations is a common error in meta-analysis that inflate effect sizes and narrows CIs [121]. While the same study [101] met all inclusion criteria, its CHO condition also contained caffeine, whereas the placebo comparator did not. Caffeine is a known ergogenic aid that can enhance RT performance [122]. Thus, the observed effect size may partially reflect a caffeine-induced benefit rather than CHO alone and performing a sensitivity analysis with this corrected effect size removed from the analysis is warranted.

Accordingly, the purpose of this updated meta-analysis is to incorporate recently published studies, correct the data extraction error, conduct sensitivity analyses by removing the caffeine-containing study, and provide an updated estimate and discussion of the effect of acute CHO ingestion on RT volume performance.

3.4 Methods

3.4.1 Updated systematic search

An updated systematic search of the literature was performed on 15th November 2025 using the same search strategy as the original review [118]. Search dates were restricted from January 2022 to

the 15th November 2025 to identify all studies published since the last search of the original review (8 January 2022). All retrieved records underwent the same screening procedure, inclusion and exclusion criteria, and data extraction methods described in the original publication. In addition, search alerts were set up and monitored for any newly indexed studies while this update was carried out. Forward citation tracking in Google Scholar of the original review and any newly included studies was completed.

3.4.2 Statistical analysis

A random effects meta-analysis of the total session volume outcome was performed with the same methods as the original review in the R language and environment for statistical computing (version 4.0.5, The R Foundation for Statistical Computing, Vienna, Austria) [85], using the Meta and Metafor packages [86, 87]. Effect sizes for any new studies meeting the full inclusion criteria were calculated according to Borenstein et al. [91] and merged with the original dataset (publicly available at osf.io/hjfbw). For the study containing the data extraction error in the original review, standard deviations were calculated from the standard errors according to Cochrane guidance [96], and then merged into the updated dataset to replace the incorrect values. Our updated main analysis incorporates this corrected effect size calculation, all effect sizes included in the original review, and any eligible new effect sizes from studies that were included or corrected in this update. A sensitivity analysis was performed with the study by Bird et al. [101] removed, as this study included the addition of caffeine with the CHO dose. Effect sizes were calculated as standardised mean differences (SMD) with Hedge's g correction and 95% CIs (lower bound, upper bound) were calculated between CHO and placebo/control condition trials using the means and standard deviations, the correlation between the trials, and the number of participants. Correlations required for accurate effect size calculation were used if available from the raw data of newly included studies. The rest of the effect sizes were calculated using the correlation in the original review (i.e., 0.78, 0.74, and 0.26 for training volume, BL, and BG, respectively). The magnitude of SMDs was interpreted as: small (0.20–0.49), moderate (0.50–0.79), and large (> 0.80) [92]. All hypothesis tests were conducted with significance set at $\alpha = 0.05$. The same sub-group (sessions and fast duration) and meta-regression (CHO dose, total sets, and load) analyses

were conducted. When studies include multiple CHO conditions, the higher CHO dose was selected to enable inclusion in the CHO dose meta-regression. Where multiple CHO conditions of the same dose were reported, the effects were combined into one using the *aggregate* function in the *metafor* package [87].

3.4.3 Updated Risk of Bias and GRADE assessment

Risk of bias was assessed on any newly included studies using the Cochrane Collaboration's risk of bias tool for randomised trials (RoB 2) [78] with online resources for cross-over trial designs. In cases where newly included studies shared authorship with members of the current meta-analysis team, an independent researcher performed the risk of bias assessment, in addition to the two assessors of the original review (AK and IJ). GRADE assessment was updated to reflect recent updates on guidance and used the GRADEpro GDT software in accordance with GRADE [123] and Cochrane [124] handbooks, including updates for inconsistency [125] and imprecision [126]. The I^2, τ^2, Cochran's Q, and PI values are reported as statistics for heterogeneity in the updated analysis with interpretation aligned to contemporary guidance [127]. For inconsistency (heterogeneity), we considered a threshold equivalent to a small effect (g = 0.20) to be of practical relevance, and we evaluated both the CIs and PIs in relation to this threshold. This effect size threshold was selected as it is the Cohen's threshold for small effects and – in the absence of established acute outcome effect size thresholds – is reasonable given that small effects for change scores of strength and conditioning outcomes generally range from SMD = 0.15 – 0.25 [128]. When the CIs and PIs supported the same conclusion – namely, that the estimated effect met or exceeded the small-effect threshold – we judged inconsistency concerns to be of *no concerns*. In contrast, when the CI suggested a smaller, larger, or null effect, but the PI extended widely in either direction, we assessed this as evidence of substantial inconsistency and of *major concerns*. *Some concerns* were rated when the CIs and PIs led to conclusions that are somewhat different but of lesser consequence for decision-making (e.g., where CIs span trivial to small effects favouring CHO and the PIs spanned trivial effects favouring the comparator to moderate effects favouring CHO).

3.4.4 Decisions in data preparation

During data preparation, we verified the data extracted from all studies in the original review. We found that (a) one study [98] was mistakenly left out of the original meta-analysis of total session volume, and (b) standard errors were extracted for three additional studies [44, 47, 48] in addition to the single study [101] already identified. The same data extraction errors applied to the post-exercise glucose and lactate analyses. We re-extracted and corrected the data for these studies in these metabolic outcomes. Therefore, additional studies were added, and standard deviations were calculated and effect sizes recalculated where necessary for this updated meta-analysis of the effect of acute CHO ingestion on total session volume performance, post-exercise BG, and post-exercise BL. For each of these three meta-analysed outcomes, we report (1) a main analysis that includes all of the original studies (with corrected effect sizes) and all studies added in this update, and (2) a sensitivity analysis with the same studies but with the study by Bird et al. [101] removed.

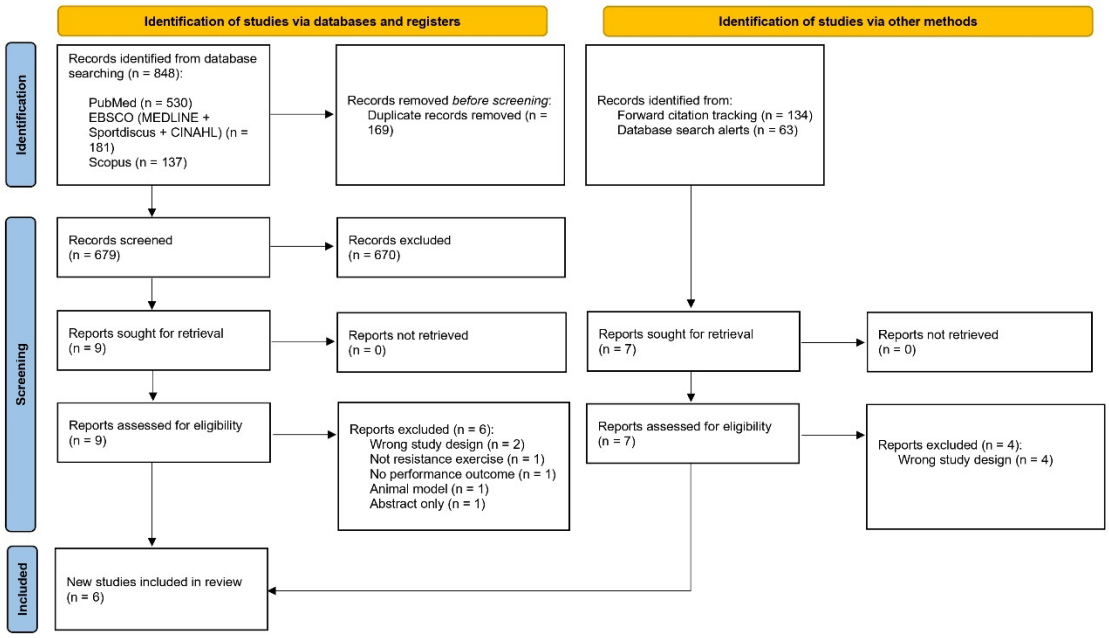
Of the newly included studies, raw data were provided by authors for one study [129] and another had publicly available data [118]. Effect sizes were calculated using these raw data and a computed between-condition within-subject correlation. No response to the data request was received from the corresponding author of the other [130]. Data for included studies not eligible for quantitative synthesis were not requested. Hatami et al. [129] reported total repetitions completed for bench press and leg press, which were combined using the raw data. Eckstein et al. [130] reported total repetitions completed for chest press and leg press, which was completed on separate testing days but with the same participants and intervention, and a composite measure combining chest press and leg press repetitions was calculated. The same study assessed RT performance with 3 different CHO sources (i.e., glucose, fructose, and an equal mix) of the same total dose (i.e., 1g/kg BM). These 3 CHO conditions were combined into a single composite effect size for the quantitative synthesis. Regarding CHO dose (g/kg BM), in one study [129] we estimated dose per gram BM by the reported total gram amount and the average body weight of the participant cohort to enable meta-regression.

3.5 Results

3.5.1 Search results

The updated systematic database search yielded 848 records, of which 9 went to full text screening, with 3 studies meeting the full inclusion criteria. An additional 7 studies went to full text screening via forward citation tracking and search alerts, of which another 3 studies met the full inclusion criteria. Of the 6 studies meeting the full inclusion criteria, 3 studies [119, 129, 130] were eligible for the updated meta-analysis on total session volume and the other 3 studies [120, 131, 132] are qualitatively discussed below. The stages of this updated search and study selection process are presented in Figure 3-1.

Figure 3-1: Literature search flow chart.



CHO carbohydrate, *n* number of studies

3.5.2 Participant characteristics

The total pooled number of participants across the original review (n = 232) and the current update (n = 116) was 351. Of these, 174 participants were included in the updated meta-analysis of total session volume performance, comprising 128 participants from the original review and an additional 46 participants from newly identified studies. Among the newly included studies eligible for quantitative synthesis, participant training status was unclear in one study [130], recreationally trained in one study [129], and resistance trained in one study (mean RT experience = 4.8 years) [119]. Studies included in the qualitative synthesis involved CrossFit athletes [131, 132] and resistance-trained participants [120]. Three studies had male only cohorts [129, 131, 132], the remaining three were mixed sex [119, 120, 130]. A comprehensive description of participant characteristics is presented in Table 3-1.

Table 3-1: Participant characteristics of the added study samples

Study (year)	Participants	Sex: M/F	Age (years)	Mass (kg)	Training history (subjective description, RT experience (years), relative strength (1RM/body mass))
Eckstein et al. [130]	CHO = 16; PLA = 16	7/9	23.8 ± 1.6	70.9 ± 10.8	Unclear; unclear; unclear
Grijota et al. [132]	CHO = 21; PLA = 21	21/0	29.5 ± 4.3	72.81 ± 12.85	CrossFit athletes; 3.41 ± 1.21; unclear
Hatami et al. [129]	CHO = 14; PLA = 14	14/0	22.4 ± 1.3	74 ± 8.4	Recreationally trained; at least 3 years; unclear
King et al. [119]	CHO = 16; PLA = 16	13/3	26 ± 4	83.7 ± 15.1	Resistance trained; 4.8 ± 2.2; back squat = 1.81 ± 0.4, bench press = 1.26 ± 0.3
Morenas-Aguilar et al. [120]	CHO = 29; PLA = 29	14/15	23.4 ± 2.9	74.1 ± 15.8	Resistance trained; unclear; unclear
Triviño et al. [131]	CHO = 23; PLA = 23	23/0	29.8 ± 2.7	88.0 ± 9.4	CrossFit athletes; unclear; approx. 1.74x BM 1RM back squat

M Male, *F* Female, *RT* Resistance Training, *1RM* 1-repetition maximum, *CHO* Carbohydrate, *PLA* Placebo, *Body mass* body mass. Values are expressed as means ± standard deviations.

3.5.3 Resistance training protocol

All six studies employed isotonic resistance training protocols. Four studies assessed the back squat [119, 120, 131, 132], two assessed the bench press and bench pull [119, 120], and two assessed the leg press [129, 130]. Additional exercises assessed included the machine chest press [130], pull-ups and press-ups [132], and the shoulder press [119]. Training intensity ranged from 30 – 90% of 1-RM with the total number of sets ranging one to 12. A comprehensive description of the RT protocols is presented in Table 3-2.

Table 3-2: Resistance training protocol of the added study samples.

Study (year)	Exercises	Exercise protocol (sets x repetitions x load, rest)	Duration (mins)	Outcomes
Eckstein et al. [130]	Machine chest press and leg press	1 x failure x 30% (females) and 70% (males) BM; 1 x failure x 100% BM (all), separate days	Unclear	Total repetitions completed per exercise
Grijota et al. [132]	Pull ups, push ups, back squat, bench press	Maximum x 5-15 x unclear	130	Total repetitions completed per WOD Bench press repetition velocity
Hatami et al. [129]	Bench press and leg press	1 x failure x 60% 1-RM	Unclear	Total repetitions completed per exercise
King et al. [119]	Back squat, bench press, bench pull, shoulder press	3 x failure x 80%1-RM, 3-min interset and 5-min inter-exercise	90	Total repetitions completed per exercise and session Blood glucose and lactate, subjective appetite
Morenas-Aguilar et al. [120]	Bench press, bench pull, squat	5 x 8-15 x 12-RM load, 2-min interset and 10-min inter-exercise	Unclear	Mean velocity, fastest mean velocity RPE and blood lactate
Triviño et al. [131]	Back squat, various CrossFit exercises	3 x 1 90%1-RM, 3 x 8 @ 70%1-RM, 3-mins interset	120	Pre- and post-exercise maximum squats completed in 30 secs, CMJ, EIMD, RPE, emotion, GI distress

BM *body mass, 1-RM* 1-repetition maximum, *CMJ* Counter Movement Jump, *BM* body mass, *EIMD* exercise induced muscle damage, *WOD* workout of the day, *RPE* Rating of perceived exertion, *GI* gastrointestinal

3.5.4 Nutrition protocol

All six studies administered CHO in liquid beverage form. Two studies used cyclic dextrin [120, 132], one used maltodextrin [119], one used a mixture of maltodextrin and fructose [131], one used a mixture of maltodextrin and sucrose [129], and one had three CHO comparators: glucose, fructose, and a mixture of glucose and fructose [130]. The dose of CHO ranged from 30 – 65g in four studies [120, 129, 132], whereas the remaining two studies prescribed CHO relative to body mass (1.0 g/kg [130] and 1.2 [119]). Five studies used an artificially sweetened placebo comparator [119, 120, 129-131] and the remaining study described the comparator as water with added dye [132]. Pre-exercise fast duration was unclear in two studies [131, 132] and ranged from 4 – 14 hrs in the remaining four studies [119, 120, 129, 130]. A comprehensive description of the nutrition protocols is presented in Table 3-3.

Table 3-3: Nutrition protocol of the added studies samples

Study (year)	Pre-trial diet	Pre-trial fast (hours)	CHO protocol (dose unit in g/kg body mass unless stated)		Placebo/control description
			CHO dose	Timing around training session	
Eckstein et al. [130]	Regular diet	12	1	0.5 hrs before exercise	AS (sucralose) beverage
Grijota et al [132]	24-hr replicated diet (60% CHO, 25% fat, 15% protein)	Unclear	30g	Between two WODs	Water and dye
Hatami et al. [129]	24-hr record of normal dietary habits	14	60g	0.5 and 0.25 hrs before exercise	AS beverage, 0.045 g/kg sodium chloride
King et al. [119]	4-7g/kg BM CHO, 1.6 g/kg BM protein for 3-days	10	1.2	2-hours before	AS liquid breakfast
Morenas-Aguilar et al. [120]	Instructed to maintain a similar diet	4	45g	50mL before each set (750mL total), ~3g per 50mL	AS non-caloric beverage
Triviño et al. [131]	24hr standardised diet (1.8/kg BM protein, 7g/kg BM CHO)	Unclear	65g	150mL during each section of training (750mL total), ~13g per 150mL	AS non-caloric beverage

AS Artificially sweetened, *BM* body mass, *CHO* carbohydrate, *WOD* Workout of the day

3.5.5 Total session volume

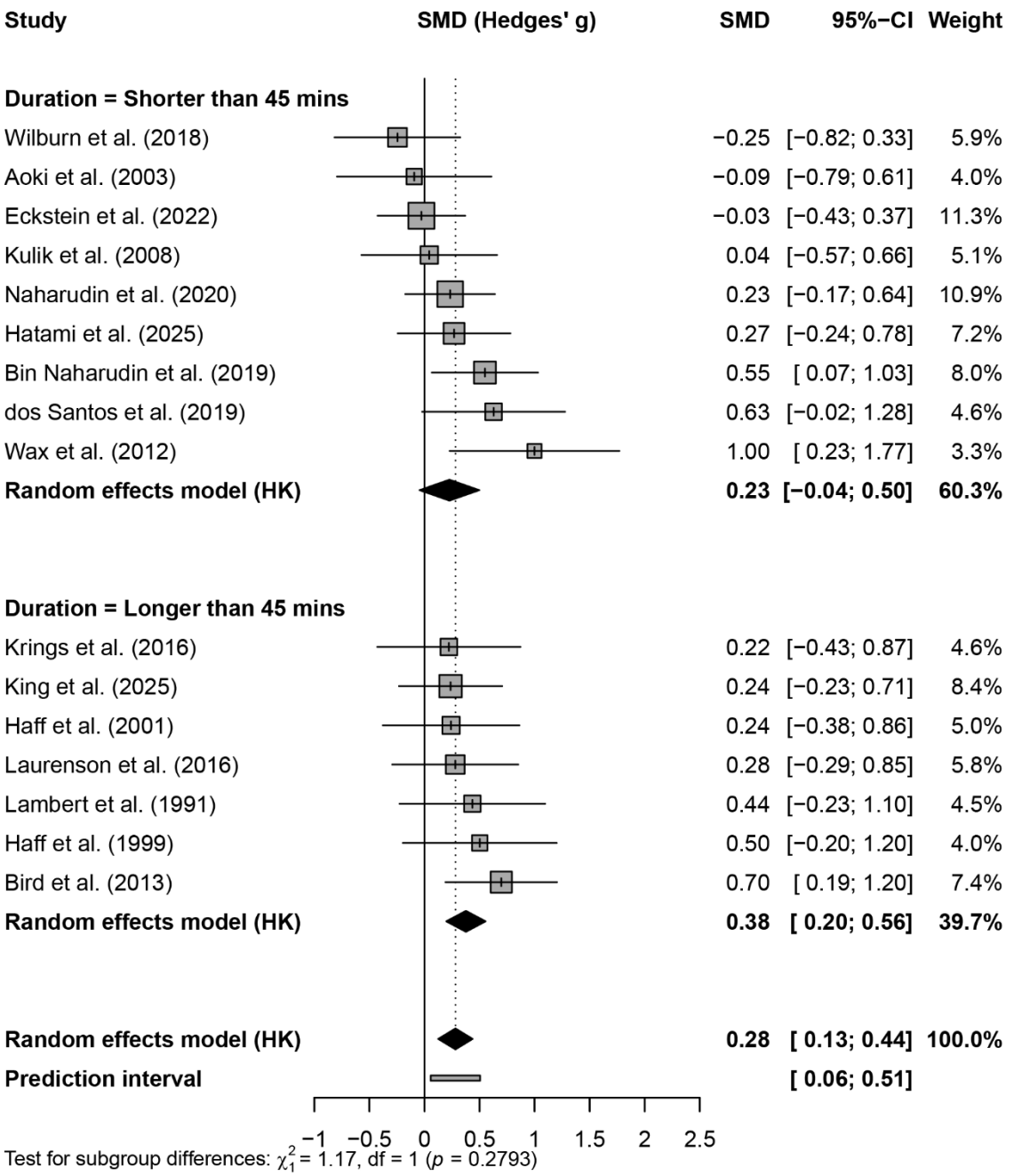
3.5.5.1 Main analysis

Pooled meta-analysis identified a statistically significant small effect of CHO ingestion relative to a placebo or control for total session training volume (SMD = 0.28, [95% CI: 0.13, 0.44]; [95% PI: 0.05, 0.51]; p = 0.002; I^2 = 7.2%; τ^2 = 0.006; *k* = 16; *high certainty*; Figure 3-2 & Figure 3-3). There was no evidence of publication bias (b = 1.46; t = 1.10; p = 0.29). All funnel plots are presented in Appendix B Ch. 3 Supplementary File I. GRADE assessment for all analyses is available in Appendix B Ch. 3 Supplementary File II.

Sub-group analysis revealed a statistically significant small effect of CHO ingestion relative to placebo or control for session durations longer than 45 min (SMD = 0.38 [95% CI: 0.20, 0.56]; [95% PI: 0.10, 0.65]; p = 0.001; I^2 = 0%; τ^2 = 0; *k* = 7; *high certainty*; Figure 3-2). For session durations shorter than 45 min, CHO ingestion did not have a statistically significant effect on training volume (SMD = 0.23 [95% CI: -0.04, 0.50]; [95% PI: -0.25, 0.70]; p = 0.09; I^2 = 35.3%; τ^2 = 0.03; *k* = 9; *moderate certainty*; Figure 3-2). The test for sub-group differences did not suggest a statistically significant interaction (p = 0.27).

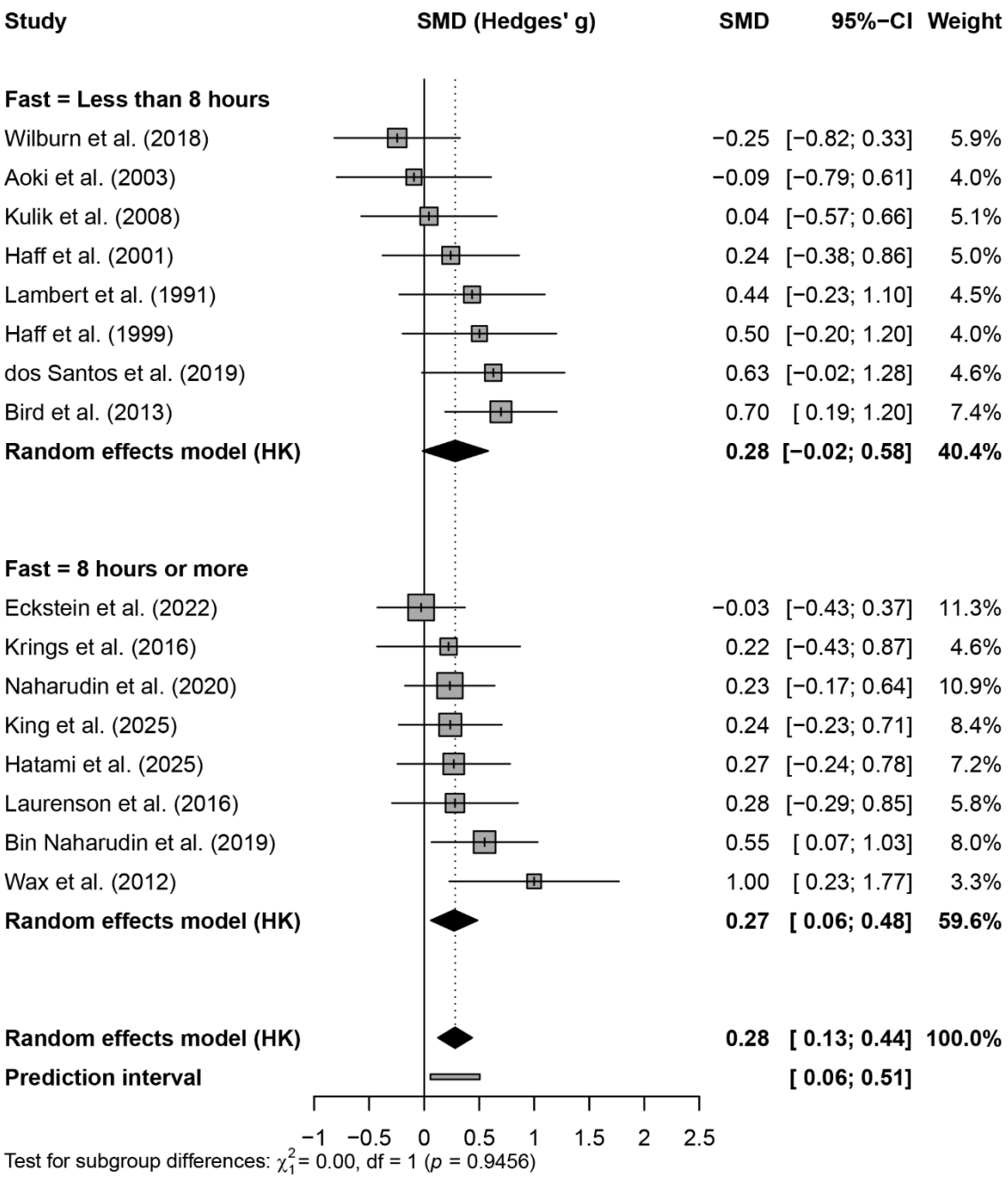
Sub-group analysis revealed a statistically significant effect of CHO ingestion for fasting periods ≥ 8 h (SMD = 0.27 [95% CI: 0.06, 0.48]; [95% PI: 0.06, 0.48]; p = 0.02; I^2 = 0%; τ^2 = 0; *k* = 8; *high certainty;* Figure 3-3). For fasting duration < 8 h, CHO ingestion did not have a statistically significant effect on training volume (SMD = 0.28 [95% CI: -0.02, 0.58]; [95%PI: -0.28, 0.84]; p = 0.06; I^2 = 24.1%; τ^2 = 0.04; *k* = 8; *moderate certainty*; Figure 3-3) relative to placebo or control. The test for sub-group differences did not suggest a statistically significant interaction (p = 0.97).

Figure 3-2: Main analysis random effects meta-analysis of the effect of acute CHO ingestion on total training volume compared to a placebo or control. Sub-group analysis based on session duration.



SMD standardised mean difference, *CI* confidence interval

Figure 3-3: Main analysis random effects meta-analysis of the effect of acute CHO ingestion on total training volume compared to a placebo or control. Sub-group analysis based on fast duration.

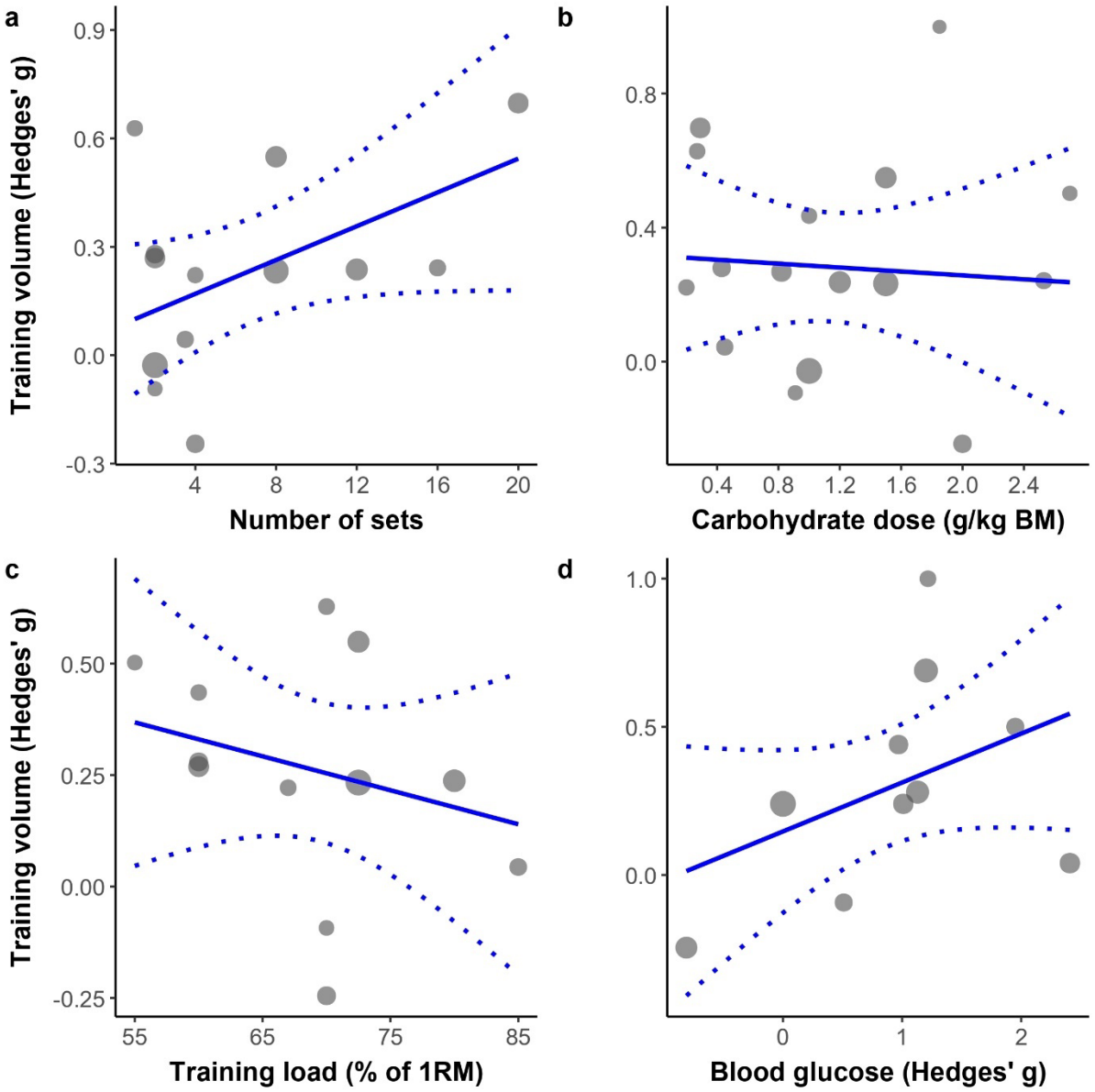


SMD standardised mean difference, *CI* confidence interval

The total number of maximal effort sets (b = 0.02 [95% CI: -0.00, 0.05]; p = 0.07), CHO dose (b = -0.03 [95% CI: -0.26, 0.21]; p = 0.79) and load used (b = -0.01 [95% CI: -0.03, 0.01]; p = 0.47) were not statistically significant moderators of the SMD for training volume (Figure 3-4, Panel A-C).

In an exploratory analysis, the post-exercise BG SMD was not a statistically significant moderator of the SMD for training volume (b = 0.17 [95% CI: -0.06, 0.39]; p = 0.14; Figure 3-4, Panel D).

Figure 3-4: Mixed-effects meta-regression of the effect of acute CHO ingestion on RT volume performance compared to a placebo or control while controlling for the effects of (a) total session sets completed, (b) CHO dose, (c) load used, and (d) post-exercise blood glucose standardised mean difference. Larger data points received greater weighting than smaller data points. Solid lines represent the estimated relationship, and dotted lines represent the upper and lower 95% confidence intervals.



BM body mass, *IRM* 1-repetition maximum

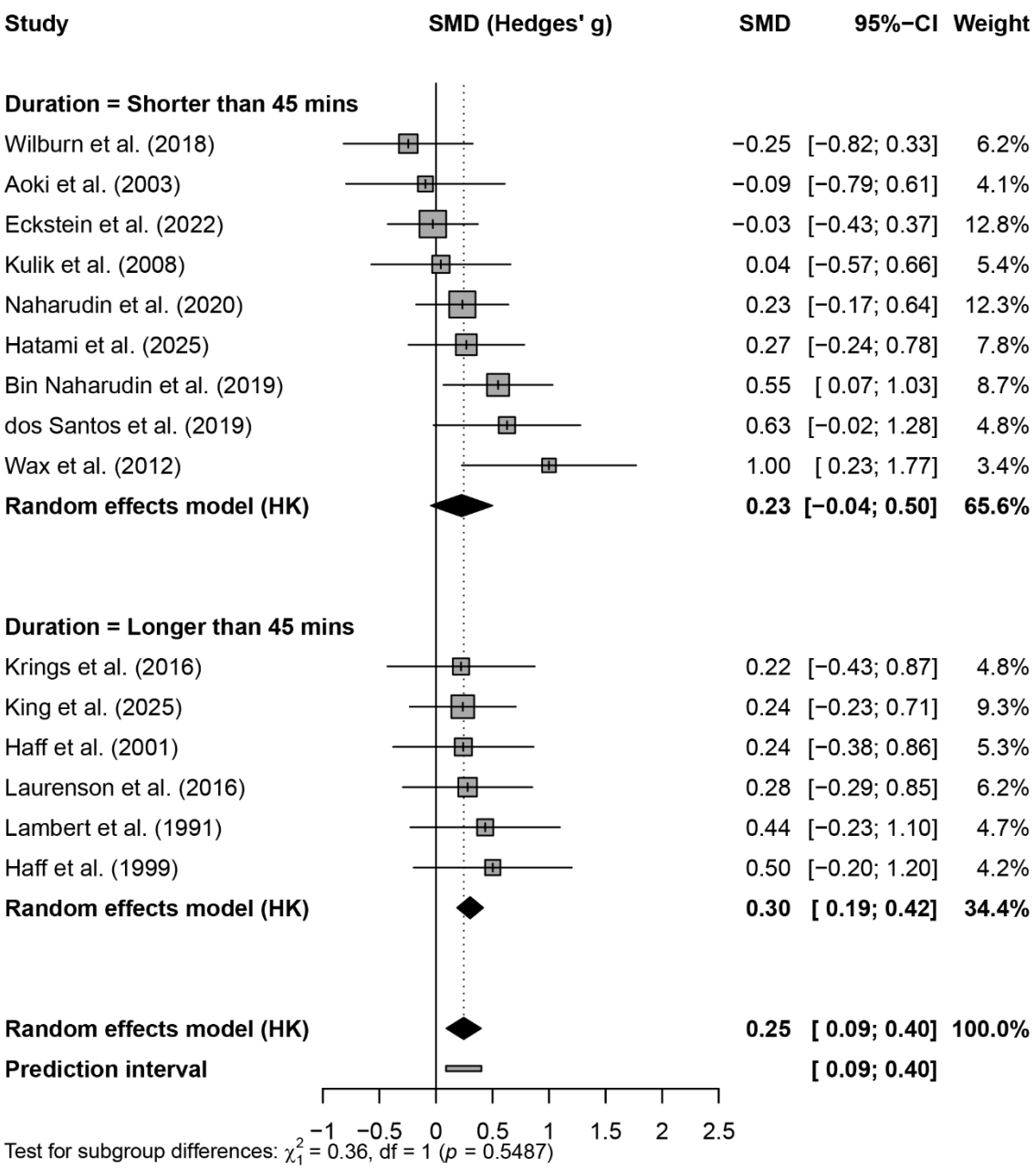
3.5.5.2 Sensitivity analysis

Pooled meta-analysis identified a statistically significant benefit of CHO ingestion in comparison to a placebo or control for total session training volume (SMD = 0.25, [95% CI: 0.09, 0.40]; [95%PI: 0.09, 0.40]; p = 0.004; I^2 = 0%; τ^2 = 0; *k* = 15; *high certainty*; Figure 3-5 & Figure 3-6). There was no evidence of publication bias (b = 1.67; t = 1.36; p = 0.20).

Sub-group analysis revealed a statistically significant effect of CHO ingestion for session durations longer than 45 min (SMD = 0.30 [95% CI: 0.19, 0.42]; [95%PI: -0.02, 0.62]; p = 0.001; I^2 = 0%; τ^2 = 0; *k* = 6; *high certainty*; Figure 3-5). For session durations shorter than 45 min, CHO ingestion did not have a statistically significant effect on training volume (SMD = 0.23 [95% CI: -0.04, 0.50]; [95%PI: -0.25, 0.70]; p = 0.09; I^2 = 35.3%; τ^2 = 0.03; *k* = 9; *low certainty*; Figure 3-5). The test for sub-group differences did not suggest a statistically significant interaction (p = 0.55).

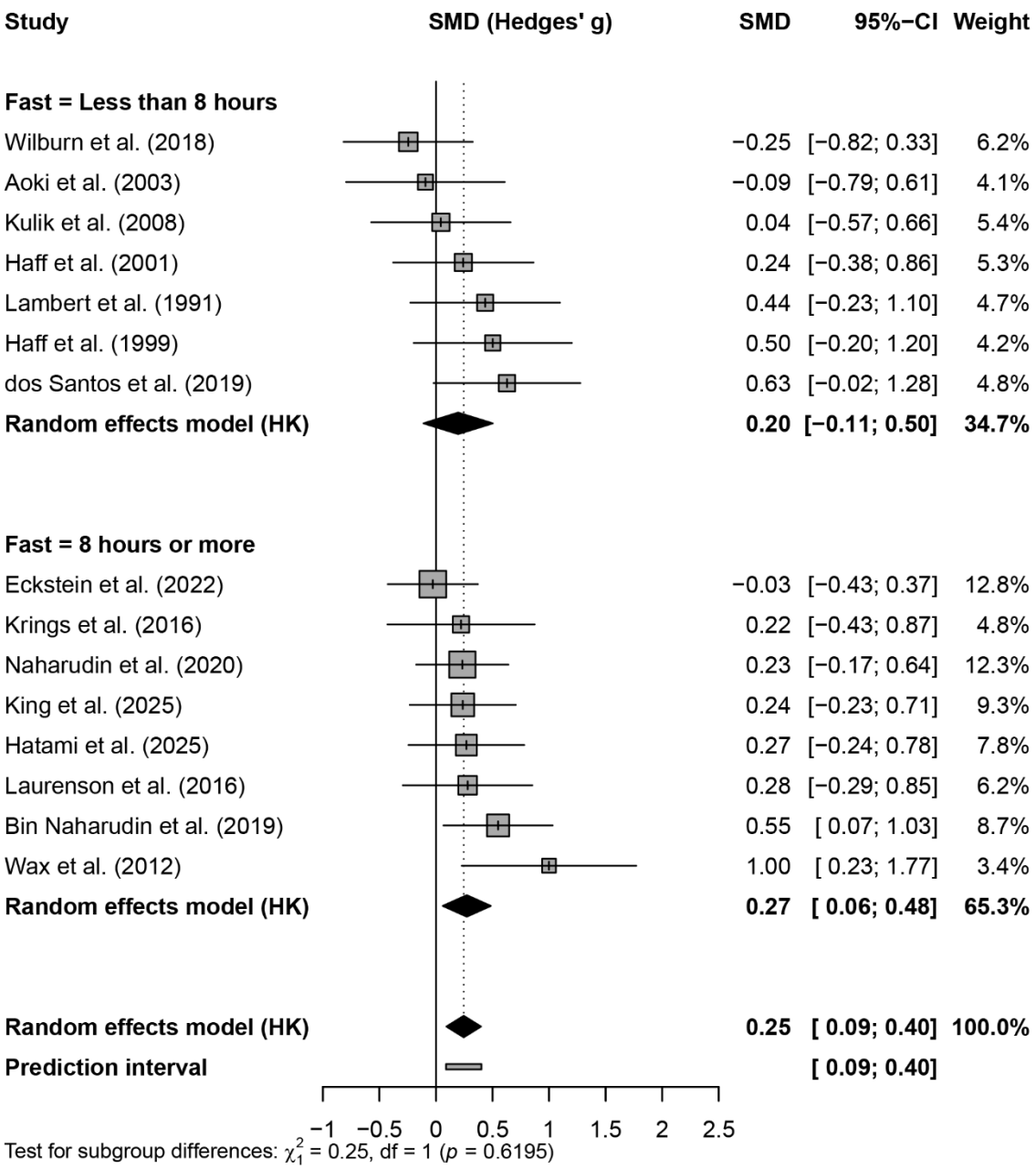
Sub-group analysis revealed a statistically significant effect of CHO ingestion for fasting periods ≥ 8 h (SMD = 0.27 [95% CI: 0.06, 0.48]; [95% PI: 0.06, 0.48]; p = 0.02; I^2 = 0%; τ^2 = 0; *k* = 8; *high certainty*; Figure 3-6). For fasting duration < 8 h, CHO ingestion did not have a statistically significant effect on training volume (SMD = 0.20 [95% CI: -0.11, 0.50]; [95%PI: -0.18, 0.57]; p = 0.17; I^2 = 2.3%; τ^2 = 0.01; *k* = 7; *low certainty*; Figure 3-6). The test for sub-group differences did not suggest a statistically significant interaction (p = 0.62).

Figure 3-5: Sensitivity random effects meta-analysis of the effect of acute CHO ingestion on total training volume compared to a placebo or control. Sub-group analysis based on session duration.



SMD standardised mean difference, *CI* confidence interval

Figure 3-6: Sensitivity random effects meta-analysis of the effect of acute CHO ingestion on total training volume compared to a placebo or control. Sub-group analysis based on fast duration.

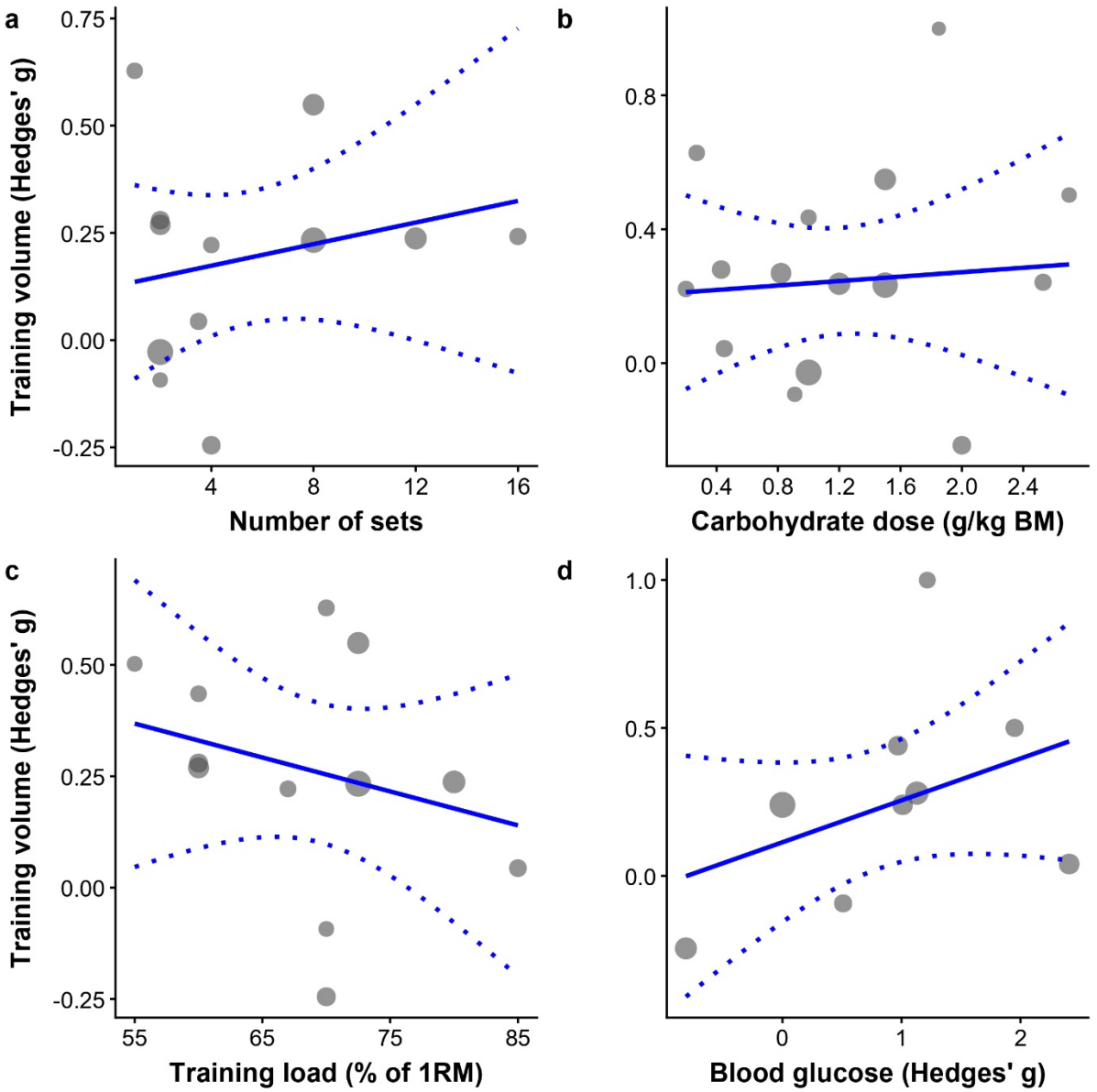


SMD standardised mean difference, *CI* confidence interval

The total number of maximal effort sets (b = 0.01, [95% CI: -0.02, 0.05]; p = 0.45), CHO dose (b = 0.03, [95% CI: -0.21, 0.27]; p = 0.77), and load used (b = -0.01 [95% CI -0.03, 0.01]; p = 0.40) were not statistically significant moderators of the SMD for training volume (Figure 3-7, Panel A-C).

In an exploratory analysis, the post-exercise BG SMD was not a statistically significant moderator of the SMD for training volume (b = 0.14 [95% CI: -0.08, 0.36]; p = 0.20; Figure 3-7, Panel D).

Figure 3-7: Sensitivity mixed-effects meta-regression of the effect of acute CHO ingestion on RT volume performance compared to a placebo or control while controlling for the effects of (a) total session sets completed, (b) CHO dose, (c) load used, and (d) post-exercise blood glucose standardised mean difference. Larger data points received greater weighting than smaller data points. Solid lines represent the estimated relationship, and dotted lines represent the upper and lower 95% confidence intervals.



BM body mass, *IRM* 1-repetition maximum

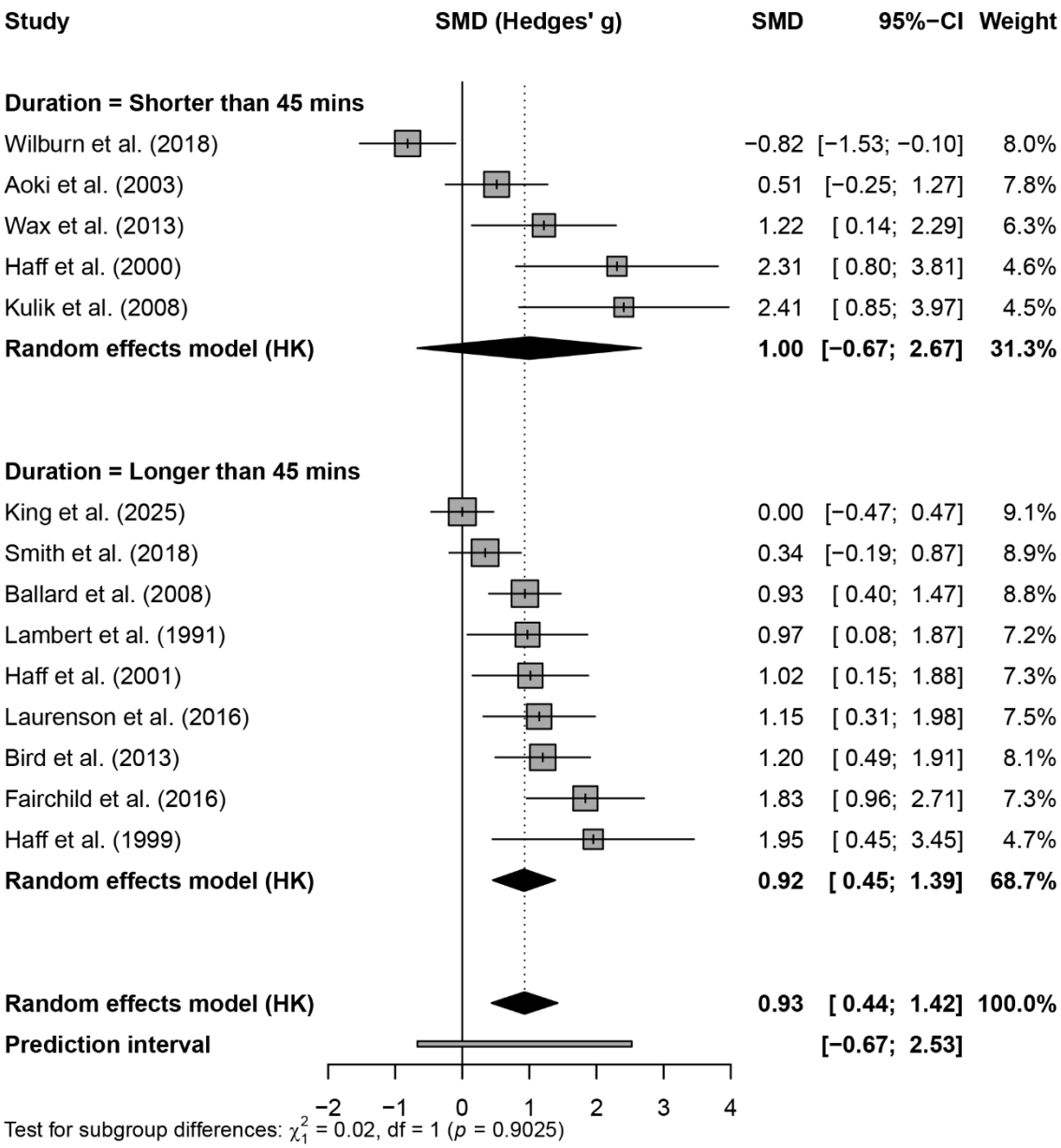
3.5.6 Post-exercise blood glucose (Main analysis)

Pooled meta-analysis identified a statistically significant effect of CHO ingestion in comparison to a placebo or control for post-exercise BG (SMD = 0.93, [95% CI: 0.44, 1.42]; [95% PI: -0.67, 2.53]; p = 0.001; I^2 = 74.7%; τ^2 = 0.49; *k* = 14; *very low certainty*; Figure 3-8 & Figure 3-9). There was evidence of publication bias (b = 3.74; t = 3.05; p = 0.01).

Sub-group analysis revealed a statistically significant effect of CHO ingestion on post-exercise BG for session durations longer than 45 min (SMD = 0.92 [95% CI: 0.45, 1.38]; [95% PI: -0.30, 2.14]; p = 0.002; I^2 = 66.7%; τ^2 = 0.23; *k* = 9; *low certainty*; Figure 3-8). For session durations shorter than 45 min, CHO ingestion did not have a statistically significant effect on post-exercise BG (SMD = 1.00 [95% CI: -0.67, 2.67]; [95% PI: -2.80, 4.79]; p = 0.17; I^2 = 84.6%; τ^2 = 1.49; *k* = 5; *very low* certainty; Figure 3-8). The test for sub-group differences did not suggest a statistically significant interaction (p = 0.84).

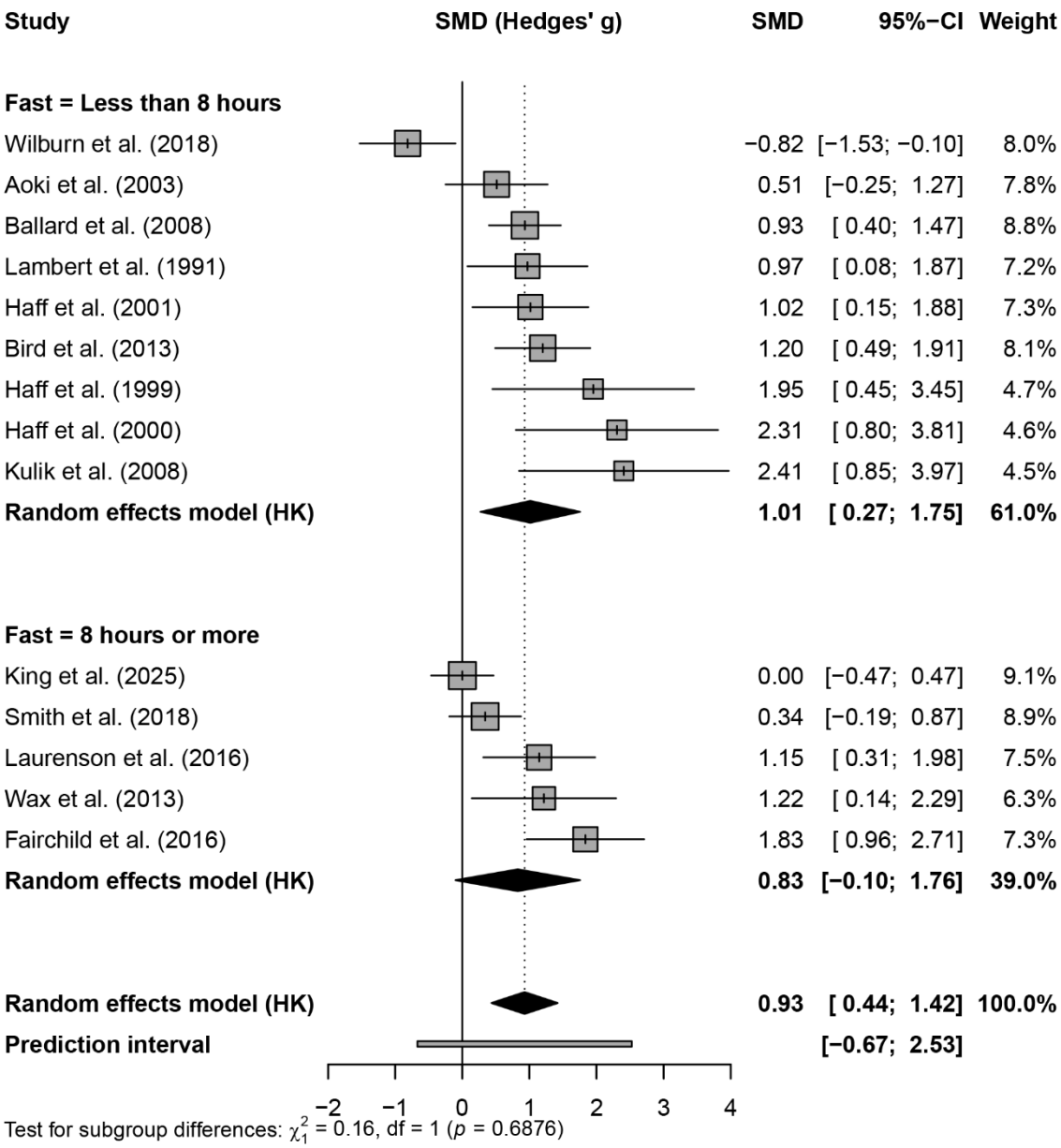
Sub-group analysis revealed a statistically significant effect of CHO ingestion on post-exercise BG for fasting periods < 8 h (SMD = 1.01 [95% CI: 0.27, 1.75]; [95% PI: -0.98, 3.01]; p = 0.01; I^2 = 75.2%; τ^2 = 0.65; *k* = 9; *low certainty*; Figure 3-9). For fasting duration ≥ 8 h, CHO ingestion did not have a statistically significant effect on post-exercise BG (SMD = 0.83 [95% CI: -0.10, 1.75]; [95%PI: -1.23, 2.89]; p = 0.07; I^2 = 77.3%; τ^2 = 0.44; *k* = 5; *very low certainty*; Figure 3-9). The test for sub-group differences did not suggest a statistically significant interaction (p = 0.97).

Figure 3-8: Main analysis random-effects meta-analysis of the effect of acute CHO ingestion on post-exercise blood glucose concentration compared to a placebo or control. Sub-group analysis based on session duration.



SMD standardised mean difference, *CI* confidence interval

Figure 3-9: Main analysis random-effects meta-analysis of the effect of acute CHO ingestion on post-exercise blood glucose concentration compared to a placebo or control. Sub-group analysis based on fast duration.



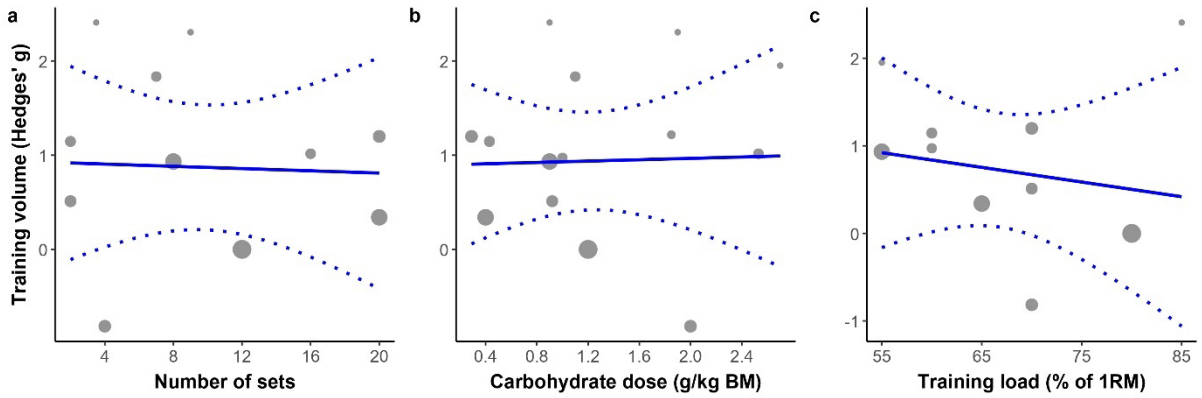
SMD standardised mean difference, *CI* confidence interval

An exploratory sub-group analysis suggested that where feeding was isolated to the pre-exercise period, the effect of CHO relative to placebo or control was not statistically significant (SMD = –0.10; [95% CI: –1.70 to 1.49]; [95% PI: –2.85 to 2.65]; p = 0.81; *very low certainty*; *k* = 3). Where feeding was pre-exercise and/or intra-exercise, the effect of CHO relative to placebo or control on post-

exercise blood glucose was statistically significant (SMD = 1.18; [95% CI: 0.79 to 1.56]; [95% PI: 0.28 to 2.07]; p < 0.0001; *high certainty*; *k* = 11). The test for sub-group differences suggested a statistically significant interaction (p = 0.003).

The total number of maximal effort sets (b = -0.01 [95% CI: -0.11, 0.10]; p = 0.90), CHO dose (b = 0.04 [95% CI: -0.68, 0.75]; p = 0.91), and load used (b = -0.02 [95% CI: -0.09, 0.06]; p = 0.61) were not statistically significant moderators of the SMD for post-exercise blood glucose (Figure 3-10).

Figure 3-10: Main analysis mixed-effects meta-regression of the effect of acute CHO ingestion on post-exercise blood glucose compared to a placebo or control while controlling for the effects of (a) total session sets completed, (b) CHO dose, and (c) load used.



BM body mass, *IRM* 1-repetition maximum

Sensitivity analysis for post-exercise BG is reported in Appendix B Ch. 3 Supplementary File I.

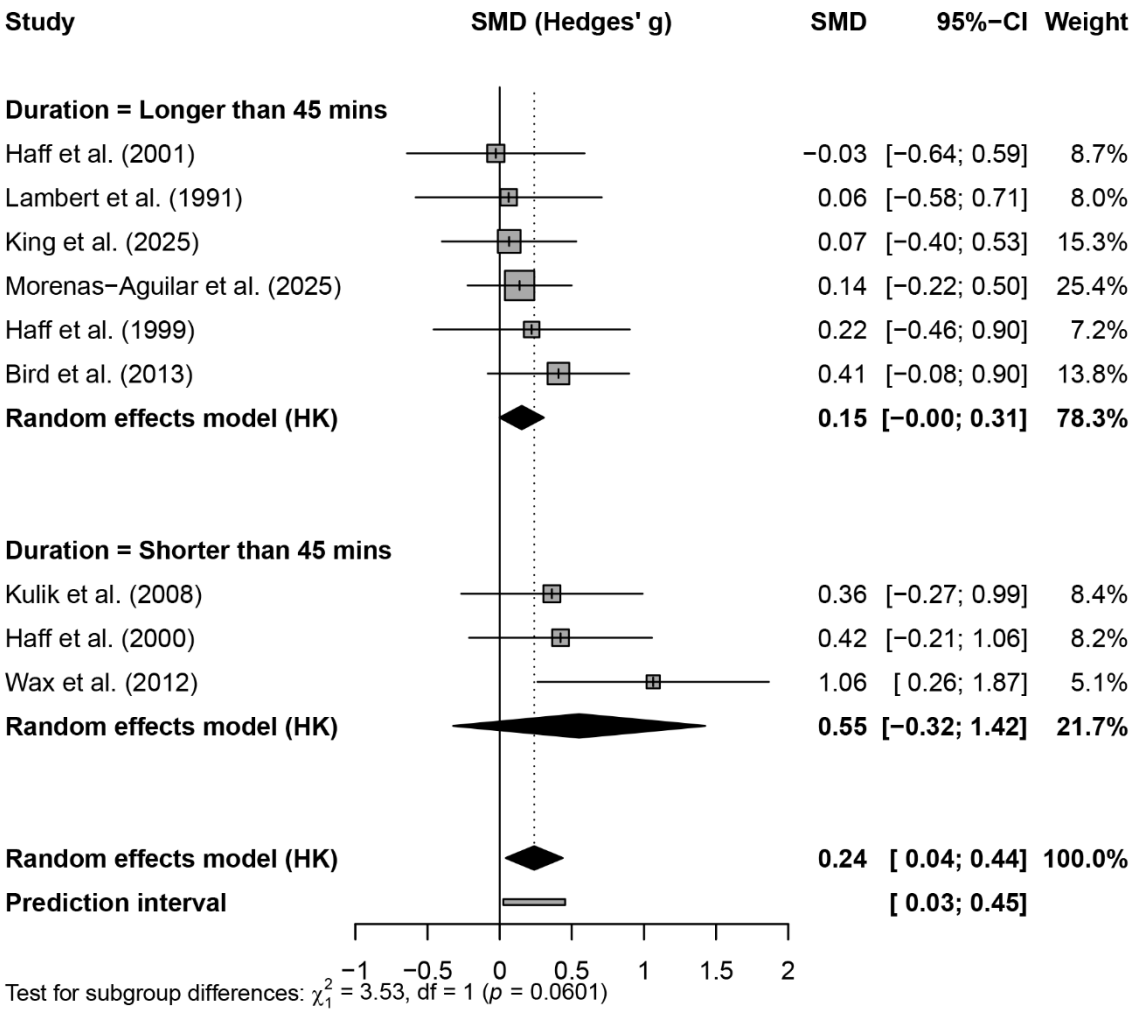
3.5.7 Post-exercise blood lactate (Main analysis)

Pooled meta-analysis identified a statistically significant effect of CHO ingestion relative to a placebo or control for post-exercise BL (SMD = 0.24, [95% CI: 0.04, 0.44]; [95% PI: 0.03, 0.45]; p = 0.02; I^2 = 0%; τ^2 = 0; *k* = 9; *high certainty*; Figure 3-11). There was no evidence of publication bias (b = 1.78; t = 1.48; p = 0.18), though caution is needed as at least *k* = 10 should be present.

Sub-group analysis revealed a non-statistically significant effect of CHO ingestion on post-exercise BL for session durations longer than 45 min (SMD = 0.15 [95% CI: 0.00, 0.30]; [95% PI: -

0.12, 0.42]; p = 0.05; I^2 = 0%; τ^2 = 0; *k* = 6; *moderate certainty*; Figure 3-11). For session durations shorter than 45 min, CHO ingestion did not have a statistically significant effect on post-exercise BL (SMD = 0.55 [95% CI: -0.32, 1.42]; [95% PI: -0.31, 1.41]; p = 0.11; I^2 = 3.9%; τ^2 = 0; *k* = 3; *low certainty*; Figure 3-11). The test for sub-group differences did not suggest a statistically significant interaction (p = 0.06).

Figure 3-11: Main analysis random-effects meta-analysis of the effect of acute CHO ingestion on post-exercise blood lactate compared to a placebo or control. Sub-group analysis based on session duration.

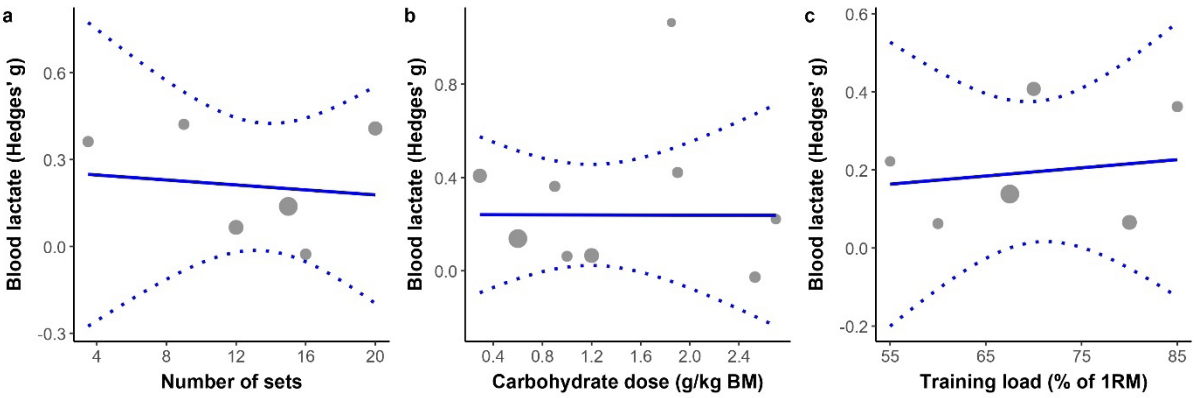


SMD standardised mean difference, *CI* confidence interval

An exploratory sub-group analysis of fast duration for post-exercise BL is presented in Appendix B Ch. 3 Supplementary File I. For fast durations ≥ 8 hrs there were insufficient studies (k = 2) to make meaningful inferences (i.e., very wide 95% CI and PI), but for fast durations < 8 hrs there were sufficient studies (k = 7) and a statistically significant small effect (SMD = 0.22, p = 0.01).

The total number of maximal effort sets (b = 0.00 [95% CI: -0.05, 0.04]; p = 0.81), CHO dose (b = 0.00 [95% CI: -0.28, 0.28]; p = 0.99), and load used (b = 0.00 [95% CI -0.02, 0.02]; p = 0.79) were not statistically significant moderators of the SMD for post-exercise BL (Figure 3-12).

Figure 3-12: Main analysis mixed-effects meta-regression of the effect of acute CHO ingestion on post-exercise blood lactate compared to a placebo or control while controlling for the effects of (a) total session sets completed, (b) CHO dose, and (c) load used.



BM body mass, *IRM* 1-repetition maximum

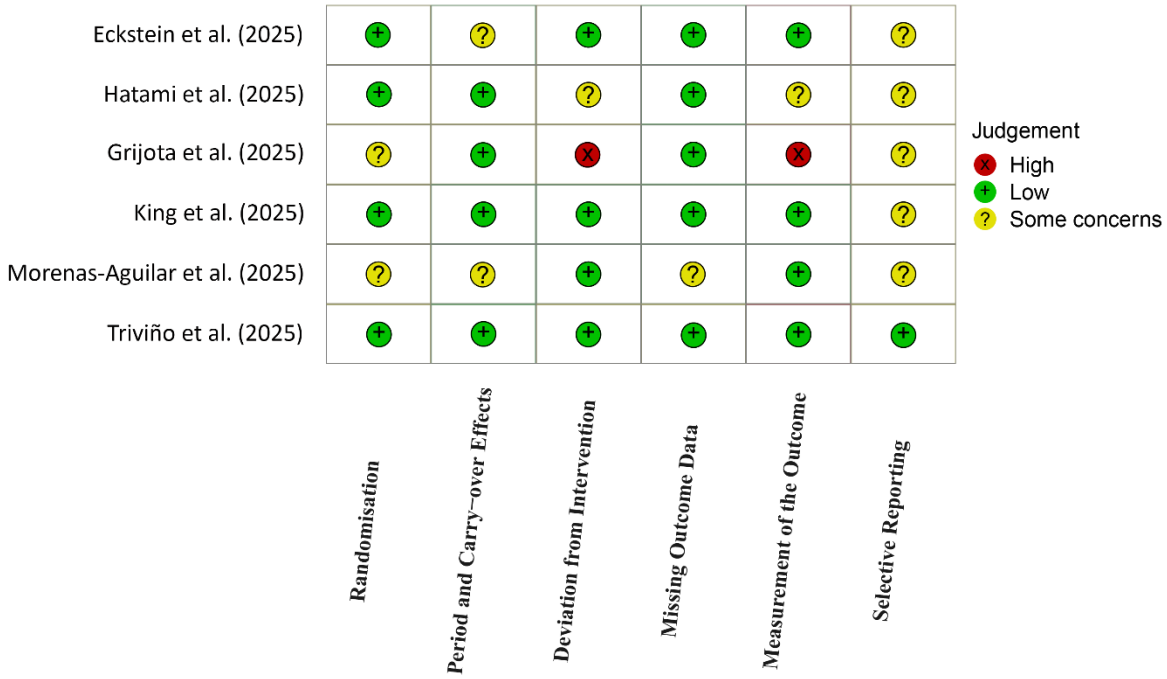
Sensitivity analysis for post-exercise BL is reported in Appendix B Ch. 3 Supplementary File I.

3.5.8 Risk of bias

Of the six studies included from the updated systematic search, one was rated low risk overall [131], 4 were rated some concerns [119, 120, 129, 130], and one was high risk [132]. Regarding bias arising from the randomisation process, four studies [119, 129-131] reported methods that indicated allocation concealment was protected (e.g., independent or 3rd party researcher) and were rated low risk.

The other two studies [120, 132] were rated some concerns due to absent or limited information regarding allocation concealment method. Regarding bias arising from carry-over effects, four studies reported methods consistent with counterbalancing and a wash-out period considered sufficient to eliminate carry-over effects [119, 129, 131, 132]. The other two studies [120, 130] were rated some concerns due to counterbalancing likely not being feasible. Regarding bias arising from deviations from the intervention, one study [132] was rated high risk due to serious concerns regarding assessor blinding, one study [129] was rated some concerns due to a lack of information regarding assessor blinding, and the other four studies [119, 120, 130, 131] reported adequate blinding procedures and were rated low risk. Regarding missing outcome data, one study [120] was rated some concerns due to limited information regarding missing data, the other five studies were rated low risk [119, 129-132]. Regarding measurement of the outcome, one study [132] was rated high risk due to serious concerns about assessor blinding and a lack of information on methods for outcome assessment, one study [129] was rated some concerns due to a lack of information on assessor blinding, and the other four studies [119, 120, 130, 131] were rated low risk. Regarding selective reporting, five studies [119, 120, 129, 130, 132] were rated some concerns due to a lack of pre-registration, the other study [131] was pre-registered and received a low risk. Risk of bias judgements are presented in Figure 3-13, and the full decision-making rationale is in Appendix B Ch. 3 Supplementary File III.

Figure 3-13: Risk of bias traffic light plot for all studies included from the updated search



3.6 Discussion

3.6.1 Total session volume performance

The purpose of this updated meta-analysis was to incorporate recently published studies, correct data extraction errors, conduct sensitivity analyses excluding the caffeine-containing study, and provide an updated estimate and interpretation of the acute effects of CHO ingestion on RT volume performance. The updated analysis indicates with high certainty that CHO ingestion produces a small ergogenic effect (SMD = 0.28, p = 0.001) on RT volume performance compared to placebo or control. This effect was robust to the sensitivity analysis (SMD = 0.25, p = 0.004). These estimates represent a decrease from the moderate effect reported in the original meta-analysis (SMD = 0.61). This reduction in magnitude is attributable to the correction of data extraction errors, the inclusion of new trials, and – in the sensitivity analysis – the removal of potentially confounded data. Precision has improved; the 95% confidence interval narrowed from 0.11 to 1.11 in the original analysis – spanning trivial to large effects – to spanning trivial to small effects (95%CI: 0.13 to 0.44) in the current main analysis. The prediction interval – which reflects the expected range of true effects across comparable future studies

– extended from a trivial effect to a moderate effect favouring CHO in the updated main analysis (95% PI: 0.05, 0.51). Using the publicly available dataset and R code from the original analysis, we calculated notably wider prediction intervals for the original meta-analysis (95% PI: –0.97 to 2.20), indicating substantially greater heterogeneity in the previous estimate. Lastly, the proportion of variance in true effects decreased in the current update (I^2 = 7.2%) compared to the original (I^2 = 79%). Overall, the updated pooled analysis supports with high certainty a small ergogenic effect of acute CHO ingestion on RT volume performance, which was robust to sensitivity analysis and accompanied by improved precision and reduced heterogeneity compared to the original meta-analytic estimate. These results suggest that while the impact of acute CHO ingestion on RT volume is not as large as previously estimated, it remains a small but consistent ergogenic benefit that can be interpreted with greater confidence given the improved precision and substantially reduced heterogeneity of the updated analysis.

The updated sub-group analyses also revealed smaller and more precise effects than those reported in the original review. For session durations longer than 45 min, CHO ingestion produced a statistically significant small effect (SMD = 0.38, p = 0.001) with high certainty, in contrast to the large effect originally reported (SMD = 1.01). Precision and heterogeneity improved in the updated analysis, with a narrower CI (95% CI: 0.20, 0.56) and PI (95% PI: 0.10, 0.65) relative to the broad intervals observed previously (95% CI: 0.11, 1.11 and 95% PI: 0.98, 2.20). For fasting durations ≥ 8 h, the original review identified a small, statistically significant effect (SMD = 0.39, p = 0.03), while the current update identified a similar small effect (SMD = 0.27, p = 0.02), with high certainty, again with improved precision (95% CI: 0.06, 0.48 vs. 0.06, 0.72) and reduced heterogeneity (95% PI: 0.06, 0.48 vs. 0.05, 0.73). The effect size magnitudes, their statistical significance, and precision were comparable in the sensitivity analysis relative to the current main analysis. Despite these more precise results, the interaction between session duration and fast duration sub-groups was not statistically significant (p = 0.28 and 0.95, respectively), which suggests the descriptive differences between the categories in each of these sub-groups are inconclusive and could reflect insufficient statistical power or be compatible with chance.

Lastly, the updated meta-regressions were consistent with the original review for CHO dose and load, but the moderating effect of the number of completed sets was not statistically significant in the current analysis (decreasing from b = 0.11, p = 0.005 to b = 0.02, p = 0.07). The slope remained positive, indicating that protocols involving more maximal-effort sets have slightly larger effects of acute CHO ingestion. However, the coefficient is smaller, and the p-value crossed our predefined α-threshold. Thus, it is now unclear whether the number of sets moderates the CHO–placebo/control difference. If a true moderating effect exists, it is likely small. For example, based on the current regression coefficient (b = 0.02), performing 10 additional maximal-effort sets would be expected to increase the predicted SMD by 0.2 on average, a magnitude within the trivial-to-small range. Collectively, these findings suggest that while descriptive sub-group analysis suggests potentially larger effects for longer training sessions (>45 min) and fasting periods ≥ 8 h, the moderators of the ergogenic effects of acute CHO ingestion remain incompletely characterised.

Several mechanisms may underlie the small ergogenic effect of acute CHO ingestion on RT volume performance. One possibility is central nervous system activation via oral CHO sensing. Mouth rinsing with maltodextrin produces a small improvement in RT volume in network meta-analysis [133], likely through increased neural activity in regions involved in motor output that transiently enhance corticomotor excitability prior to ingestion [39, 40]. However, several studies [73, 74, 119] reported effects favouring CHO even when ingestion occurred well before or outside the training session, making it unlikely that transient oral sensing fully explains the observed benefits. Another candidate mechanism is that ingested CHO improves feelings of subjective appetite, such as hunger and fullness, which may in turn affect RT volume performance, as demonstrated by a handful of trials by one group [74, 75]. Independent replication could further strengthen support for this mechanism.

The metabolic effects of acute CHO ingestion also remain plausible contributors. Elevated BG could plausibly be used as a readily available fuel source [16]. To explore this possibility, we conducted a meta-regression among studies reporting both RT volume performance and post-exercise BG (k = 10). Although the magnitude of the glucose response was not a statistically significant predictor of performance (b = 0.17, 95% CI: –0.06 to 0.39; p = 0.14), the positive slope and wide CI suggest an

imprecise but potentially meaningful association, limited by the smaller pool of studies. These findings provide preliminary evidence supporting further investigation into the metabolic role of BG in RT volume performance.

Another plausible yet underexplored metabolic contributor is muscle glycogen [3]. Standard RT induces modest reductions to total muscle glycogen (10 – 42%) [20-22] and can deplete specific subcellular locations (i.e., intramyofibrillar) in type II fibres [29]. Only one eligible study to date was included which directly quantified muscle glycogen in the context of the effects of acute CHO ingestion on RT performance [52]. CHO ingestion in the extended pre-exercise period (e.g., 1 - 4 h) can increase muscle glycogen stores, with CHO-rich breakfasts providing 2 - 3 g/kg BM, elevating muscle glycogen by approximately 10 - 42% over the subsequent 3 - 4 h postprandial period [33, 34, 36]. Thus, acute CHO intake may augment muscle glycogen availability and improve RT performance. However, findings are not entirely consistent; in well-trained cyclists, a 3 g/kg BM CHO breakfast did not increase muscle glycogen after 3 h [134]. Future trials comparing acute CHO ingestion with appropriate placebo conditions (non-caloric or isoenergetic but CHO-free) and directly assessing liver and/or muscle glycogen before and after RT are needed to clarify the extent to which glycogen availability mediates any observed ergogenic effects.

3.6.2 Post-exercise blood glucose

The updated pooled effect size for post-exercise BG decreased relative to the original review, although a large effect remained evident (SMD reduced from 2.36 to 0.93). This large elevation in BG following acute CHO ingestion was consistent across both session duration and fasting duration sub-groups (SMD = 0.83 - 1.03), with no statistical differences between sub-groups when testing for interaction ($p = 0.84$ and 0.97, respectively). The precision of the pooled estimate improved substantially, with the updated CI narrowing to span small to large effects of CHO ingestion (95% CI: 0.44, 1.42), compared with the broader interval reported previously (95% CI: 1.17, 3.35). Heterogeneity was also reduced; the updated PI (95% PI: –0.67, 2.53) is narrower than that of the original review

(95% PI: –1.58, 6.30), although substantial variability in possible true effects still exists, which contributed to a *very low* certainty of evidence for the pooled post-exercise BG estimate.

The reduced pooled effect size and improved precision and heterogeneity likely reflect two factors: correction of effect size calculations that previously inflated individual study estimates, and the inclusion of a newly identified study administering CHO exclusively 2 h before exercise. Nevertheless, PIs suggest that the magnitude of BG elevation varies widely across trials, and session duration and fasting state did not explain this variability. As noted in the original review, these findings may indicate that intra-exercise ingestion of rapidly digestible liquid CHO sources produces robust increases in post-exercise BG relative to placebo or control.

Exploratory sub-group analyses support this interpretation. When CHO ingestion was restricted to the pre-exercise period only, the pooled effect was small, imprecise, and not statistically significant (SMD = –0.10; p = 0.81; *very low certainty*). In contrast, intra-exercise CHO ingestion, with or without additional pre-exercise ingestion, produced a statistically significant large effect (SMD = 1.18; $p < 0.0001$; *high certainty*). However, the small number of studies in the pre-exercise–only sub-group ($k = 3$) precludes firm inferences. Collectively, the updated results suggest acute CHO ingestion has a large effect on post-exercise BG with very low certainty, and preliminary analyses indicate fast digesting CHO sources ingested during RT induce a higher post-exercise BG response relative to pre-exercise ingestion only.

3.6.3 Post-exercise blood lactate

The updated pooled effect size for post-exercise BL was small with high certainty and reduced relative to the moderate effect reported in the original review (SMD decreased from 0.55 to 0.24). The updated estimate is also more precise, with its CI spanning trivial to small effects favouring CHO relative to placebo or control (95% CI: 0.04, 0.44), in contrast to the original interval that ranged from trivial to large effects (95% CI: 0.03, 1.14). Heterogeneity improved as well, with the PI narrowing substantially from the original (95% PI: –0.75, 1.92) to the current update (95% PI: 0.03, 0.45), such that the 95% PI now closely reflects the CI.

Sub-group analyses for session duration indicated longer session durations (> 45 min) were associated with a moderate certainty non-statistically significant trivial effect favouring CHO (SMD = 0.15, p = 0.05; *moderate certainty*); which was similar in sensitivity analysis (SMD = 0.10, p = 0.06). Given the arbitrary nature of the $\alpha = 0.05$ threshold, we emphasise interpretation based on effect magnitude and precision rather than statistical significance alone. As discussed in the original review, lactate serves as a fuel source during exercise and is unlikely to be a primary contributor to fatigue [111], but it is a useful, strong correlate of metabolic and neuromuscular fatigue during high-intensity exercise [112, 113]. Therefore, higher post-exercise lactate with CHO ingestion likely reflects greater total work performed rather than detrimental metabolic consequences. The updated results remain consistent with this interpretation, though the magnitude of the pooled effect is now small.

3.6.4 Qualitative discussion of other included studies

Three studies [120, 131, 132] met the full inclusion criteria in the updated systematic search but reported outcomes not eligible for quantitative synthesis. Morenas-Aguilar et al. [120] reported improved barbell mean velocity with CHO ingestion (45g CHO) relative to a placebo for men – but not women – in an RT session consisting of five sets of eight repetitions with a 12-repetition maximum load during the bench press, bench pull, and squat exercises. One other study [55] reported improved average velocity during five sets of 10 repetitions at 75% of 1-RM when ingesting 1.2g/kg BM CHO relative to a placebo. The other two studies [131, 132] reported on CrossFit performance. Triviño et al. [131] reported no effect of ingesting 60g CHO during a CrossFit session on the number of squat repetitions completed at 75% 1-RM within 30 seconds, assessed before and after the session. Grijota et al. [132] reported no differences between 30 g CHO and a placebo ingested during a CrossFit session on bench press velocity, assessed before and after the session. One additional study [97] identified in the original review assessed repetition performance within a CrossFit session and likewise reported no differences between CHO ingestion and placebo. Collectively, these findings suggest a potential ergogenic effect of acute CHO ingestion on average barbell velocity during RT, which warrants future quantitative synthesis as additional primary studies become available. In contrast, evidence for CrossFit performance remains unclear due to heterogeneous outcome measures.

3.7 Conclusion

In conclusion, this updated meta-analysis demonstrates with high certainty that acute CHO ingestion relative to a placebo or control confers a small but robust ergogenic effect on RT volume performance, with improved precision and reduced heterogeneity compared to the original review. Sub-group analyses for volume performance suggest that this small ergogenic benefit occurs during longer training sessions (> 45 mins) and after extended fasting periods (≥ 8 hrs) with high certainty. Acute CHO ingestion also produces large increases in post-exercise blood glucose, especially when fast-digesting CHO sources are ingested during exercise. There were small increases in post-exercise blood lactate with CHO ingestion, a finding consistent with greater total volume performed rather than alterations in fatigue-related metabolic pathways. Preliminary mechanistic evidence suggests potential contributions to these effects may stem from central nervous system activation, appetite modulation, and/or substrate availability, though these remain incompletely understood and future research is needed. Collectively, the updated evidence supports a small, reliable volume performance benefit of acute CHO ingestion before and/or during RT with high certainty.

Chapter 4: The effects of carbohydrate mouth rinsing on muscle strength and endurance: A systematic review with network meta-analysis

This chapter has been pre-printed on SportRXiv (https://doi.org/10.51224/SRXIV.686) and is currently under peer review at Sports Medicine.

4.1 Preface

This chapter continues the theme of original evidence synthesis by conducting a prospectively registered network meta-analysis on CMR and RT performance. Key issues regarding an existing CMR and RT systematic review with pairwise meta-analysis [135] were raised related to effect size calculation in cross-over designs, dependence among effect sizes, meta-regression procedures, and we specifically noted the absence of clearly reported GRADE assessments in a published letter to the editor [136]. Subsequent work constructively addressed several of these concerns [137], but limitations in the clarity of reporting and the transparency of risk-of-bias and GRADE decision-making remain and hinder a robust appraisal of the updated conclusions.

Accordingly, building on the CHO ingestion-focused syntheses in Chapters 2 and 3, this chapter systematically compares multiple active CMR formulations (maltodextrin, glucose, maltose) against a range of non-active comparators (placebo, water rinse, no-rinse control) across key outcomes: peak force, maximum dynamic strength, and total session volume.

By using cross-over–appropriate effect size calculations, multi-arm network methods, and GRADE-based CINeMA evaluations, this chapter refines when and to what extent CMR may mitigate neuromuscular fatigue or enhance volume performance, while qualifying the very low certainty of the current evidence. These results sharpen the conceptual distinction between centrally and metabolically mediated CHO effects and clarify the magnitude and context of any practical benefit. Thus, this chapter informs interpretation of applied nutritional behaviours among powerlifters (Chapters 5 and 6) and

helps frame the rationale for the subsequent experimental work on pre-exercise CHO feeding and glycogen-related mechanisms in Chapters 7 and 8.

4.2 Abstract

4.2.1 Background

CMR can influence RT performance, but different forms of CMR and varying non-active comparators (e.g., placebo rinse, water rinse, and no rinse control) have not been quantitatively synthesised in a network meta-analysis.

4.2.2 Objective

To determine if, when, how, and to what degree CMR, placebo rinse, water only rinse, and a no rinse control influence RT performance.

4.2.3 Methods

Five databases were searched following Cochrane and PRISMA guidelines, to compare muscle strength and endurance outcomes with either CMR or comparator condition (placebo, water only, no rinse). A prospectively registered (osf.io/9v68j) random-effects network meta-analysis was performed for pre- to post-exercise change in peak force production, maximum dynamic strength, and total session volume. Hedge's *g*, CI, PI, and p-values are reported. Evidence quality was assessed using the Cochrane RoB 2 and GRADE-based Confidence in Network Meta-Analysis criteria.

4.2.4 Results

Twenty-four studies involving 385 participants (78% resistance trained, 73% male) were included and three primary performance outcomes were sufficiently reported to enable network meta-analysis. With very low certainty of evidence, CMR with maltodextrin (g = 0.41; 95% CI [0.08, 0.74]; 95% PI [-0.50, 1.32]; p = 0.01) and glucose (g = 0.68; 95% CI [0.19, 1.18]; 95% PI [-0.35, 1.71]; p = 0.006) enhanced pre- to post-exercise peak force relative to placebo. With very low certainty of evidence, maltodextrin (g = 0.04; 95% CI [-0.14, 0.23]; 95% PI [-0.22, 0.31]; p = 0.64) and glucose (g = 0.06; 95% CI [-0.42, 0.54]; 95% PI [-0.61, 0.73]; p = 0.80) did not produce statistically significant effects on maximum dynamic strength relative to placebo. With very low certainty of evidence,

maltodextrin had a statistically significant small effect (g = 0.29 95% CI [0.12, 0.45]; 95% PI [-0.23, 0.81]; p = 0.0008) while glucose did not have a statistically significant effect (g = 0.05; 95% CI [-0.39, 0.49]; 95% PI [-0.64, 0.73]; p = 0.83), on total session volume. Secondary outcomes of RPE, BG and BL, HR, and FA did not produce statistically significant effects of CMR relative to placebo.

4.2.5 Conclusion

CMR with maltodextrin and glucose may enhance pre- to post-exercise peak force, which indicates CMR may alleviate neuromuscular fatigue during exercise. CMR with maltodextrin has a small ergogenic effect on total session volume which may be enhanced by shorter fasting durations, more sets completed, higher intensity, and for lower body exercise. CMR does not appear to have an ergogenic effect on maximum dynamic strength. The certainty of evidence was generally very low due to the included studies' risk of bias, as well as imprecision and heterogeneity of effect size estimates.

4.3 Introduction

Acute pre-exercise nutritional status is considered to play a key role in athletic performance and adaptation [138], and CHO ingestion before or during training can improve endurance [139] and RT performance [118]. This ergogenic effect of CHO is often considered metabolic in nature, augmenting or preserving the glycogen storage in the muscle and liver, and by preserving euglycemic BG [140]. However, CHO can enhance training performance even when stores of glycogen and BG are unlikely to limit exercise performance (e.g., durations <1 hour) [141, 142].

These findings led to the hypothesis that some of the ergogenic effect of CHO is centrally mediated. Supporting this, Chambers et al. [39] demonstrated that mouth rinsing with glucose or maltodextrin was associated with the greater activation of the insula and anterior cingulate cortex regions of the brain implicated in reward and motivation. Although brain imaging is associative and open to reverse inference [143], there is a centrally mediated mechanism by which CMR may influence exercise performance. Importantly, because CMR likely exerts its effects without requiring CHO ingestion, it may represent a practical ergogenic strategy in situations where athletes are energy restricted or where gastrointestinal symptom management is a priority.

The effect of CMR on RT performance was previously systematically reviewed and meta-analysed [135], concluding that CMR did not enhance maximal strength but did enhance repetition performance compared to placebo. Several new studies were published since [58, 144, 145], and at least two existing candidate studies that quantified total session volume performance [64, 72] were not included in this systematic review [135]. In addition, a transparent accounting of the risk of bias in the extant literature and a framing of the current meta-analytical results around certainty of evidence (i.e., the GRADE [Grading of Recommendations Assessment, Development and Evaluation] framework [81]) has not been completed as our group highlighted in a previously published commentary [136].

A pairwise comparison of CMR to placebo also fails to capture the full range of potential comparators and their treatment effects estimates. Some studies use water-only rinsing as the comparator condition [64, 72, 145]. A water-only rinse comparator captures any expectancy from

merely performing a rinse but does not sufficiently blind participants to the treatment due to a lack of taste and texture matching [146]. A no rinse control condition is used by some studies [65, 67, 70-72, 144] where the participant knows they had not received an active intervention, which allows the influence of positive expectancy from mouth rinse to be isolated, but also may result in a negative expectancy effect. Additionally, several studies used varying CHO sources (e.g., maltodextrin, glucose, maltose), which may have distinct treatment effects due to their concentration or chemical structure. As such, there are multiple possible CMR conditions (i.e., different CHO sources) and comparator conditions (i.e., placebo, water only, and no rinse control) that could have a unique influence on the effect size estimate of performance outcomes. Overall, these treatments in theory could be ranked from lowest to highest efficacy: no rinse control, water only control, taste and texture matched placebo, and CMR.

Given the diversity in intervention and control conditions, a network meta-analysis offers a more comprehensive framework for synthesising the available evidence, allowing simultaneous comparison of all available treatments with relative effectiveness ranking, even if two treatments have not been directly compared [147]. In addition, an updated review could incorporate recent publications and other existing literature. Thus, the present systematic review aimed to identify and synthesise all currently available literature and quantify the range of possible treatment effects contained within that literature using network meta-analysis. Additionally, the current systematic review aimed to evaluate the risk of bias in the available literature and frame the results around the certainty of evidence within the GRADE framework.

4.4 Methods

A systematic review was performed in accordance with the Cochrane Handbook for Systematic Reviews (version 6.3.0) and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [77]. The protocol was pre-registered on the Open Science Framework and occurred after pilot searches, but before any formal searches were conducted (https://osf.io/3uwcb).

4.4.1 Search Strategy

A patient/population, intervention, comparison, and outcomes (PICO) systematic search strategy was developed for PubMed using several automated tools [148]. The Word Frequency Analyser tool (http://sr-accelerator.com/#/help/wordfreq) was used to suggest potentially relevant search terms. The Research Refiner Tool (https://ielab-sysrev2.uqcloud.net/) was subsequently used to optimise the sensitivity and specificity of the search, while the Polyglot Search Translator Tool (https://sr-accelerator.com/#/polyglot) was used to adapt the search to other databases [149]. The PubMed, MEDLINE, SPORTDiscus, Scopus, and CINAHL electronic databases were initially searched from inception to 28th of February 2022 using the following keywords for the PubMed/MEDLINE database: "carbohydrate" OR "glucose" OR "maltodextrin" OR "cho" AND "mouth rins*" OR mouth-rins* OR "mouth" AND "resistance training" OR "resistance exercise" OR "weight training" OR "strength" OR "endurance". The search strings for all electronic databases can be found in Appendix B Ch. 4 Supplementary File I. Secondary searches included (a) forward citation tracking of included studies using Google Scholar (performed in October 2025), and (b) setting up search alerts to identify any new search results after the last search date. No year restrictions were applied to the search. Search alerts were monitored from the original search, and the systematic searches were performed again in October 2025 to double-check and corroborate that the search alert records between February 2022, and October 2025 captured all the added records.

4.4.2 Text Screening

Search records were imported into Endnote (version X9, Clarivate Analytics, Philadelphia, USA). Duplicates were removed using Endnote's deduplication function and manual methods. Records were independently screened by title and abstract by two investigators (AK and IJ) to determine initial eligibility using the systematic review software Rayyan (https://rayyan.ai/). The full texts of the remaining records were then retrieved and assessed by the same investigators for inclusion in the review. Disagreements between investigator's eligibility decisions were resolved via discussion and consensus, or in consultation with a third investigator (EH) where required.

4.4.3 Inclusion Criteria

All studies included in this systematic review met the following inclusion criteria: (1) the study was a peer-reviewed research article; (2) was written in the English language; (3) included healthy human participants with no musculoskeletal injury; (4) used a cross-over study design to assess the acute effect of CMR on outcomes of muscle force production (e.g., maximal strength and power) and/or muscle endurance; and (5) used a low to zero-caloric placebo (≤ 25 total kilocalories) or water only comparator condition. Performance indices considered for inclusion were those related to muscle force production (e.g., 1 repetition-maximum, isokinetic/isometric force production, power) and endurance (e.g., repetitions completed per set or exercise, total session work or volume, session duration). Perceptual measures (e.g., RPE, FA) and metabolic markers (e.g., BL and BG) were considered secondary outcomes of interest.

4.4.4 Study Coding and Data Extraction

The following data was extracted from the studies identified as meeting the full inclusion criteria: (1) study design information such as allocation concealment, blinding, and the number of periods and sequences, (2) number of participants and their characteristics (e.g. age, sex, BM, height, and training history), (3) pre-testing diet/fasting standardisation including the length and dietary tracking method, (4) CMR concentration, type, duration and frequency; (5) description of control or placebo condition; (6) RT intensity, volume, rest periods, and exercise selection; (6) means and standard deviations of the relevant primary and secondary outcomes. Where insufficient data were reported, the corresponding authors were contacted via email with a request to provide relevant data (or group-level information) or the raw data. If authors did not respond or responded but couldn't provide the requested data, data were extracted using WebPlotDigitizer and/or calculated in accordance with the Cochrane Handbook [150]. All data extraction was completed independently by two investigators (AK and IJ) using a pilot-tested form that was completed for five randomly selected studies. Coding files were cross-checked between the two investigators, and any differences were resolved via discussion and consensus.

4.4.5 Risk of bias and Evidence Certainty

Risk of bias was assessed using the Cochrane Collaboration's risk of bias tool for randomised trials (RoB 2) [78] with online resources for cross-over trial designs (https://www.riskofbias.info/welcome/rob-2-0-tool/rob-2-for-crossover-trials). Given the relative ease with which blinding can be achieved, information regarding how blinding was achieved was considered important in this systematic review. Additionally, risk of bias related to the standardisation of lead-in diet and the time of day at which testing occurred was also considered important and was assessed as outlined in a previous review [118]. Rating and grading were completed independently by two investigators (AK and IJ). Differences in risk of bias assessment were resolved via discussion and agreement before judgement scores were merged into a single spreadsheet. The spreadsheet with consensus judgement scores is available on the Open Science Framework project repository.

The GRADE-based [81] Confidence in Network Meta-Analysis (CINeMA) [151] online tool (https://cinema.ispm.unibe.ch/) and guidance document [152] were used to assess the certainty of evidence for each primary outcome included in the quantitative synthesis. This tool assesses six domains: (1) within-study bias, (2) reporting bias, (3) indirectness, (4) imprecision, (5) heterogeneity, and (6) incoherence. Within-study bias was assessed via the risk of bias results, with the majority score used to derive the domain rating. Reporting bias was evaluated as publication bias through visual inspection of funnel plots and Egger's regression test. Indirectness reflected the representativeness of participants and exercise protocols relative to RT contexts (e.g., studies of endurance-trained participants or endurance-based interventions were rated as indirect). Imprecision was judged according to whether the 95 % CIs included values that could lead to different practical interpretations in either direction, using an SMD = 0.2 as the smallest effect size of interest. This effect size threshold was selected as it is the Cohen's threshold for small effects and – in the absence of established acute outcome effect size thresholds – is reasonable given that small effects for change scores of strength and conditioning outcomes generally range from SMD = 0.15 – 0.25 [128]. Heterogeneity considered agreement between CIs and PIs for each contrast in the network meta-analysis. Incoherence was

assessed by the design-by-treatment interaction and Separating Indirect and Direct Evidence (SIDE) tests.

For the domains of imprecision, heterogeneity, and incoherence, a standardised mean difference (SMD) = 0.2 threshold (small effect) was used to judge whether observed differences were practically meaningful in accordance with the guidance document criteria [152]. Domain judgments were made jointly where conceptual overlap existed (e.g., between indirectness and incoherence, or imprecision and heterogeneity). Because the CINeMA platform assumes independent-group designs when computing effect sizes, the results were manually adjusted to reflect the dependent-group (cross-over) SMDs used in this review. The CINeMA datasheets and final reports for each primary outcome are available in the project's OSF repository (osf.io/9v68j).

4.4.6 Statistical analysis

Effect sizes were calculated in accordance with Borenstein et al. [91]. To account for the within-participant design inherent to cross-over trials, the following formulas were used:

Equation 1 $$SMD = \frac{\overline{X_1} - \overline{X_2}}{SD_{pooled}} J$$,

Equation 2: $$SD_{pooled} = \frac{S_{diff}}{\sqrt{2(1-r)}}$$,

Equation 3: $$SD_{diff} = \sqrt{SD_1^2 + SD_2^2 - 2 * r * SD_1 * SD_2}$$,

Equation 4: $$J = 1 - \frac{3}{4(n-1)-1},$$

where $\overline{X_1}$ and $\overline{X_2}$ are the mean, SD_{diff} is the standard deviation of the within-participant difference between means or mean change scores, J is a correction factor, and r is the between-condition, within-subject correlation of the mean. Where *r* was not available, the average correlation of the corresponding contrast (e.g., maltodextrin versus placebo) from other studies included in the analysis was imputed.

The main network meta-analysis was performed with random effects and placebo as the reference category using the *netmeta* package [153]. We assessed global between-design inconsistency using a design-by-treatment interaction random-effects model, visually examined net heat plots, and performed node splitting to compare direct and indirect evidence for each treatment contrast [154]. When inconsistency was detected, we used design-by-treatment decomposition to identify influential study designs and explored whether study-level or individual-level covariates could explain observed inconsistency [155]. The direct evidence proportion for each network estimate was calculated and a mean path length of >2 for any given contrast was considered as needing specific caution in interpretation [156]. Treatments were ranked under the frequentist framework according to their P-score [157], and forest plots were generated to further contextualise the results. SMD magnitude was interpreted as small (0.20-0.49), moderate (0.50-0.79), and large (>0.80) [92]. The 95% CIs and PIs are reported to quantify the uncertainty around the estimated average effect of CMR, and to indicate the range within which the true effect of CMR is expected to lie for 95% of similar future studies, respectively [158]. Potential moderators (e.g., fast duration, number of mouth rinses completed, upper versus lower body exercise, session duration, total sets completed) were explored using network meta-regression when there was sufficient between-study heterogeneity in methods to justify a meaningful analysis. Statistical significance was set at $\alpha \leq 0.05$.

Sensitivity analysis was performed by removing high-risk-of-bias studies and by checking for similar inferences under a Bayesian framework that used a hierarchical network meta-analysis in the *gemtc* [159], *rjags*, and *dmetar* [154] packages, and *jags* [160] software. Markov Chain Monte Carlo sampling was first performed with a small number of burn-in iterations (n = 50) followed by a large number (n = 5000), which were assessed for convergence by inspecting trace and Gelman-Rubin plots. Inconsistency was assessed by performing nodesplitting [161]. Treatments were ranked under the Bayesian framework by the Surface Under the Cumulative Ranking (SUCRA) score [162]. Publication bias was assessed by Egger's test and visual inspection of funnel plots [163]. If the Egger's test or visual inspection of the Funnel Plot indicated potential publication bias, the study that contained the offending

contrast/s was removed from the network and the model was re-run. This was treated as a sensitivity analysis due to it being impossible to distinguish between true outliers and large sampling error [164].

4.4.7 Decisions in data preparation

The maximum strength and session volume outcomes were reported on the same scale (kg and repetitions, respectively). However, a standardised mean difference was calculated for these outcomes due to maximum dynamic strength being reported in different exercises (i.e., bench press and back squat) and session volume being reported in protocols that markedly differed in exercise type, total sets, and intensity (%1-RM). Given these differences in testing protocol, a raw mean difference was deemed inappropriate and SMD (Hedge's *g*) was used. Secondary outcomes of BG, BL, HR, and FA were all measured on comparable scales across studies, which would typically allow for meta-analysis using raw mean differences. However, for multi-arm cross-over studies, the variance calculations for raw mean differences did not satisfy the mathematical constraints required by *netmeta*'s multi-arm adjustment procedures. Calculating SMD's (Hedges' *g*) resolved these issues by providing variance estimates compatible with multi-arm network meta-analysis. Therefore, all secondary outcomes were analysed using SMD.

One study [62] used a CMR formulation consisting of a 2:1 ratio of glucose to fructose. For the purposes of meta-analysis, this condition was included in the glucose node to reduce network sparsity, as the formulation was predominately glucose and no other study used fructose. One study [70] reported the use of dextrose, which was included in the glucose node, as dextrose is the D-isomer of glucose and chemically equivalent. One study [63] reported recruiting 29 participants of which raw data for 28 participants were available in the dataset; effect sizes were calculated on the available raw data.

Where studies reported multiple effect sizes per comparison (e.g., multiple arms or repeated measures within the same study), we combined these within-study following Cochrane Handbook guidance and using *metafor's* [87] aggregate function with an assumed within-study correlation ($\rho = 0.6$) to account for dependence. This avoids nesting effects in the network models, which do not accept multiple correlated effects from the same study in the currently available R packages. For the peak force

outcome, Black et al. [69] and Jensen et al. [165] reported 3 post-exercise measures of isometric peak force which were combined. Black et al. [166] reported data for isometric peak force performed before and after fatiguing contractions at 20% and 80% of established MVC, which were combined. Jeffers et al. [167] measured isometric peak force before and after a pre-load and time trial bout of cycling exercise which were combined. For maximum dynamic strength, Karayigit et al. [59] reported 3 CMR groups of differing doses (i.e., 6%, 12%, and 18%), which were combined. Karayigit et al. [57] reported 1-RM data in the back squat and bench press, which were combined. For total volume, Bastos-Silva et al. [67] reported total leg press and bench press repetitions which were combined. Clarke et al. [65], Durkin et al. [60], and Karayigit et al. [57] reported total back squat and bench press repetitions, which were combined for each condition. Decimoni et al. [68] reported half squat, bench press, leg press, military press, and seated row repetitions which were combined for each condition. Karayigit et al. [59] reported 3 CMR groups of differing doses (i.e., 6%, 12%, and 18%), which were combined. Karayigit et al. [58] reported total bench press repetitions completed at 40% and 80% 1-RM, which were combined for each condition. For RPE, all extracted effect sizes were based on a post-exercise measurement, except for one study [64] which reported RPE averaged across multiple timepoints of the training session and we elected to include in the analysis. For FA, one study [60] was omitted from the analysis as no data were reported for this outcome and the raw data were not available.

4.4.8 Changes from pre-registration

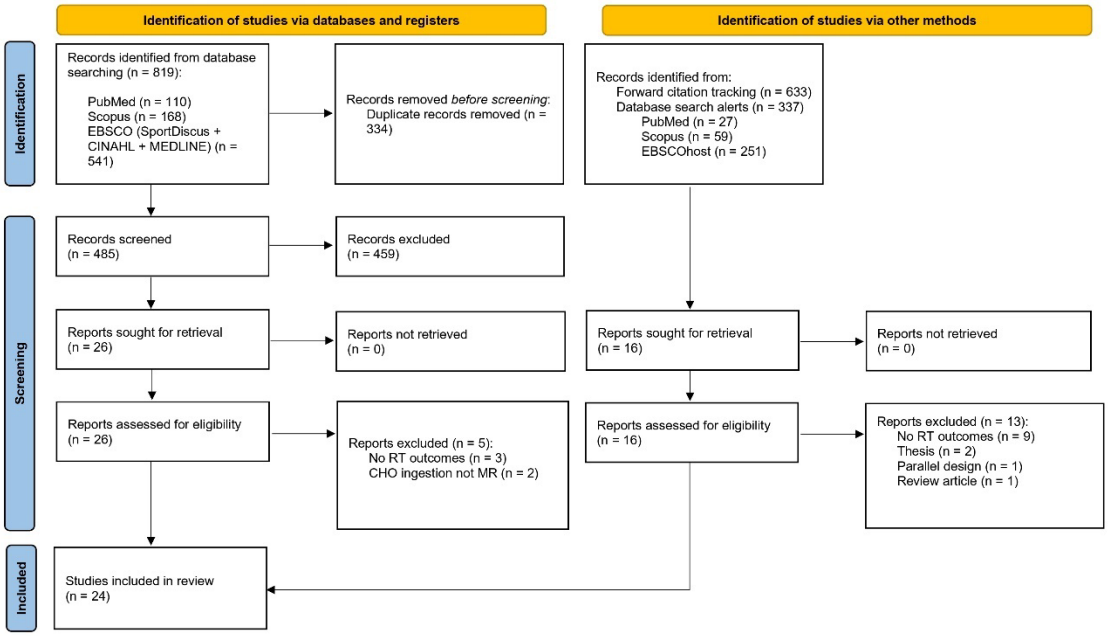
We initially pre-registered that the GRADE system would be used to evaluate the certainty of evidence for the studies included in the quantitative synthesis [3]. As it is specific to network meta-analysis, we opted to update this to use the GRADE-based Confidence in Network Meta-analysis tool [151] to assess the certainty of evidence for each of the outcomes included in the quantitative synthesis.

4.5 Results

4.5.1 Identification and selection of studies

Our systematic search yielded 819 records. Search alert monitoring and forward citation tracking yielded an additional 970 records. After deduplication and initial title and abstract screening, 42 articles were assessed by full text during the study identification process. Of these, 12 were excluded for no relevant outcome of interest, two were CHO ingestion rather than CMR, two were PhD theses, one was a parallel design, and one was a review article. This left 24 studies included in the systematic review, 21 of which were identified in the original search, and another three by monitoring search alerts and forward citation tracking. For 11 of the included studies, raw data or required values for direct effect size calculation were available on a public repository [63, 68] or upon request from authors [59, 61, 65, 66, 70, 71, 144, 168, 169]. For six included studies, raw data were lost/unretrievable [57, 58, 60, 64, 67, 170] and for seven included studies, no response from the corresponding author was received [62, 69, 72, 145, 166, 167, 171] and data were extracted from the full-text. The PRISMA flow diagram is presented in Figure 4-1.

Figure 4-1: Literature search flow chart.



n number of studies, *RT* resistance training, *CHO* carbohydrate, *MR* mouth rinse

4.5.2 Study characteristics

An overview of the participants, mouth rinse treatments, and RT sessions of the included studies is available in Table 4-1, Table 4-2, and Table 4-3, respectively. The pooled number of participants across all studies was 385, of which 78% were resistance trained (> 6 months) and 73% were male. Of 17 studies with RT trainees, the participants of one study had at least five years of RT experience [58], two studies required a minimum of two years of RT experience [60, 67], while the remaining fourteen studies required between half to one year at minimum. The participants of the remaining studies were endurance-trained [167], endurance or team sport athletes [168], or recreational with moderate to high levels of physical activity outside of RT [69, 72, 166, 169, 171]. Twenty used a CMR concentration of 6 or 6.4%, three studies used 8% [69, 166, 168], one study used 12% [59], and two studies used 18% [59, 61]. One study used dextrose [70], one study used a 2:1 glucose:fructose

mixture [62], three included glucose CMR [72, 169, 171], 1 study included maltose [171], and 21 studies included a maltodextrin CMR. Two studies compared more than one CMR type [72, 171] and one study compared three different concentrations of a maltodextrin CMR [59]. Twenty one studies included a placebo comparator that was AS and non-caloric, although one study [63] was unclear in the composition ("placebo solution"). Of these, one study additionally used a water-only [64], no rinse control [61, 65, 70, 71, 144], or water-only and no rinse control [72] as a comparator. The remaining three studies without a placebo comparator used a water-only comparator [145, 167, 169]. The number of CMRs during testing ranged from one to 30. Nine studies required that the participants fast 1.5 – 4 hrs before testing, 11 studies between 8-12 hrs, two studies were "overnight" [168, 169], and two studies were unclear [64, 71]. The bench press was used by 16 studies (13 were free weight, three were Smith machine), followed by the back squat in six studies, a row variation in four studies, and the shoulder press and leg press in three studies each. In studies assessing isometric pre- and post-exercise isometric peak force, 5 studies used knee extension, one used knee flexion, and one used elbow flexion.

Table 4-1: Participant characteristics of individual study samples

Study (year)	Participants	Sex: M/F	Age (years)	Mass (kg)	Training history (subjective description, RT experience (years), relative strength (1-RM/body mass))
Bailey et al. [171]	CHO = 10; PLA = 10	5/5	24 ± 1	61 ± 3	Moderate to high physically active; unclear; unclear
Bastos-Silva et al. [67]	CHO = 12; PLA = 12; CON = 12	12/0	22.1 ± 1.9	76.7 ± 14.1	Resistance trained; at least 2 years; unclear
Bazzucchi et al. [72]	CHO = 18; PLA = 18; WAT = 18; CON = 18	18/0	26.1 ± 5	70.6 ± 7.9	Moderately active; unclear; unclear
Black et al. [69]	CHO = 13; PLA = 13	6/7	27 ± 3	76.9 ± 15	Recreationally active; none; unclear
Black et al. [166]	CHO = 12; PLA = 12	12/0	22.5 ± 2.3	82.2 ± 13.9	Recreationally active; no lower RT in 0.5 years; unclear
Clarke et al. [71]	CHO = 15; CON = 15	15/0	21 ± 2	77 ± 6	Resistance trained; at least 0.5 years; unclear
Clarke et al. [65]	CHO = 12; CON = 12	12/0	23.3 ± 3	75.4 ± 7.5	Resistance trained; at least 0.75 years; unclear
Clarke et al. [144]	CHO = 21; PLA = 21; CON = 21	21/0	24 ± 4	78.6 ± 8.1	Resistance trained; at least 0.75 years; unclear
Decimoni et al. [68]	CHO = 15, PLA = 15	0/15	26 ± 4	59 ± 8	Resistance trained; at least 1 year; unclear
Dunkin et al. [61]	CHO = 12; CON = 12	12/0	22 ± 1	80.9 ± 6.1	Resistance trained; at least 0.5 years; unclear
Durkin et al. [60]	CHO = 12; PLA = 12	12/0	22 ± 4	78.7 ± 7.8	Resistance trained; at least 2 years; established 1.5x BM squat and 1.0x bench press 1-RM
Green et al. [66]	CHO = 36; PLA = 36	18/18	21.5 ± 1.6	72.8 ± 13.4	Resistance trained; at least 6 months; 1.3x & 0.8x BM bench press 1-RM
Jeffers et al. [167]	CHO = 9; WAT = 9	9/0	33.2 ± 7.4	76.7 ± 6.0	Endurance trained (cyclists/triathletes); none; unclear
Jensen et al. [165]	CHO = 12; PLA = 12	12/0	26.7 ± 6.7	78.2 ± 5.5	Endurance/team sport; none; unclear
Karayigit et al. [59]	CHO = 16; PLA = 16	0/16	20 ± 1	67 ± 4	Resistance trained; at least 1 year; able to bench press 1x BM
Karayigit et al. [57]	CHO = 27; PLA = 27	13/14	M = 24 ± 3 F = 21 ± 1	M = 84 ± 8 F = 68 ± 6	Resistance trained; at least 1 year; unclear
Karayigit et al. [170]	CHO = 15; PLA = 15	15/0	21.6 ± 1.3	83.3 ± 14.4	Resistance trained; at least 1 year; unclear
Karayigit et al. [58]	CHO = 16; PLA = 16	16/0	25 ± 3	86 ± 3	Resistance trained; at least 5 years; unclear
Khong et al. [169]	CHO = 10; WAT = 10	10/0	22 ± 1	65.3 ± 12.4	Recreationally trained; unclear; unclear
Krings et al. [62]	CHO = 17; PLA = 17	17/0	21 ± 1	83.5 ± 9.3	Resistance trained; at least 0.5 years; unclear
Painelli et al. [70]	CHO = 12; PLA = 12, CON = 12	12/0	24 ± 3	79 ± 8	Resistance trained; at least 1 year; unclear
Pereira et al. [63]	CHO = 29; PLA = 29	0/29	24 ± 4.5	60 ± 7.9	Resistance trained; at least 1 year; unclear
Valleser et al. [64]	CHO = 14; PLA = 14	14/0	20.1 ± 0.8	Unclear	Resistance trained; 1.4 ± 0.4 years; unclear
Yang et al. [145]	CHO = 20, WAT = 20	20/0	22.4 ± 3.7	76.4 ± 11	Resistance trained; unclear; unclear

M Male, *F* Female, *RT* Resistance Training, *1-RM* 1-repetition maximum, *CHO* Carbohydrate, *PLA* Placebo. Values are expressed as means ± standard deviations.

Table 4-2: Resistance training protocol characteristics of the studies included in the systematic review

Study (year)	Exercises	Exercise protocol (sets x repetitions x load, rest)	Outcomes
Bailey et al. [171]	Isometric knee extension	3 x 10 sec MVIC, 3 x 10 x 50% MVIC 1-min MVIC, 0.5-min 50% MVIC interset rest	MVIC, MEP (with/without TMS)
Bastos-Silva et al. [67]	Smith machine bench press, leg press	1 x failure x 80%1-RM per exercise	Repetitions completed per exercise, Total volume load per exercise
Bazzucchi et al. [72]	Isokinetic elbow flexion	3 x MVIC, 5 x 30 x maximal flexions, 3 x MVIC 1-min interset rest for maximal flexions	Total work, MVIC, RPE, RMS, MDF, MFCV
Black et al. [69]	Isometric knee extension	3 x 3 sec MVIC, 50% MVC to failure	MVIC, Voluntary contraction Twitch torque, motor-unit activation, rise time, half-relaxation time, rate of rise, rate of decline
Black et al. [166]	Isometric knee extension	20 or 80% MVC until fatigue, 3 x 3 sec MVC's pre-fatigue, immediately and 5-mins after fatigue	MVIC, VA, twitch torque, rate of torque rise and decline
Clarke et al. [71]	Bench press	1 x 1 x 100% 1-RM, 1 x AMRAP x 60% 1-RM, 3-min for 1-RM attempts, 1-min rest for AMRAP	1-RM, Repetitions completed Total volume load, HR, FA, RPE
Clarke et al. [65]	Isometric mid-thigh pull, bench press and back squat	1 x AMRAP @ 60% 1-RM, 5 mins interset rest	CMJ height, MTP peak force, Sprint time, Repetitions completed, RPE, FA, HR
Clarke et al. [144]	Bench press	1 x AMRAP @ 60% 1-RM	Repetitions completed, FA, RPE
Decimoni et al. [68]	Half squat, leg press, bench press, military press, seated row	3 x AMRAP @ 10-RM per exercise, 2 mins interset rest	Repetitions completed HR, RPE
Dunkin et al. [61]	Bench press	1-5 x 1 x 100% 1-RM, 3 mins interset rest 1 x AMRAP x 40% 1-RM, 1 min interset rest	1-RM, Repetitions completed Total volume load, HR, FA, RPE
Durkin et al. [60]	Bench press and back squat	6 x failure @ 40% 1-RM, 2 and 5 mins interset and between exercises, respectively	Total volume load Repetitions completed, Mood, FA
Green et al. [66]	Bench press	4 x 10 @ 65% 1-RM, 2 mins interset rest 1 x failure @ 60% 1-RM	Repetitions completed, RPE Pleasure/displeasure, BG, BL
Jeffers et al. [167]	Isometric knee flexion	3 x 1 @ maximal effort, 3-min interset	MVC, VA, MEP, Maximal M-wave Potentiated quadriceps twitch
Jensen et al. [165]	Isometric knee extension	3 x 1 @ MVC (5 secs), 60 secs interset rest, Hold contraction @ 50% MVC until fatigue, 3 x 5 @ MVC, 10 secs interset rest	Peak and average torque EMG root mean square EMG median frequency
Karayigit et al. [59]	Bench press	3-5 1-RM attempts, 1 x failure @ 40%1-RM, 3 mins interset rest, 2 mins between 1-RM and STF	1-RM, Repetitions completed HR, BG, RPE
Karayigit et al. [57]	Smith machine bench press, free weight back squat	3-5 1-RM attempts, 3 mins interset rest 3 x failure @40% 1-RM, 2 mins interset rest	1-RM, Repetitions completed Cognitive (response accuracy and time)

		2 mins between 1-RM and STFs	HR, BG, FA, RPE
Karayigit et al. [170]	Bench press	3-5 1-RM attempts, 3 x failure @ 40% 1-RM, 3 mins interset rest, 2 mins between 1-RM and STFs	1-RM, Repetitions completed HR, BG, BL, FA, RPE
Karayigit et al. [58]	Bench press	3 x failure @ 40 or 80% 1-RM, 3 mins interset rest	Repetitions completed, HR, FA, RPE, BG
Khong et al. [169]	Isometric knee extension	3 x 1 @ maximal effort, 2 mins interset rest 1 @ maximal effort for 90 secs	MVC Sustained MVC (90 secs)
Krings et al. [62]	Bench press, bent-over row, incline press, close-grip row, hammer curl, skull crushers, push-ups, pull-ups	2-3 x 10 @ 70%1-RM per exercise, 1 x failure @ 70% 1--RM or BM, 1.5 mins interset and inter-exercise rest	Repetitions completed to failure, total volume HR, FA, RPE
Painelli et al. [70]	Smith machine bench press	1-5 x 1-RM attempts, 3 mins interset rest 6 x failure x 70%1-RM, 2-min interset rest	1-RM, Repetitions completed BG, BL
Pereira et al. [63]	Squat, leg press, bench press, shoulder press, and row	3 x failure @ 10-RM load per exercise, 1 min interset rest	Repetitions completed HR, RPE
Valleser et al. [64]	Deadlift, squat, bench press, military press	3 x failure x 10-RM load per exercise, 2 mins interset rest	Total session volume RPE
Yang et al. [145]	Inertial Romanian deadlift	5 x 6 @ maximum inertial resistance, 3 mins interset rest	Concentric and eccentric peak power Average power, Average force, Total work

1-RM 1-repetition maximum, *CMJ* Counter Movement Jump, *RT* Resistance Training, *STF* set to failure, *MVC* Maximum Voluntary Contraction, *MVIC* Maximum Voluntary Isometric Contraction, *ES* electrostimulation, *RPE* Rating of Perceived Exertion, *HR* heart rate, *FA* felt arousal, *BG* blood glucose, *BL* blood lactate, *MDF* median frequency, *MFCV* mean fibre conduction velocity

Table 4-3: Nutrition protocol characteristics of the studies included in the systematic review

Study (year)	Pre-trial diet	Pre-trial fast (hours)	CHO MR protocol		Placebo/control description
			CHO MR concentration, bolus, length	Frequency and timing around training session	
Bailey et al. [171]	Unclear	4	MDX, MAL, and GLU, 6.4%, 25mL, 20 secs	1 MR mid-session (1 total)	PLA = AS non-caloric
Bastos-Silva et al. [67]	24-hr record of normal dietary habits	2	6.4% MDX, 25mL, 10 secs	1 MR immediately before each exercise (2 total)	PLA = non-caloric juice CON = no rinse
Bazzucchi et al. [72]	Standardised meal night prior	8	MDX: 6.4%, 25mL, 10 secs GLU: 7.1%, 25mL, 10 secs	1 MR immediately before each set, 1 MR after last set (6 total)	PLA = AS (saccharine + aspartame) non-caloric WAT = water only CON = no rinse
Black et al. [69]	Standardised pre-exercise meal (~50% CHO, 30% fat, 20% protein)	2	8% MDX, 25mL, 20 secs	1 MR mid-session (1 total)	PLA = AS (sucralose) non-caloric
Black et al. [166]	Standardised pre-exercise meal (~50% CHO, 30% fat, 20% protein) and 24h-hr record	2	8% MDX, 25mL, 20 secs	1 MR mid-session (1 total)	PLA = AS (sucralose) non-caloric
Clarke et al. [71]	24-hr record of normal dietary habits	unclear	6% MDX, 25mL, 10 secs	1 MR immediately before exercise (1 total)	PLA = AS non-caloric CON = no rinse
Clarke et al. [65]	24-hr record of normal dietary habits	11	6% MDX, 25mL, 10 secs	1 MR before each exercise (5 total)	PLA = Orange flavoured water CON = no rinse
Clarke et al. [144]	7-day dietary record	4	6% MDX, 25 mL, 10 secs	1 MR prior to STF (1 total)	PLA = non-caloric orange squash CON = no rinse
Decimoni et al. [68]	Standardised breakfast	1	6% MDX, 100mL, 10 secs	1 MR before session and mid-session (2 total)	PLA = AS (aspartame and saccharin) non-caloric
Dunkin et al. [61]	24-hr record of normal dietary habits	1.5	18% MDX, 25mL, 10 secs	1 MR before 1-RM, 1 MR before RTF (2 total)	PLA = AS non-caloric CON = no rinse

Durkin et al. [60]	Standardised meal the morning of (223 kcal, 14.4g CHO), and evening before (408 kcal, 14.4g CHO) testing	2	6.4% MDX, 25mL, 10 secs	1 MR before each STF (12 total)	PLA = Electrolyte and AS (saccharine) non-caloric
Green et al. [66]	Normal dietary habits, not controlled	12	6.4% MDX, 25mL, 10 secs	1 MR 30 secs before each set (5 total)	PLA = AS (Powerade Zero) non-caloric
Jeffers et al. [167]	24-hr record of normal dietary habits, CHO rich meal the preceding evening	4	6.4% MDX, 25 mL, 5 secs	1 MR at various timepoints in the hour before post-testing (7 total)	WAT = water only
Jensen et al. [165]	24-hr record of normal dietary habits	Overnight	8% MDX, unclear bolus size, 10 secs	1 MR after fatiguing protocol (1 total)	PLA = AS (sucralose) non-caloric
Karayigit et al. [59]	24-hr record of normal dietary habits	10	6%, 12%, or 18% MDX, 25 mL, 10 secs	1 MR before each 1-RM attempt and STF (4-6 total)	PLA = AS (sucralose) non-caloric
Karayigit et al. [57]	24-hr record of normal dietary habits	12	6% MDX, 25mL, 10 secs	8 MR before warm-up, 1 MR before each 1-RM attempt, 3 MR before each set to failure (26 – 30 total)	PLA = AS (sucralose) non-caloric
Karayigit et al. [170]	24-hr record of normal dietary habits	10	6% MDX, 25mL, 10 secs	1 MR before each 1-RM attempt, 2 MR before 3 STFs (7-10 total)	PLA = AS (sucralose) non-caloric
Karayigit et al. [58]	24-hr record of normal dietary habits	12	6% MDX, 25 mL, 10 secs	3 MR before each STF (9 total)	PLA = AS (sucralose) non-caloric
Khong et al. [169]	Unclear	Overnight	6% GLU, 25 mL, 5 secs	4 MR at 10-min intervals, last MR immediately prior to post-test MVC (5 total)	WAT = water only
Krings et al. [62]	24-hr record of normal dietary habits	10	6% 2:1 GLU:FRU, 25 mL, 10 secs	1 MR after warm-up and before each STF (9 total)	PLA = AS (unclear) non-caloric
Painelli et al. [70]	Standardised prior evening meal	8	6.4% DEX, 25 mL, 10-15 secs	1 MR before each 1-RM attempt and 1 MR before 6 STFs (7 – 11 total)	PLA = AS non-caloric CON = no rinse
Pereira et al. [63]	Standardised breakfast	1	6% MDX, 100 mL, 10 secs	1 MR before the training session (1 total)	PLA = unclear
Valleser et al. [64]	Unclear	3	6% MDX, 100 mL, 10 secs	1 MR at session start, 1 MR midsession (2 total)	PLA = AS (unclear) non-caloric WAT = water only
Yang et al. [145]	24-hr photographic record	3	6.4% MDX; 25 mL; 20 secs	1 MR at session start (1 total)	WAT = water only

AS Artificially sweetened, *CHO* carbohydrate, *CON* control, *MDX* maltodextrin, *MAL* maltose, *GLU* glucose, *DEX* dextrose, *FRU* fructose, *MR* mouth rinse, *PLA* placebo, *STF* set to failure

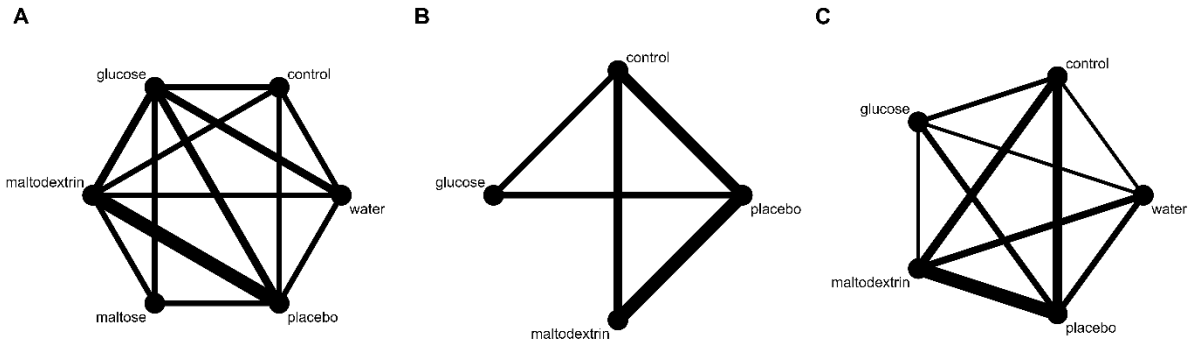
Four primary muscle strength or endurance outcomes were assessed by more than one study: pre- to post-exercise change in peak force (k = 7), maximum dynamic strength (k = 6), total session volume (k = 16), and total session work (k = 2). Peak force was measured by isometric dynamometry pre- and post-exercise. Maximum dynamic strength involved traditional RT exercises (e.g., back squat, bench press) performed for a 1-RM. Total session volume involved traditional RT exercises with a component of repetition failure. Total session work involved a fixed set and repetition scheme, without a component of repetition failure, which was performed in an isokinetic dynamometer in one study [72] and on a flywheel device [145]. Other applied performance outcomes included CMJ height, sprint time, and isometric mid-thigh pull [65]. Other neuromuscular outcomes (comprising electromyography [EMG], peripheral contractile properties, and central activation) included maximum evoked potential [167, 171], median frequency [72, 168], root mean square [72, 168], and mean fibre conduction velocity [72], maximal M-wave [167], potentiated twitch [167], voluntary activation [166, 167] twitch torque [69, 166], motor-unit activation [69], rise time [69], half-relaxation time [69], rate of rise and decline [69, 166].

Five secondary outcomes were assessed by more than one study: RPE (k = 14), HR (k = 10), BG (k = 6), BL (k = 3), and FA (k = 8). One study [63] did not report HR in the associated manuscript but did in the raw data, which was used in meta-analysis. One study [60] had to be omitted from the meta-analysis of FA as the data were not presented in the associated manuscript nor were raw data available. Other secondary outcomes included mood [60], pleasure/displeasure [66], and cognitive tasks (i.e., response time and accuracy) [57].

4.5.3 Study Outcomes

Figure 4-2 shows the network plots for the peak force, maximum dynamic strength, and total session volume.

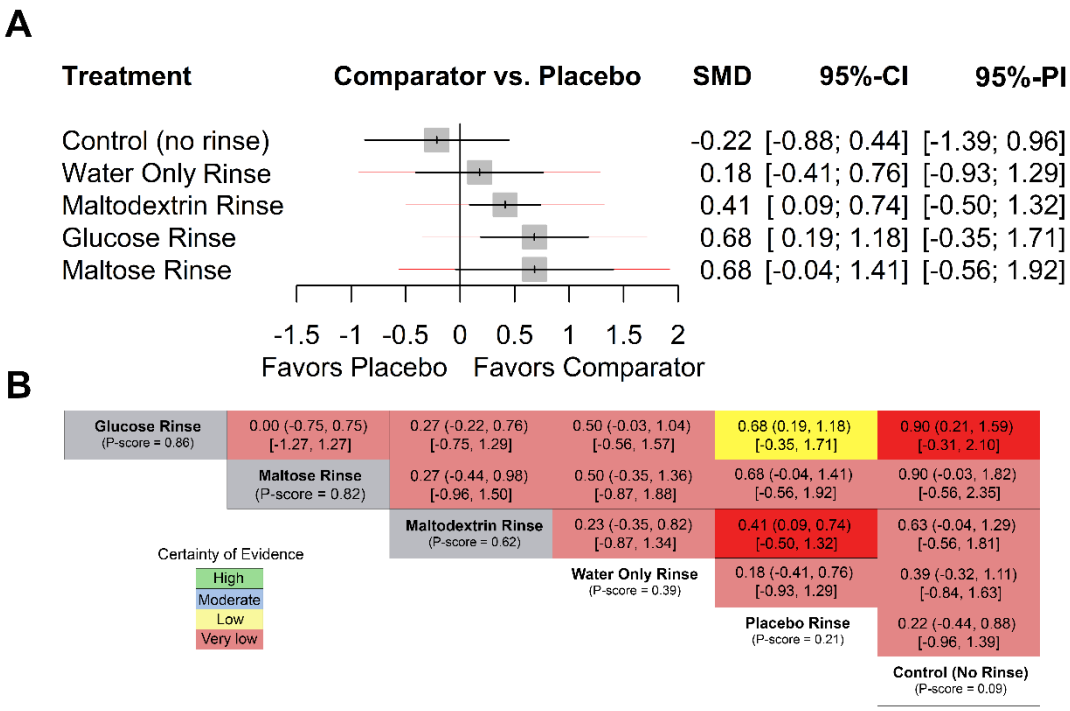
Figure 4-2: Network plots for the (A) peak force, (B) maximum dynamic strength, and (C) total session volume outcomes.



4.5.3.1 Peak Force

Treatments were ranked in order as (1) glucose (P-score = 0.86), (2) maltose (P-score = 0.82), (3) maltodextrin (P-score = 0.62), (4) water rinse (P-score = 0.39), (5) placebo (P-score = 0.21), and (6) no rinse control (P-score = 0.09). The pooled main network meta-analysis revealed a statistically significant effect favouring CMR relative to placebo for glucose (g = 0.68; 95% CI [0.19, 1.18]; 95% PI [-0.35, 1.71]; p = 0.006; *very low certainty*) and maltodextrin (g = 0.41; 95% CI [0.08, 0.74]; 95% PI [-0.50, 1.32]; p = 0.01; *very low certainty*). Maltose was revealed to have a non-statistically significant effect relative to placebo (g = 0.68; 95% CI [-0.04, 1.41]; 95% PI [-0.56, 1.92]; p = 0.06; *very low certainty*). There were no statistical differences between placebo and a water rinse (g = 0.18; 95% CI [-0.41, 0.76]; 95% PI [-1.29, 0.93]; p = 0.55; *very low certainty*) and no rinse control (g = -0.22; 95% CI [-0.88, 0.44]; 95% PI [-1.39, 0.96]; p = 0.52; *very low certainty*). A forest plot for placebo versus comparator, and a league table presenting all model contrasts, is presented in Figure 4-3.

Figure 4-3: Forest plot for comparator relative to placebo (A) and league table presenting the main random effect model contrasts (B) for the pre- to post-exercise peak force outcome. In the forest plot (A), the reference comparator is placebo, grey boxes are the model estimate, horizontal black lines are the 95% CIs, and the red lines are the 95% prediction intervals. In the league table (B), comparators are ranked diagonally by P-score under a random effect model, and results are presented as Hedge's *g* (95% CI) [95% prediction interval]. Negative values favour the column-defining treatment, while positive values favour the row-defining treatment. Grey boxes represent an active CHO comparator (e.g., maltodextrin, glucose, maltose); white boxes represent a non-active comparator (i.e., placebo, water only rinse, or no rinse control). Results are colour coded green, blue, yellow, and red, to represent high, moderate, low, or very low certainty of evidence for the corresponding contrast. Darker shades of green, blue, yellow, and red represent statistical significance favouring the column-defining comparator.



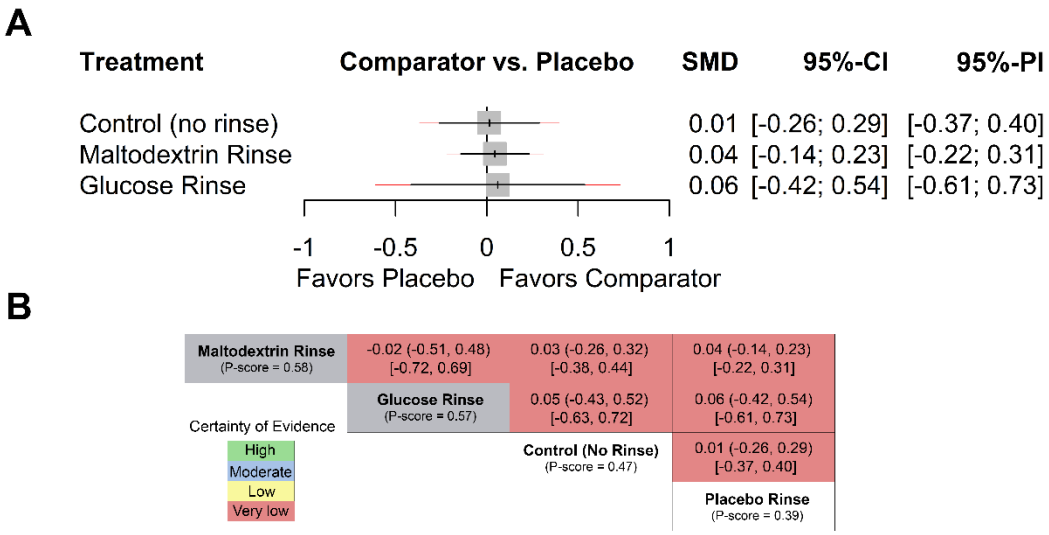
Across all contrasts in the network, meta-regression revealed no statistically significant moderating effects for fast duration, number of mouth rinses completed, or upper versus lower body exercise (all $p > 0.05$).

The Egger's test (p = 0.01) suggested publication bias. Visual inspection of the funnel plot (Appendix B Ch. 4 Supplementary File II) didn't suggest asymmetry but did suggest one potential influential contrast. Relative to the main analysis, removal of the study containing the potentially influential contrast decreased the effect size for maltodextrin (g = 0.23; 95% CI [0.01, 0.55]; p = 0.04) (Appendix B Ch. 4 Supplementary File II). Regarding statistics for heterogeneity, τ^2 was 0.09 and I^2 was 59.3% (95% CI: 11.1, 81.3%). The global test of the full design-by-treatment interaction random-effects model indicated statistically significant inconsistency across the network (Q = 22.02, p = 0.0002). Node-splitting analysis revealed one statistically significant disagreement between direct and indirect evidence under the random-effects model (maltodextrin vs maltose, p = 0.029). Design-specific inconsistency diagnostics did not suggest that detaching the glucose vs water (Q = 21.64, p < 0.0001) and maltodextrin vs placebo (Q = 9.66, p = 0.02) designs meaningfully mitigated inconsistency. Results were robust to sensitivity analyses (Bayesian lens, exclusion of high-risk-of-bias studies, and removal or exploration of contrasts contributing to heterogeneity or incoherence). Under the Bayesian framework, maltose achieved the highest SUCRA ranking, followed by glucose, reversing the order obtained under the frequentist P-score approach. Full sensitivity analysis results are provided in Appendix B Ch. 4 Supplementary File II.

4.5.3.2 Maximum dynamic strength

Treatments were ranked in order as (1) maltodextrin (P-score = 0.58), (2) glucose (P-score = 0.57), (3) control (P-score = 0.46), and (4) placebo (P-score = 0.39). The pooled main network meta-analysis revealed non-statistically significant effect sizes favouring CMR relative to placebo for maltodextrin (g = 0.04; 95% CI [-0.14, 0.23]; 95% PI [-0.22, 0.31]; p = 0.64; *very low certainty*) and glucose (g = 0.06; 95% CI [-0.42, 0.54]; 95% PI [-0.61, 0.73]; p = 0.80; *very low certainty*). There were no statistical differences between placebo and a no rinse control (g = 0.01; 95% CI [-0.26, 0.29]; 95% PI [-0.37, 0.40]; p = 0.92; *very low certainty*). A forest plot for placebo versus comparator, and a league table presenting all model contrasts, is presented in Figure 4-4.

Figure 4-4: Forest plot for comparator relative to placebo (A) and league table presenting the main random effect model contrasts (B) for the maximum dynamic strength outcome. Description for how to interpret is in Figure 4-3.



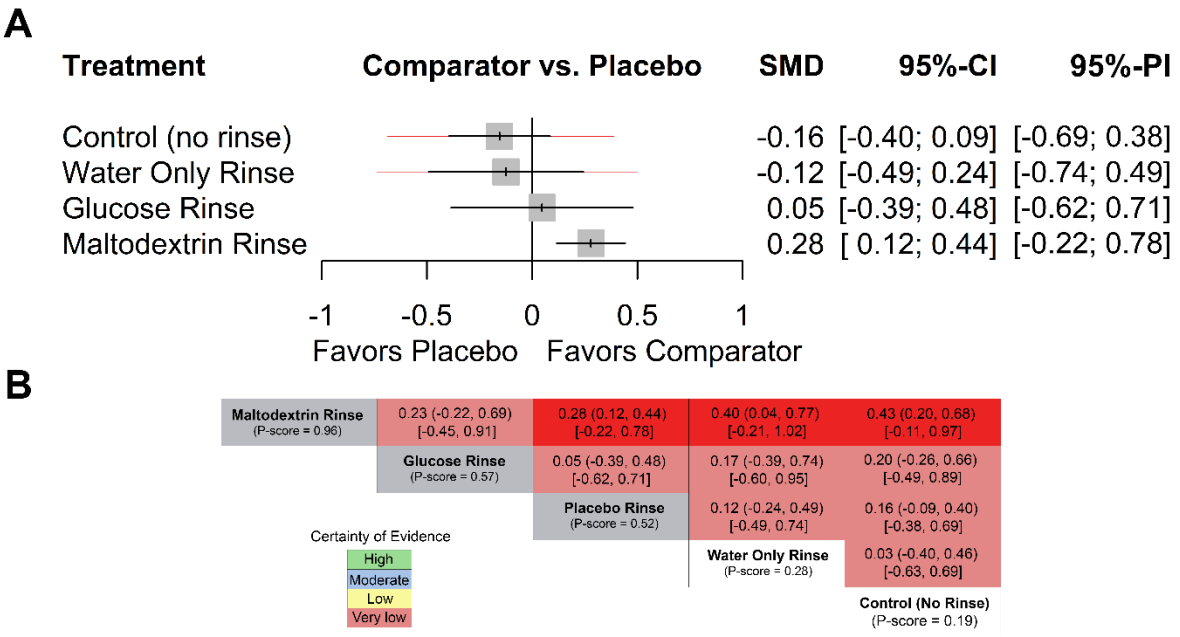
Network meta-regression was not conducted for the maximum dynamic strength outcome due to similarity in methods between studies.

Visual inspection of the funnel plot and the Egger's test ($p = 0.17$) did not indicate publication bias (Appendix B Ch. 4 Supplementary File II). Regarding heterogeneity, τ^2 was 0 and I^2 was 0% (95% CI: 0, 70.8%). The global test of the full design-by-treatment interaction random-effects model indicated no evidence of inconsistency across the network ($Q = 0.27$, $p = 0.87$). Node-splitting analysis revealed no statistically significant disagreement between direct and indirect evidence under the random-effects model ($p > 0.05$). Under a common-effects framework, design-specific inconsistency diagnostics indicated that no single design was an influential contributor to network inconsistency ($p > 0.05$). Results were robust to sensitivity analyses (Bayesian lens, exclusion of high-risk-of-bias studies, and removal or exploration of contrasts contributing to heterogeneity or incoherence). Full sensitivity analysis results are presented in Appendix B Ch. 4 Supplementary File II.

4.5.3.3 Total session volume

Treatments were ranked in order as (1) maltodextrin (P-score = 0.96), (2) glucose (P-score = 0.57), (3) placebo (P-score = 0.52), (4) water (P-score = 0.28), and (5) control (P-score = 0.19). The pooled main network meta-analysis revealed a statistically significant effect favouring CMR relative to placebo for maltodextrin (g = 0.28; 95% CI [0.12, 0.44]; 95% PI [-0.22, 0.78]; p = 0.0008; *very low certainty*) but not glucose (g = 0.05; 95% CI [-0.39, 0.48]; 95% PI [-0.62, 0.71]; p = 0.83; *very low certainty*). There were no statistical differences between placebo and water only mouth rinse (g = -0.12; 95% CI [-0.49, 0.24]; 95% PI [-0.74, 0.49]; p = 0.51; *very low certainty*) or a no rinse control (g = -0.16; 95% CI [-0.40, 0.09]; 95% PI [-0.69, 0.38]; p = 0.21; *very low certainty*). A forest plot for placebo versus comparator, and a league table presenting all model contrasts, is presented in Figure 4-5.

Figure 4-5: Forest plot for comparator relative to placebo (A) and league table presenting the main random effect model contrasts (B) for the total session volume outcome. Description for how to interpret is in Figure 4-3.



For the maltodextrin versus placebo contrast, the fast duration (β = -0.04; 95% CI: [-0.08, -0.01]; p = 0.01), the total number of sets (β = 0.04; 95% CI: [0.02, 0.07]; p = 0.001), upper relative to lower body exercise (β = -0.42; 95% CI: [-0.71, -0.13]; p = 0.005), and training intensity (β = 0.01; 95%

CI: [0.00, 0.02]; p = 0.01) were statistically significant moderators of the SMD for total session volume. All other contrasts for the tested moderators (i.e., fast duration, total sets completed, intensity, number of CMRs performed, upper versus lower exercise) were not statistically significant (p > 0.05).

Visual inspection of the funnel plot and the Egger's test (p = 0.37) did not indicate publication bias (Appendix B Ch. 4 Supplementary File II). Regarding heterogeneity, τ^2 was 0.05 and I^2 was 47.9% (95% CI: 13.4, 68.6%). The global test of the full design-by-treatment interaction random-effects model indicated no evidence of inconsistency across the network (Q = 0.99, p = 0.91). Node-splitting analysis revealed no statistically significant disagreement between direct and indirect evidence under the random-effects model (p > 0.05). Under a common-effects framework, design-specific inconsistency diagnostics suggested that studies including the maltodextrin vs placebo comparison (Q = 24.14, p = 0.0005) were influential contributors to network inconsistency. Results were robust to sensitivity analyses (Bayesian lens, exclusion of high-risk-of-bias studies, and removal or exploration of contrasts contributing to heterogeneity or incoherence). Full sensitivity analysis results are presented in Appendix B Ch. 4 Supplementary File II.

4.5.3.4 Secondary outcomes

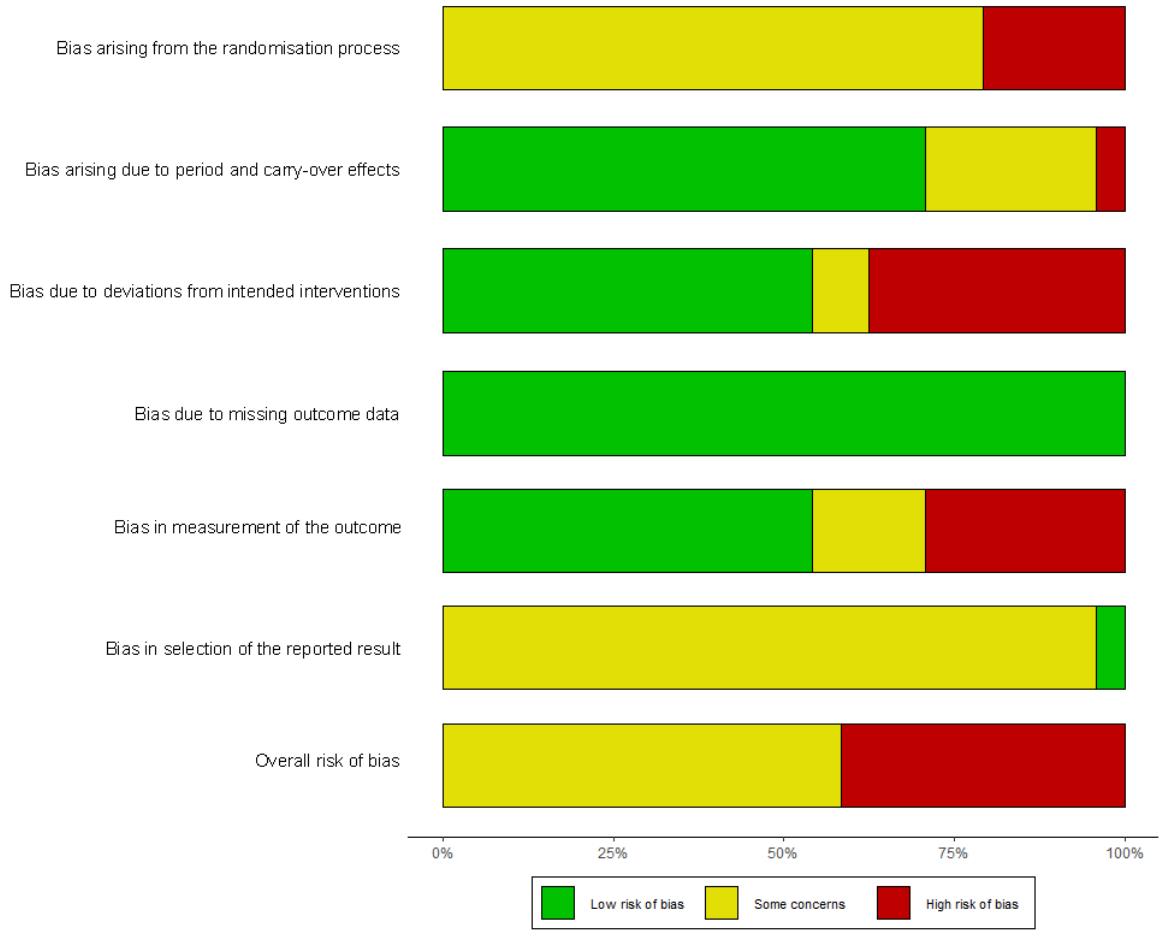
There were no statistically significant differences among all comparators relative to placebo for all the tested contrasts in the RPE, BL and BG, HR, and FA outcomes. The full results for all secondary outcomes are reported in Appendix B Ch. 4 Supplementary File II.

4.5.4 Risk of bias

Regarding bias arising from the randomisation process, most studies reported that a non-affiliated researcher coded the order but there is otherwise no information about how allocation was concealed or how randomisation was conducted. Of those receiving high risk, two studies [60, 170] were single blind, one study stated a double-blind design but that an investigator prepared the mouth rinse [57], one study [64] stated double-blind with no information on mouth rinse preparation or the involvement of a third party, and one study did not mention blinding [169] which led to judgement calls

that allocation was not concealed. Regarding bias arising from period or carry-over effects, most studies (k = 17) reported a wash-out period of 2-7 days, which was deemed reasonable given the exercise protocol and nutritional standardisation, and were rated low risk. Six studies were rated some concerns of which two were due to counterbalancing being impossible [71, 171], two where counterbalancing was not mentioned [64, 145], and two studies provided no information about a wash-out period [60, 63]. One study was rated high risk due to high volumes of RT being completed with a short wash-out period, which would likely be insufficient for the dissipation of fatigue from the previous period [57]. Regarding bias due to deviations from the intended intervention. Nine studies were rated high risk due to it being likely that outcome assessors were also responsible for allocation and/or mouth rinse preparation or participants being aware of the intervention. Two were rated some concerns due to concerns about how allocation was handled but took other steps to try and mitigate the issue (e.g., no encouragement from assessors) [60, 167]. The remaining 13 studies were rated low risk of bias for this domain. Regarding bias due to missing outcome data, all studies were rated low risk of bias. Regarding bias in the measurement of the outcome, 13 studies were rated low risk of bias and four were rated some concerns. Seven studies were rated high risk due to concerns about blinding of outcome assessors or insufficient wash-out period. Regarding bias in selection of the reported result, one study [145] was pre-registered and was rated low risk, the remaining 23 studies were not pre-registered and were rated some concerns. No studies were rated low risk overall, 14 were rated some concerns, and 10 were rated high risk. The final decision-making sheet for risk of bias is available on the OSF repository. The overall summary risk of bias is presented in Figure 4-6. Contrast-level visualisation of risk of bias for the meta-analysed primary outcomes is available in Appendix B Ch. 4 Supplementary File II.

Figure 4-6: Overall risk of bias assessment.



4.6 Discussion

The aim of this systematic review with network meta-analysis was to simultaneously model multiple active CMR (i.e., different types of CHO) and non-active placebo/control (i.e., taste matched placebo, water only rinse, no rinse control) conditions simultaneously to explore the effects of CMR on indices of muscle strength and endurance. Three performance outcomes were reported by enough studies to enable meta-analysis: pre- to post-exercise change in peak isometric force, maximum dynamic strength, and total session volume. One outcome – total session work – was reported by two studies and was qualitatively synthesised. The meta-analysis findings broadly suggest that CMR relative to placebo (a) improves pre- to post-exercise peak force, (b) does not enhance maximal dynamic strength, (c) improves total session volume.

4.6.1 Peak force

The main random-effects network meta-analysis revealed, with very low certainty of evidence, moderate effects of CMR with glucose (g = 0.68, p = 0.002) and small effect of CMR with maltodextrin (g = 0.41, p = 0.01) on peak force, relative to placebo. CMR with maltose had a non-statistically significant, moderate effect (g = 0.68, p = 0.06) but with substantial uncertainty in the estimate (95% CI [-0.04, 1.40]) and a very low certainty of evidence. Since maltose was investigated by only one study with 55% direct evidence, additional research is needed to improve the estimate certainty. All contrasts included in the network were downgraded to a very low certainty of evidence due to risk of bias and at least one of imprecision, heterogeneity, or incoherence. Overall, the results indicate that with very low certainty of evidence, CMR with glucose and maltodextrin can attenuate peak force declines after exercise, relative to a placebo.

These findings suggest that CMR may influence exercise performance by attenuating exercise-induced neuromuscular fatigue. However, there are additional caveats in addition to the low certainty of evidence. The studies included in this review examined a range of EMG, peripheral contractile, and central activation–related outcomes. At the peripheral contractile properties, potentiated twitch [167], twitch torque [69, 166], rise time [69], half-relaxation time [69], and rate of rise and decline [69, 166] were all similar for a maltodextrin MR relative to placebo. No differences were reported between central activation-related outcomes, including voluntary activation [166, 167] and motor unit activation [69]. Similarly, EMG-related outcomes of root mean square [72, 168] and median frequency [72, 168] were not improved with CMR relative to placebo. One study [167] also reported no improvement in root mean square values, but CMR with maltodextrin in another improved maximum evoked potential more than a placebo and CMR with glucose [171]. Evidence from one study indicated that mean fibre conduction velocity was improved with a CMR containing glucose, but not maltodextrin, compared with water and placebo [72]. Additionally, one study found a smaller decrease in maximal M-wave amplitude following endurance exercise with maltodextrin mouth rinse relative to placebo [167]. Overall, EMG measures of root mean square and maximum evoked potential, and mean fibre conduction velocity offer the only potential mechanistic explanations so far, but these were limited to

one or two studies which sometimes contradicted each other. There may be small differences in these outcomes that individual studies were not powered to detect, and future research on mechanistic outcomes is warranted to enable future quantitative synthesis.

Statistical inconsistency was detected in the network for peak force. At the network level, the design-by-treatment interaction model indicated statistically significant between-design inconsistency ($Q = 22.02$, $p = 0.0002$). At the design level, design-specific decomposition revealed that detaching the placebo–maltodextrin design attenuated but did not eliminate the inconsistency signal (p-value increased from 0.0002 to 0.02), while detaching the glucose–water design produced negligible change ($p < 0.0001$). Node splitting identified statistically significant disagreement between direct and indirect evidence for the maltodextrin versus maltose comparison ($p = 0.03$), where direct evidence from a single study favoured maltodextrin ($g = 0.21$) but indirect evidence strongly favoured maltose ($g = -1.59$). Modest, but not statistically significant, inconsistency was observed for the glucose versus maltodextrin comparison ($p = 0.10$), suggesting that CHO versus CHO contrasts may be susceptible to network inconsistency. Given that CHO versus CHO comparisons were informed by limited direct evidence ($k = 1 - 2$), future studies comparing different CMR could help resolve this network inconsistency and clarify the relative efficacy of specific CHO types. Overall, these findings indicate that inconsistency was distributed across the network rather than concentrated in specific contrasts, suggesting modest but broad network incoherence. This warrants caution when interpreting the P-score rankings and model estimates that are closely ranked. Nonetheless, there are practically relevant statistical differences between CMR and the non-active comparators, which cautiously suggests CMR improves peak force from pre- to post-exercise.

4.6.2 Maximum dynamic strength

The random-effects network meta-analysis ranked the four treatments (maltodextrin, glucose, placebo, and no-rinse control) similarly (P-scores ranging from 0.39–0.58). Compared with placebo, the estimated SMDs were glucose ($g = 0.06$; $p = 0.80$), maltodextrin ($g = 0.04$; $p = 0.64$), and no-rinse control ($g = 0.01$; $p = 0.92$). These findings suggest that, with a very low certainty of evidence, CMR

does not provide an ergogenic benefit for maximal dynamic strength. The network was comparably smaller for this outcome, comprising six studies and maltodextrin, glucose, placebo, and control comparators. Future research with other sources of CHO (e.g., maltose) and a water-only rinse could improve inferences. For all comparisons, the 95% CIs and PIs spanned small to large effects, favouring either placebo or the comparator. These intervals widened further when high risk of bias studies were removed in the sensitivity analysis. Consistent with this, Bayesian sensitivity analyses yielded posterior distributions with credible intervals ranging from small to moderate effects in either direction. Indeed, all contrasts in the maximum dynamic strength network were downgraded twice due to imprecision in the effect estimate, contributing to the very low certainty of evidence overall for this outcome. Thus, while the current findings indicate no statistically significant effect of CMR on maximum dynamic strength, additional studies could improve the precision of the pooled effect estimates and improve the certainty of evidence.

Potential moderators of CMR on maximum dynamic strength remain unexplored due to similar study methods. For instance, of the six studies included in the present review, all assessed bench press 1-RM as the strength outcome, and only one study also included squat 1-RM. In that study [57], the placebo performed nominally better than maltodextrin, but conclusions are limited given that the finding came from a single study. All six studies also used resistance-trained individuals. It's conceivable that the null findings in the literature so far reflect resistance-trained individuals' greater motor unit activation capability [172] and that untrained individuals could benefit from the purported additional neural drive of CMR, although the specific mechanism remains unclear. Lastly, one study used a female participant cohort, another a mixed sex cohort, and the other four were male only. In the mixed sex cohort, bench press and squat 1-RM were similarly unaffected by CMR in both sexes. Nonetheless, the current evidence exploring potential sex differences is limited to one study and future research on mixed sex or female-only cohorts is needed. Taken together, the balance of evidence to date suggests that CMR does not affect dynamic maximal strength performance.

4.6.3 Total session volume

The main random-effects network meta-analysis revealed, with very low certainty of evidence, a statistically significant, small effect of CMR with maltodextrin (P-score = 0.96, g = 0.28, p = 0.0008) on total session volume, relative to placebo. Several moderators were associated with variation in the effect of maltodextrin CMR. Specifically, the ergogenic effect increased as fast duration decreased (β = -0.04, p = 0.01), as the number of sets increased (β = 0.04, p = 0.001), and as training intensity increased (β = 0.01, p = 0.01). In addition, maltodextrin CMR produced larger effects during lower- compared with upper-body exercise (β = 0.42, p = 0.005). The ranked P-scores reflect what would be predicted by theory (CMR > PLA > water only > no rinse control), but several issues remain unresolved. CMR with glucose had a statistically non-significant effect relative to placebo (g = 0.05, p = 0.83). It's unclear why maltodextrin would have an ergogenic effect on volume performance, but glucose would not. It is proposed that CMR activates the relevant regions of the brain involved in motivation and motor control due to the presence of the CHO, as opposed to sweetness [39]. Thus, it would be anticipated that CMRs of different types would have comparable ergogenic effects on exercise performance, as reported by Bazzucchi et al. [72] comparing glucose and maltodextrin CMR – perceived as sweet and non-sweet, respectively – on total session work during five sets of 30 maximal isokinetic elbow flexions. Nonetheless, the direct comparison between glucose and maltodextrin favoured maltodextrin (g = -0.23) but was not statistically significant (95% CI [-0.69, 0.22], p = 0.83). CMR with glucose was examined in only two studies, which may have resulted in insufficient statistical power. The wide PI for glucose relative to placebo (95% PI [-0.62, 0.71]) spanning from moderate effects favouring placebo to moderate effects favouring glucose underscores the heterogeneity of the estimate and highlights the need for additional research. Wide spanning CIs and PIs were consistent across all contrasts in the network, which resulted in double downgrades for imprecision or heterogeneity, resulting in very low certainty across the board. Overall, current evidence indicates CMR with maltodextrin produces a small ergogenic effect on total session volume, which is larger with shorter fast durations, a greater number of sets performed, higher %1-RM loads, and during lower-body exercise.

CHO availability may influence the erogenicity of CMR on session volume performance. Clarke et al. [144] reported an inverse association between habitual dietary CHO intake and repetition performance in a single set of bench press performed at 60% 1-RM. In addition, Durkin et al. [60] reported an ergogenic effect of CMR when participants restricted EI after performing a glycogen-depleting exercise bout the night before completing six sets of bench press and squat to failure at 40% 1-RM. Thus, limiting dietary CHO may influence the erogenicity of CMR. While most studies in the current review standardised participant diets before testing, there was not enough information to meta-analyse the effect of dietary CHO intake on session volume performance with CMR. In partial disagreement with these findings, the fast duration before training was a statistically significant moderator of the effect of a CMR with maltodextrin relative to placebo on session volume performance, but with a negative slope ($\beta = -0.04$, $p = 0.01$) and most studies that completed a higher range of sets (12 – 15 total) also had a shorter fast duration (1 – 3 hours). The overnight fast depletes liver – but not skeletal muscle – glycogen [30, 31]. While CHO intake was negatively associated with an ergogenic effect of CMR on repetition performance in the study by Clarke et al. [144], it is possible that the muscle glycogen stores of these participants were not depleted (as no exercise bout was completed before the testing session) but may have differed in the degree of skeletal muscle repletion due to the differences in dietary CHO intake. In the study by Durkin et al. [60] an exercise protocol known to deplete muscle glycogen was used before the RT session, which – possibly in combination with a larger set volume being completed compared to Clarke et al. [144] – could explain the ergogenic effect of CMR on repetition performance in that study. Future work should manipulate dietary CHO and levels of skeletal muscle glycogen, while assessing glycogen levels (e.g., via biopsy or MRI techniques), to fully resolve the role of glycogen stores as a possible moderator of the ergogenic effect of CMR on total session volume performance.

4.6.4 Total session work

We elected not to meta-analyse total session work as only two studies [72, 145] assessed this outcome and one was rated high risk of bias, which could lead to misleading conclusions. Thus, a qualitative discussion with future research directions is better suited. Bazzucchi et al. [72] reported that

CMR with maltodextrin or glucose improved total session work during five sets of 30 maximal isokinetic elbow flexions relative to a no rinse control. Yang et al. [145] reported greater total work with a maltodextrin MR, relative to a water-only control, during five sets of 6 isoinertial Romanian deadlift repetitions. Due to major concerns regarding investigator and participant blinding (the principal investigator prepared a water-only rinse, which the participant conceivably could distinguish), this study was rated as high risk of bias. These two protocols differ substantially in the exercise modality (isoinertial v isokinetic), upper versus lower exercise selection, and repetition and set schemes. However, these studies [72, 145] establish preliminary evidence that total work performed within a fixed repetition and set scheme, which does not involve exercise failure, can be improved with CMR. Future research varying the exercise protocol (sets, repetitions, exercise selection), participants (male and female), and aspects of CMR (e.g., type, dose, timing) is needed to quantitatively synthesise this outcome.

4.6.5 Secondary outcomes

For CMR relative to placebo, there were no statistically significant differences for any of the secondary metabolic (BG and BL), HR, or perceptual (RPE, FA) outcomes. FA was included as a secondary outcome given the proposed central mechanisms of CMR [39]. However, no statistically significant effects were observed, suggesting any ergogenic benefit of CMR is unlikely to be mediated by changes in conscious affective arousal. Instead, performance improvements may reflect alterations in subconscious processes such as central motor drive or the neural perception of neuromuscular fatigue [40]. Similarly, null findings for BG and BL are consistent with a central nervous system mechanism [39]. However, the small number of studies contributing to these outcomes (BG: $k = 6$; BL: $k = 3$) limits statistical power to detect modest effects, warranting caution. It is possible that CMR may influence post-exercise lactate in contexts where an ergogenic effect on total session volume is observed due to more volume performed. Although BL is unlikely to be a central cause of fatigue [111], it remains a useful correlated marker of neuromuscular and metabolic fatigue [112, 113]. Overall, while these secondary outcome analyses were null, they support the notion that ergogenic benefits of CMR are central in nature.

4.6.6 Limitations and considerations

There are several limitations and considerations arising from the current systematic review with network meta-analysis. First, all the meta-analysed primary performance outcomes were graded as providing very low certainty of evidence due to varying combinations of risk of bias, imprecision, heterogeneity, and incoherence. None of the included studies were rated as a low risk of bias overall, with 14 studies rated some concerns and 10 rated as high risk. There were several trends in the risk of bias ratings that offer insight into how future research could improve inferences. It is important to distinguish between allocation concealment and blinding in the reported methods. Allocation concealment occurs before or at the point of randomisation – during participant assignment to groups – and prevents selection bias (i.e., researchers or participants influencing who gets which treatment or sequence). Blinding occurs after randomisation and during intervention delivery, outcome assessment, and data analysis. Most included studies were stated as double-blind but lacked detail on exactly who was blinded to the intervention (e.g., participants, data collectors/outcome assessors, data analysts, and manuscript writers). The included studies also often did not provide information on how allocation concealment and blinding of outcome assessors were achieved (e.g., third-party or independent researcher-generated and assigned sequences, prepared mouth rinse solutions). For example, using sealed, opaque envelopes that are opened and irreversibly assigned to a participant at study sign-up by a third party or researcher not affiliated with data collection or outcome assessment could form a good reason to award low risk of bias for the domains concerning allocation concealment and blinding. Sufficient wash-out periods should be provided, especially where higher volumes of RT are completed. Lastly, only one included study was pre-registered. We encourage future research to pre-register their projects with clear primary outcomes and analysis plans.

For the pre- to post-exercise peak force and maximum dynamic strength outcomes, the included studies generally overlapped in design, limiting sub-group or meta-regression analysis to identify potential moderators of the effect. For instance, all included studies assessing peak force used untrained male or mixed sex participants. For maximum dynamic strength, nearly all studies used trained males performing upper-body exercise with a longer fast duration. These homogenous methods limit

generalisation to participant and exercise characteristics outside of what was studied. Future research with varying methods could elucidate potential moderators for these outcomes.

4.7 Conclusions

With very low certainty of evidence, CMR can mitigate exercise-induced neuromuscular fatigue, as measured by change in pre- to post-exercise isometric peak force relative to placebo. Also, with low certainty of evidence, CMR relative to placebo does not improve maximum dynamic strength but may be ergogenic for total session volume performed to failure. The ergogenic effect of CMR on total session volume may be enhanced where the pre-exercise fast duration is shorter, more sets are completed, training intensity is higher, and for lower body exercise. For CMR relative to placebo, there were no statistically significant differences for any of the secondary metabolic (BG and BL), HR, or perceptual (RPE, FA) outcomes. Varying combinations of risk of bias with imprecision, heterogeneity, and/or incoherence contributed to the downgraded very low certainty of evidence across the three primary performance outcomes. Future research is needed to provide a mechanistic explanation for why CMR could assist in mitigating neuromuscular fatigue, contribute evidence that is at a low risk of bias, explore potential moderating variables (e.g., exercise selection, biological sex), and improve the precision of estimates across the three performance outcomes quantitatively synthesised.

Chapter 5: The general nutrition practices of competitive powerlifters vary by competitive calibre and sex, weight, and age class

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5.1 Preface

This chapter shifts the thesis from evidence synthesis (Chapters 2 - 4) to applied practice: determining how RT-centric athletes eat for their sport. Focusing on competitive, drug-tested powerlifters, it examines how athletes structure their nutrition across the training year, between distinct competitive phases, and on harder versus easier training days. It provides the first detailed description of nutrition periodisation, macronutrient-focused approaches (e.g., IIFYM/flexible dieting), and EI strategies in a large, international cohort stratified by sex, weight class, age class, and competitive calibre. By comparing these self-reported practices with contemporary sport nutrition guidelines and the broader ergogenic evidence for acute CHO ingestion developed in earlier chapters, this survey highlights where current behaviours align with, or diverge from, current sport nutrition recommendations.

5.2 Abstract

5.2.1 Purpose

To characterise self-reported nutrition practices and beliefs of powerlifters.

5.2.2 Methods

Actively competing male (n = 240) and female (n = 65) powerlifters completed a cross-sectional online survey of self-reported nutrition practices across the competitive cycle, within specific competitive phases, and hard and easy training days. Data are presented as number (*n*) and percentage (%) of all powerlifters practising a given strategy followed by a % of responses reporting various practices or beliefs within this strategy. Differences in categorical sub-groups (sex, age, and weight class; and competitive calibre) were analysed with a chi-square test and denoted where significant ($p \leq 0.05$).

5.2.3 Results

Most powerlifters reported following a specific diet long-term (n = 203, 66.6%) of which If It Fits Your Macros (IIFYM)/flexible dieting was most common (n = 159, 78.3%). Over half reported introducing a special diet for a competitive phase (n = 162, 53.1%), of which IIFYM/flexible dieting was most followed for competition preparation (n = 80, 63%) and off-season (n = 48, 71.6%). Compared to normal dietary intake, most reported eating more on harder training days (n = 219, 71.8%) and refraining from eating less on easier training days (n = 186, 61%).

5.2.4 Conclusions

IIFYM/flexible dieting is commonly followed by powerlifters to support performance and body composition goals. Females seemed to report more often restricting energy and dieting for body composition reasons than males. Powerlifters tailor their EI on harder training days to the higher training demands but refrain from reducing EI on rest/easier training days.

5.3 Introduction

Powerlifting is a strength sport consisting of three lifts: the back squat, bench press, and deadlift. Powerlifters are delineated by competitive federation (e.g., drug-tested, or not), the use of supportive lifting equipment or not (i.e., equipped, or classic), and their age, sex, and weight category. Performance is determined by the cumulative total weight lifted from the three lifts; therefore, powerlifters manipulate their training and nutrition with the intention of enhancing strength. RT, as completed by powerlifters, can lead to fibre type transition, neuromuscular adaptation (e.g., increased motor unit recruitment), and increases in FFM [173]. Skeletal muscle hypertrophy, specifically, is a strong predictor of powerlifting performance [174]. Consequently, dietary strategies for powerlifters are of acute (e.g., before, during, and after a training session) and longitudinal (e.g., across one or more competitive phases) interest. For instance, acute dietary strategies are of interest to fuel and recover from individual training bouts (e.g., aid performance and recovery). Additionally, powerlifters in weight classes with an upper weight limit may also use acute nutrition strategies to induce a rapid weight cut in the day/s before competition. On the other hand, chronic dietary strategies are of interest to powerlifters to aid in the optimisation of body composition (i.e., body weight manipulation such as periods of intentional gain/loss and lean mass accumulation).

One such nutritional strategy is the concept of nutritional periodisation, which can be summarised as the planned, purposeful, and strategic use of nutritional interventions to enhance adaptations across a training session or plan, or to enhance long term performance [175]. Nutritional periodisation is thoroughly studied in the context of endurance exercise [175], but nutritional periodisation for RT-centric athletes is less researched [176]. Different powerlifting competitive phases, such as the off-season/general preparation and competition preparation phases, have distinct theoretical considerations [177]. Off-season and general preparation phases typically consist of higher training volumes (i.e., the total amount of mechanical work performed); therefore, higher (absolute or relative to BM) EI are required to match the demands of the increased workload. Additionally, a small calorie surplus is advised to maximise lean mass gains, emphasising the need for adequate EI during the off-season/general preparation phase [178]. Conversely, competition preparation in the weeks and months

before competition usually culminates in a training volume taper with more lifts completed at a higher percentage of 1-RM closer to competition [179]. Thus, EI needs may be lower during the competition preparation phase to match the lower energetic demands of training. Powerlifters commonly induce gradual weight loss via caloric restriction in the weeks/months preceding competition [180, 181]. In addition, powerlifters may combine gradual dieting with rapid weight loss strategies in the days/hours preceding weigh-in on competition day to compete in a weight class lower than their habitual body weight would allow [180, 181]. Overall, there are several competitive phases in powerlifting that require different nutrition strategies depending on the training volume performed and the body composition goals of the athlete.

Current RT nutrition recommendations are to ingest 4-7g/kg bodyweight of CHO and 1.6 – 2.2g/kg bodyweight protein per day [5, 182]. Dietary fats are less emphasised, but guidelines advise the remaining 20-30% of daily caloric intake be allotted to them, sourced from mono- and poly-unsaturated fats [183]. These guidelines exist because sufficient dietary protein is necessary to optimise muscle mass accretion [182] and adequate dietary CHO intake can, in some circumstances, enhance aspects of RT performance [118]. The IIFYM diet is common within various fitness communities and is characterised as an eating approach designed to reach specific daily targets in grams of protein, CHO, and fats without a restriction on food source [184, 185]. In addition, IIFYM is often paired with 'flexible' dieting, which is an approach to dieting that represents a more moderate, balanced approach to dieting for weight loss, and is generally contrasted by 'rigid' dieting where the dieter is either 'on' or 'off' a diet [186]. However, it is not known whether these dietary approaches assist powerlifters with meeting current sport nutrition guidelines or if they implement unique nutritional periodisation approaches. One study quantified nutrition intakes of powerlifters in the off-season [187]; however, no study has investigated the nutrition strategies of powerlifters during the competitive season. Given their competitive phase-specific training demands and goals (i.e., maximal strength in the three competition lifts), the aim of this study was to survey the nutrition practices of competitive powerlifters around the competitive cycle, and individual training sessions (harder versus easier/rest days). This exploration

allows for an account of current practices used by powerlifters, their underlying rationale, and a discussion of how practices relate to current sport nutrition guidelines.

5.4 Methods

An open invite, anonymous international survey was developed to investigate the nutrition practices and beliefs of competitive powerlifters. Data collection for this study was completed between November 2020 and February 2021. The methods of this survey are reported in accordance with the Checklist for Reporting Results of Internet E-surveys (CHERRIES) [188]. The study protocol was approved by the Auckland University of Technology Ethics Committee (20/312).

5.4.1 Survey Development and Design

The structure and content of the questionnaire was based on previously published work investigating the nutrition practices of elite race walkers [10], with content either adapted or added to suit a powerlifting context. A first draft of the survey was piloted with a convenience sample of powerlifters (n = 8) who provided feedback. Based on feedback from pilot testing, the survey was modified to improve content and readability. The final version of the survey was built and distributed online using Qualtrics software (Seattle, WA, USA) and contained 81 questions in total. Display logic and exclusive answers were used to build a custom path through the questionnaire dependent on the participant's answer such that 30 – 40 questions over 16 – 22 pages were answered by each participant. Participants were shown 1-3 questions per page, and a back button was enabled that allowed participants to amend/change previous answers.

The questionnaire was split into ten sections, of which the first five (i.e., general nutrition practices) are of interest in this manuscript. In order of appearance, Section 1 covered participants' descriptive characteristics (e.g., nation of competition and competitive division) and training history (e.g., powerlifting experience and competitive calibre). Section 2 covered general dietary themes for the overall competitive cycle. Section 3 covered the general dietary themes for specific competitive phases (e.g., off-season, competition preparation). Sections 4 and 5 covered harder and easier training

day nutrition practices, respectively. A full transcript of the questionnaire with display logic can be found in Appendix B Ch. 5 Supplementary File I.

Definitions for concepts were provided to participants in the survey. A hard training day was defined as a high volume and/or high intensity session. A rest/easier training day was defined as passive or active recovery or lower volume accessory days where none of the three powerlifting lifts are completed. A figure (Page 32 of Appendix B Ch. 5 Supplementary File I) was presented to participants visualising a generic, periodised competition cycle and competitive phases within the cycle (i.e., off-season, competition preparation, competition, and transition) [177]. The competition preparation phase was presented as including specific preparation for, and then a taper into, competition. The competition phase was defined as including the day of competition and the 48 hours preceding. The transition phase was defined as occurring immediately post-competition, which led into an off-season or general preparation. The off-season was presented as including general preparation for competition, which preceded a competition preparation phase and followed a transition phase.

5.4.2 Survey Distribution and Sample Selection

The survey was distributed via advertisement on social media with an accompanying internet link to the anonymous survey. A downloadable information sheet detailing the purpose, content, and length of the survey; how, when, and where data will be stored; and who the investigators were was displayed as the first page before commencing any survey questions. Due to the survey being anonymous, participants were advised in the information sheet that participation was voluntary, and consent was provided by submitting the completed survey. Participant inclusion criteria were to (a) be 18 years of age or older (which excluded sub-junior age class powerlifters less than 18 years of age from participating in the present study), and (b) have competed in a drug-free sanctioned powerlifting competition within the previous 18 months.

5.4.3 Statistical Analysis

Only fully completed questionnaires were analysed. Missing data checks were performed to verify data integrity. Descriptive data were presented as number (*n*) and percentages (*%*). Categorical data were assessed by chi-square test and Cramer's V (φ_c). Where >20% of cells had an expected count of less than 5, Fisher's exact test was used. For the weight-class sub-group (4x2 contingency table), a follow-up individual chi-square test (or Fisher's exact test where the >20% expected count rule was violated) with Holm-Bonferroni correction were performed when a statistically significant result was observed. Statistical significance was set at $p \leq 0.05$. Data were prepared and analysed in SPSS (version 27.0; IBM Corp, Armonk, NY), and follow-up chi-square and Fisher's tests were completed in R language for statistical computing (R Foundation for Statistical Computing, Vienna, Austria, 2021) using the "*Fifer2*" package (https://github.com/dustinfife/fifer2/).

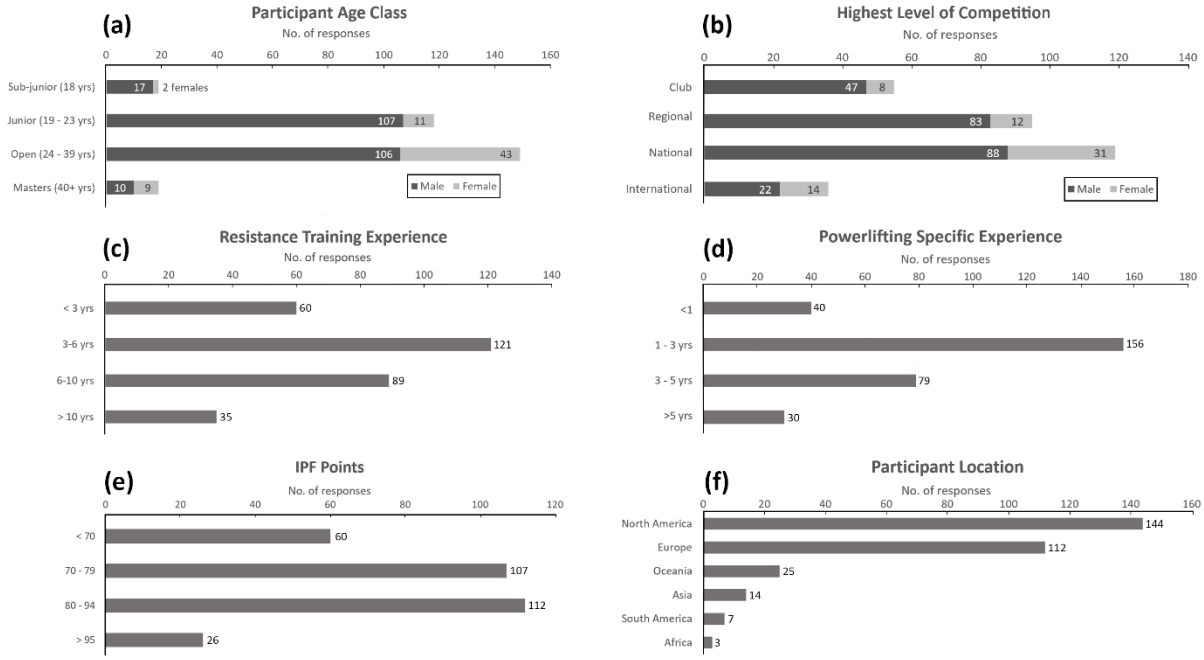
Participants could select multiple answers for most questions; therefore, the percentage of responses for some questions could add up to more than 100%. Text answers to "other" responses were grouped into common themes/responses by the primary investigator (AK). Responses were analysed by sub-groups based on competitive division (males vs. females), age class (sub-juniors and juniors [SJ + J] vs. open and masters [O + M]), weight class (women's under 63, 57, 52, and 47kg classes [W63-] vs. women's under 72, 84 kg classes and 84 kg plus class [W72+] vs. men's under 83, 74, 66, 59, and 53 kg classes [M83-] vs. men's under 93, 105, 120 kg classes and 120 kg plus class [M93+]), and competitive calibre (i.e., IPF points where higher values indicate stronger powerlifters relative to bodyweight) from the best 3-lift total in competition (less than 80 IPF points [79- IPF] vs. 80 IPF points or more [80+ IPF]).

5.5 Results

There were 385 responses, of which 305 (240 male and 65 female) fully completed the survey (79.8% completion rate) and were included in the analysis. Most participants resided in the United States (n = 115, 37.7%), Canada (n = 29, 9.5%), United Kingdom (n = 22, 7.2%), and New Zealand (n = 19, 6.2%), while the rest were from a variety of other countries (n = 120, 39.3%). Most participants

competed in the open age class (n = 149, 48.9%), followed by juniors (n = 118, 38.7%), sub-junior (n = 19, 6.2%), and masters (n = 19, 6.2%). Descriptive characteristics are presented in Figure 5-1.

Figure 5-1: Descriptive participant characteristics of (a) age class, (b) competitive calibre, (c) resistance training experience in years, (d) powerlifting specific experience in years, (e) International Powerlifting Federation (IPF) points based on best total in competition, and (f) participants location. For (f), participants were from 47 countries, which were grouped by continent.

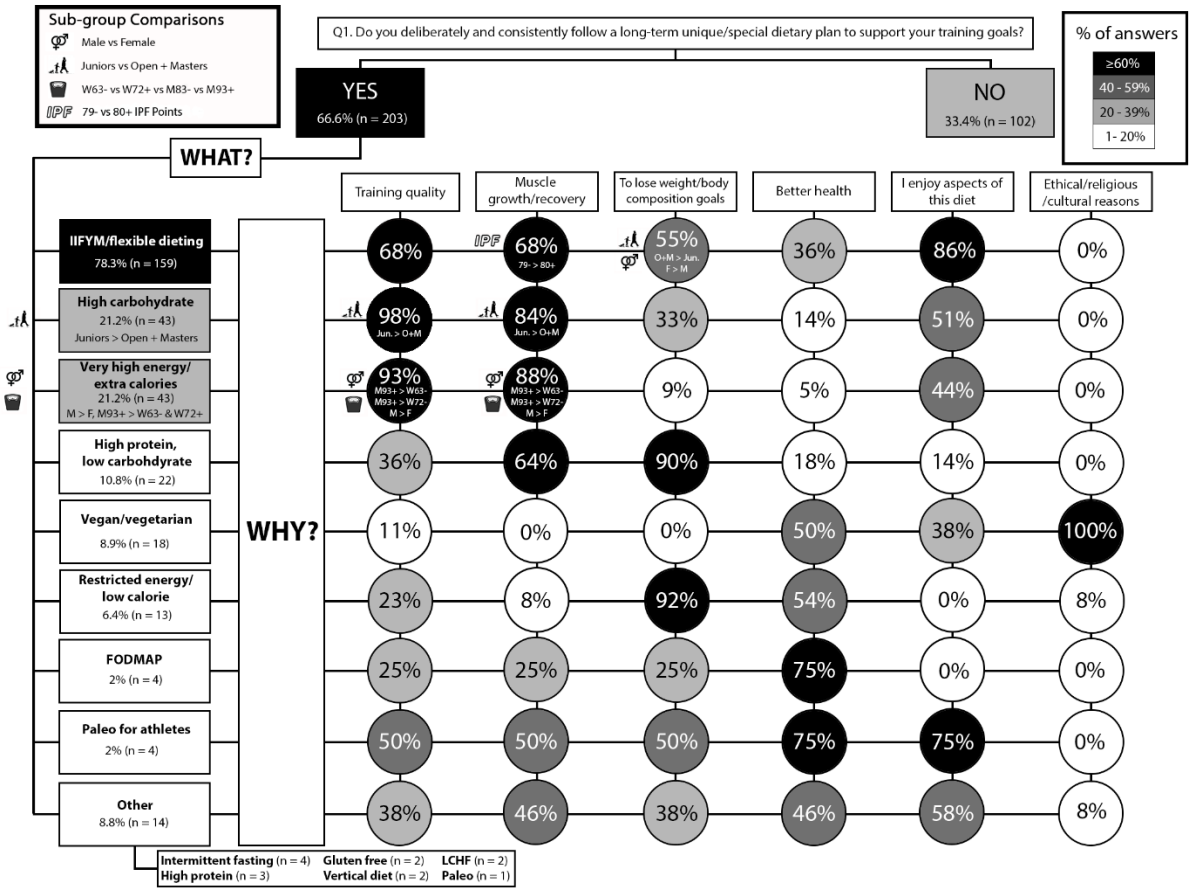


5.5.1 Question 1. Nutrition for the Competitive Cycle

Overall, 66.6% (n = 203) of participants reported following a long-term special/unique dietary plan (Figure 5-2). Of these, 78.3% (n = 159) reported following an IIFYM/flexible dieting approach, followed by a high CHO (21.2%, n = 43) and a high energy approach (21.2%, n = 43). SJ + J reported following a long-term high CHO diet more than O + M ($p = 0.027$; $\varphi_c = 0.127$) for training quality ($p = 0.040$; $\varphi_c = 0.117$) and muscle growth/recovery ($p = 0.038$; $\varphi_c = 0.119$). Males more often reported following a high energy diet than females ($p = 0.001$; $\varphi_c = 0.188$) for training quality ($p = 0.002$; $\varphi_c = 0.178$) and muscle gain/recovery ($p = 0.003$; $\varphi_c = 0.172$). M93+ more often reported following a high energy diet than W63- ($p = 0.049$; $\varphi_c = 0.209$) and W72+ ($p = 0.014$; $\varphi_c = 0.230$). M93+ more often reported following a high energy diet for training quality ($p = 0.048$, $\varphi_c = 0.182$; $p = 0.027$, $\varphi_c = 0.203$)

and muscle growth/recovery ($p = 0.048$, $\varphi_c = 0.182$; $p = 0.027$, $\varphi_c = 0.203$) than W63- and W72+, respectively. Females more often than males ($p = 0.045$; $\varphi_c = 0.115$) and 79- IPF more often than 80+ IPF ($p = 0.050$; $\varphi_c = 0.112$), reported following an IIFYM/flexible dieting approach for muscle growth/recovery. O + M more often reported following an IIFYM/flexible diet for weight/body composition goals than SJ + J ($p = 0.049$; $\varphi_c = 0.218$). The results for nutrition practices across the competitive cycle are presented in Figure 5-2. The information sources used to inform nutrition practices across the competitive cycle are presented in Table 5-1.

Figure 5-2: Q1: Overall dietary practices across the year. The prevalence of a specific and consistent overall long-term dietary approach (e.g., high CHO) across the year and the reasons for following them in 305 actively competing powerlifters. Percentages (%) are presented as the proportion of all participants that chose a specific answer (YES/NO), followed by a % of responses reporting various practices and reasons within these strategies. Number (n) of participants has been provided. Answer boxes and circles are colour coded based on the % of responses: ≥ 60%, black box with white font; 40–59%, dark grey box with white font; 20–39%, light grey with black font; < 20%, white box with black font. Symbols are used to indicate statistical significance between sub-groups for sex (vector sex symbol), age class (human life cycle symbol), weight class (weight scale symbol), and International Powerlifting Federation (IPF) points (IPF symbol). Where significant differences were detected, the direction of difference is indicated in the corresponding box/circle (e.g., males reported more often than females would be indicated by M > F).



IIFYM If It Fits Your Macros, *LCHF* low carbohydrate, high fat.

Table 5-1: Source of information informing nutrition practices of powerlifters

Question	**Answer**	**Source of Information (*n*)**								
		No specific source	*I read/ watched it*	*Coach*	*Sport Nutr.*	*Dietician*	*Scientist*	*Friend*	*Training Partner*	*Other*
Competitive Cycle: Do you follow a long term special/unique dietary plan?	Yes (n = 203)	162	21	9	6	4	6	9	5	4
Do you follow a unique/special dietary plan during **competition preparation**?	Yes (n = 127)	122	3	1	2	2	1	0	0	0
Do you follow a unique/special dietary plan during **competition**?	Yes (n = 109)	103	4	3	4	1	2	0	0	0
Do you follow a unique/special dietary plan during **off-season**?	Yes (n = 67)	65	1	0	1	1	1	0	0	0
Do you intentionally eat more food/calories on all **harder training days**?	Yes (n = 219)	61	101	73 †	47	15 ‡	21	21	22	2
	No (n = 86)	52	20	16	3	6	6	2	3	9
Do you intentionally eat less food/calories on **rest/easier training days**?	Yes (n = 119)	37	43	30	28	10	15	6	9	10
	No (n = 186)	97	60 ‖ §	36	11	7	6	5	7	9

Sport Nutr. Sport Nutritionist

"*Other*" includes medical doctor, physiotherapist, family member, and personal trainer.

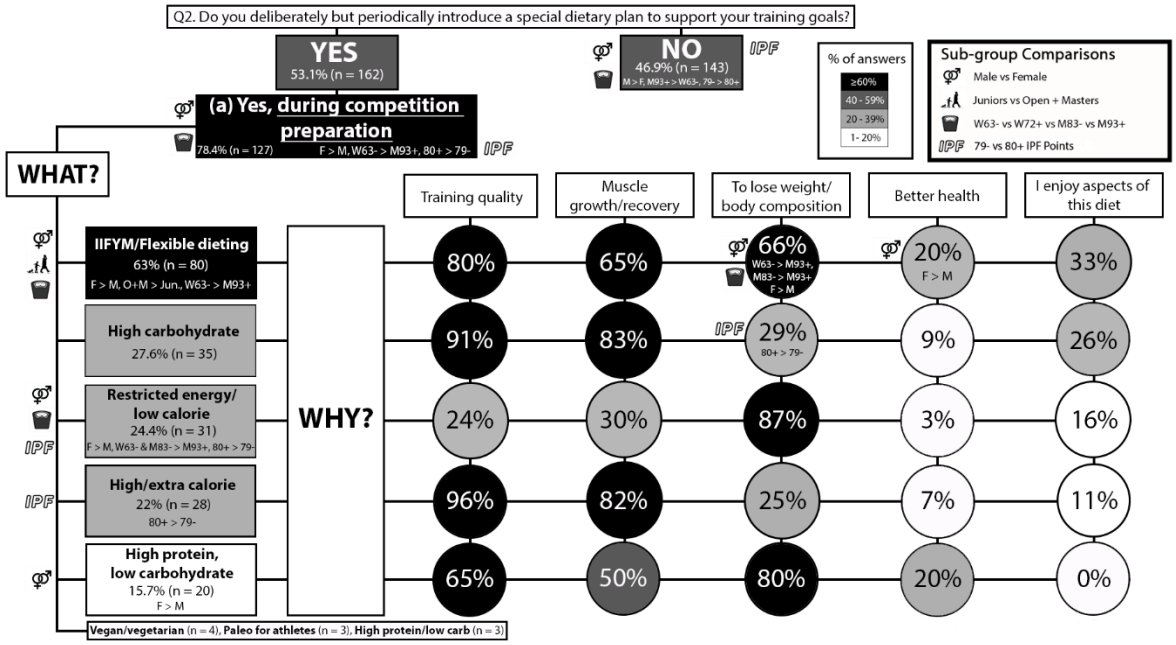
Significant differences ($p \leq 0.05$) marked as: † females > males; ‖ males > females; ‡ 80+ IPF Points > 79- IPF Points; § M93+ > W72+.

5.5.2 Question 2. Nutrition for Specific Competitive Phases

5.5.2.1 *Competition Preparation*

Overall, 46.9% (n = 143) reported no introduction of a special/unique dietary plan during for a specific competition phase, which was reported more often by males than females (p = 0.018; φ_c = 0.136), M93+ more often than W63- (p = 0.016; φ_c = 0.185), and 79- IPF more often than 80+ IPF (p = 0.003; φ_c = 0.168). Conversely, 53.1% (n = 162) of powerlifters followed a special/unique dietary plan in one or more specific competitive phase/s. A special/unique diet during competition preparation was reported by 78.4% (n = 127) of powerlifters. Females more often reported than males (p = 0.002; φ_c = 0.178); W63- more often than M93+ (p = 0.001; φ_c = 0.329) and M83- (p = 0.016; φ_c = 0.251); and 80+ IPF more often than 79- IPF (p = 0.001; φ_c = 0.194), reported a special/unique dietary plan during competition preparation. During competition preparation, females more often than males (p = 0.002; φ_c = 0.181), W63- more often than M93+ (p = 0.002; φ_c = 0.312), and O + M more often than SJ + J (p = 0.038; φ_c = 0.119), reported following an IIFYM/flexible diet. Females more often reported a restricted energy (p = 0.042; φ_c = 0.116) and a high protein, low CHO (p = 0.001; φ_c = 0.186) diet than males. W63- (p = 0.018; φ_c = 0.270) and M83- (p = 0.044; φ_c = 0.178) more often reported a restricted energy diet than M93+. 80+ IPF more often reported a restricted energy (p = 0.023; φ_c = 0.130) and high energy (p = 0.012; φ_c = 0.144) diet than 79- IPF. Regarding the reason for a specific diet, females more often reported an IIFYM/flexible diet for the purpose of losing weight/body composition goals (p = 0.002; φ_c = 0.342) and better health (p = 0.007; φ_c = 0.304) than males. W63- (p = 0.001; φ_c = 0.641) and M83- (p = 0.010; φ_c = 0.426) more often reported following an IIFYM/flexible diet for the purpose of losing weight/body composition goals than M93+. 80+ IPF more often reported following a high CHO diet to lose weight/body composition goals than 79- IPF (p = 0.028; φ_c = 0.334). The results for competition preparation are presented in Figure 5-3.

Figure 5-3: Q2 (**a)** Dietary practices for the competition preparation phase. The prevalence of introducing a unique dietary approach for a specific competition phase (YES/NO) followed by the competition preparation phase and the reasons for following them. Description of how to interpret is in the Figure 5-2 caption.

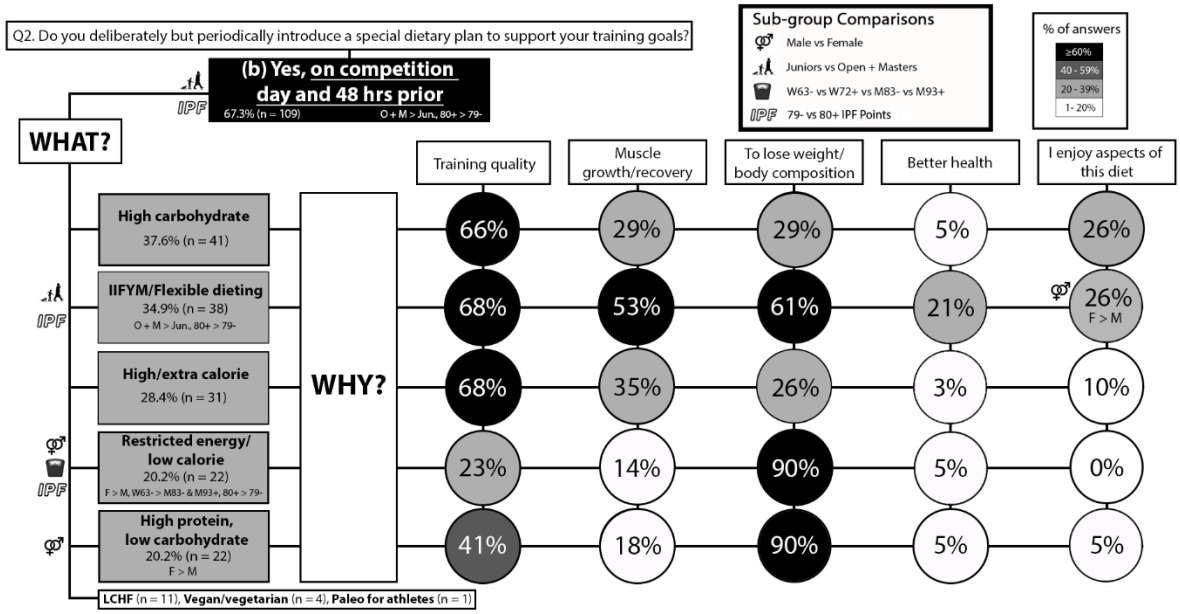


IIFYM If It Fits Your Macros

5.5.2.2 *Competition*

During competition, O+M more often than SJ + J ($p = 0.017$; $\varphi_c = 0.137$) and 80+ IPF more often than 79- IPF ($p = 0.001$; $\varphi_c = 0.202$), reported the introduction of a special/unique dietary plan. O + M more often than SJ + J reported following an IIFYM/flexible diet ($p = 0.001$; $\varphi_c = 0.251$). 80+ IPF more often than 79- IPF reported following IIFYM/flexible dieting ($p = 0.043$; $\varphi_c = 0.116$) and restricted energy ($p = 0.025$; $\varphi_c = 0.128$). Females more often than males reported restricted energy ($p = 0.020$; $\varphi_c = 0.133$) and high protein, low CHO ($p = 0.025$; $\varphi_c = 0.128$) diet. W63- more often than M83- ($p = 0.011$; $\varphi_c = 0.140$) and M93+ ($p = 0.010$; $\varphi_c = 0.155$) reported restricted energy. Regarding the reason for following a specific diet, females more often than males reported following an IIFYM/flexible diet for enjoyment reasons ($p = 0.012$; $\varphi_c = 0.419$). The results for the competition phase are presented in Figure 5-4.

Figure 5-4: Q2 (**b)** Dietary practices for the competition phase (day of competition and the 48-h preceding). The prevalence of introducing a unique dietary approach for the competition phase and the reasons for following them. Please note that the initial YES/NO responses are reported in Figure 5-3 only. Description of how to interpret is in the Figure 5-2 caption.

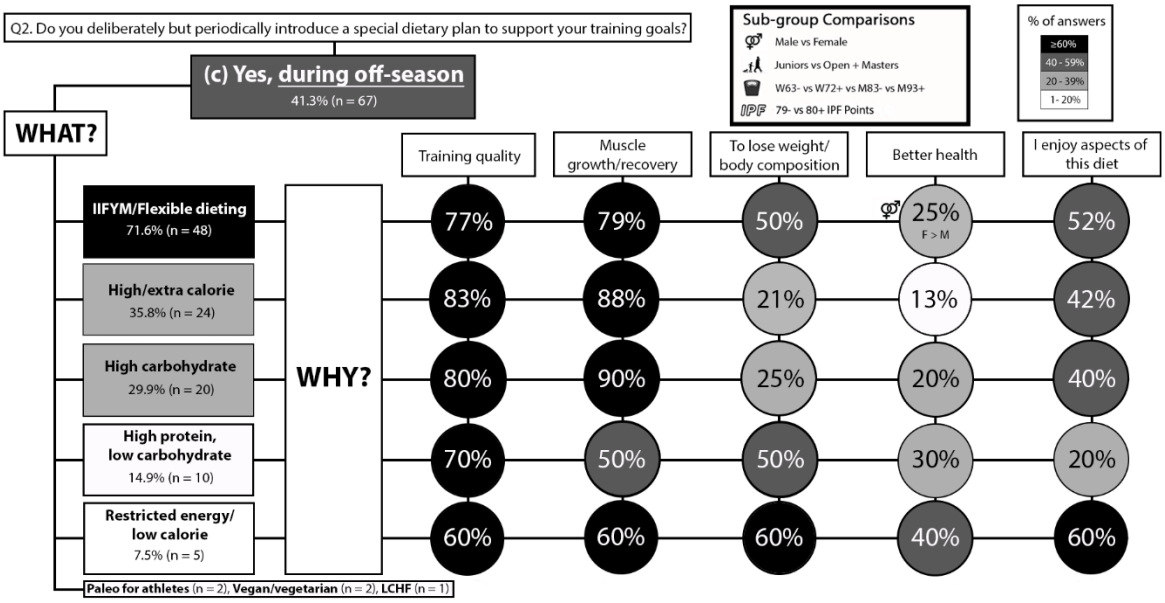


IIFYM If It Fits Your Macros.

5.5.2.3 Off-season

During the off-season, females more often reported following an IIFYM/flexible diet for the purpose of bettering their health than males ($p = 0.001$; $\varphi_c = 0.476$). The results for the off-season phase are presented in Figure 5-5. The information sources used to inform nutrition practices for specific competitive phases are presented in Table 5-1. The results for transition and return from injury are reported in Appendix B Ch. 5 Supplementary File II.

Figure 5-5: Q2 (**c)** Dietary practices for the off-season phase. The prevalence of introducing a unique dietary approach for the off-season and the reasons for following them. Please note that the initial YES/NO responses are reported in Figure 5-3 only. Description of how to interpret is in the Figure 5-2 caption.

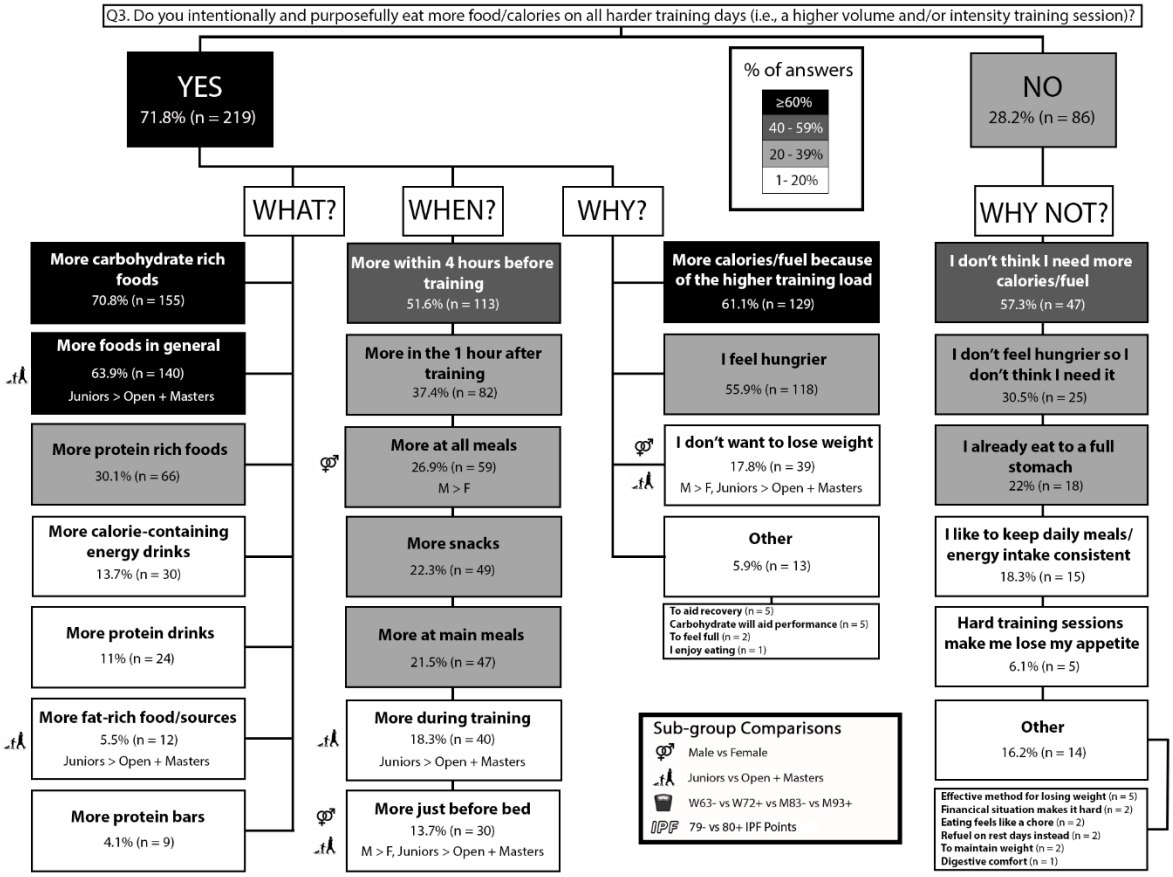


IIFYM If It Fits Your Macros, *LCHF* low carbohydrate, high fat.

5.5.2.4 *Question 3. Harder Training Days*

Overall, 71.8% (n = 219) of participants reported eating more food on harder training days via eating more CHO-containing foods (n = 155) or more foods in general (n = 150), and most participants reported eating more foods to get in the energy required to support the higher training volume (n = 129). SJ + J more often reported eating more foods in general ($p = 0.019$; $\varphi_c = 0.134$) and more fat rich foods/sources ($p = 0.033$; $\varphi_c = 0.122$) than O + M. Males more often reported eating more at all meals ($p = 0.020$; $\varphi_c = 0.133$) and just before bed ($p = 0.039$; $\varphi_c = 0.118$) than females. SJ + J more often reported eating more during training ($p = 0.040$; $\varphi_c = 0.118$) and before bed ($p = 0.012$; $\varphi_c = 0.144$), than O + M. Males more often than females ($p = 0.026$; $\varphi_c = 0.126$) and SJ + J more often than O + M ($p = 0.010$; $\varphi_c = 0.148$), reported eating more to avoid weight loss. The results for nutrition practices on harder training days are presented in Figure 5-6.

Figure 5-6: Q3. Nutrition on hard training days. The prevalence of specific nutrition practices on harder (i.e., higher volume/intensity) training days and the reasons for following them. Description of how to interpret is in the Figure 5-2 caption.



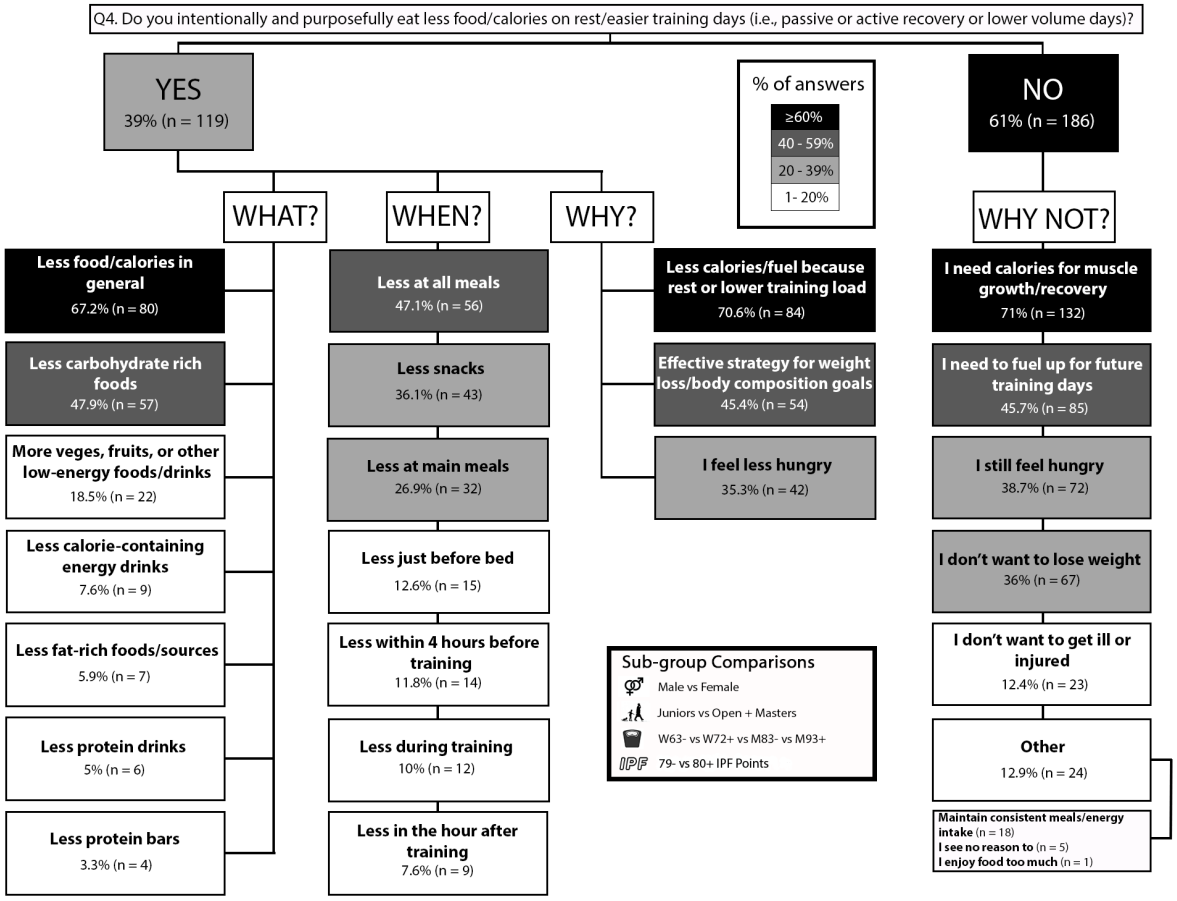
Females more often than males informed the practice of eating more on harder training days with information from their coach ($p = 0.035$; $\varphi_c = 0.121$). 80+ IPF more often than 79- IPF informed their decision to eat more on harder training days with information from a dietician ($p = 0.025$; $\varphi_c = 0.128$). The information sources used to inform harder training day nutrition practices are presented in Table 5-1.

5.5.2.5 Question 4. Easier Training Days

Overall, 61% (n = 186) of participants did not eat less food on easier training days. The most common reason was that calories were needed to support muscle growth/recovery (71%, n = 132). Of the 39% (n = 119) that did reduce food intake on easier training days, 67.2% (n = 80) reported eating

less at all meals and 70.6% (n = 84) ate less because of the lower training load. There were no significant sub-group differences for easier training day nutrition practices ($p > 0.05$). The results for easier training day nutrition practices are displayed in Figure 5-7.

Figure 5-7: Q4. Nutrition on rest/easier training days. The prevalence of specific nutrition practices on rest/easier training days and the reasons for following them. Description of how to interpret is in the Figure 5-2 caption.



Males more often than females ($p = 0.017$; $\varphi_c = 0.137$) and M93+ more often than W72+ ($p = 0.046$; $\varphi_c = 0.162$), reported informing their decision not to eat less on easier training days based on information they had read or watched. The information sources used to inform easy training day nutrition are presented in Table 5-1.

5.6 Discussion

The purpose of the current study was to explore the general nutrition practices in competitive powerlifters. To our knowledge, this is the first study to characterise the general nutrition practices of powerlifters across competitive calibre, and sex, weight and, age class. There are several key findings: (1) Powerlifters use IIFYM/flexible dieting year-round, and during the competition preparation and off-season phases for performance and diet enjoyment; (2) nutrition strategies differ between competitive phases and there are various approaches to the competition phase; (3) female powerlifters are more conscious of EI than male counterparts; and (4) powerlifters focus on adequate EI on hard training days, but refrain from tailoring EI to the lower training workload on rest/easier training days.

5.6.1 Nutrition Practices and the Competitive Cycle

IIFYM is popular in various fitness communities and the findings of the present study indicate that this approach is also popular with powerlifters as a long-term approach to the diet (Figure 5-2), and within the competition preparation (Figure 5-3) and off-season (Figure 5-5) phases. IIFYM is characterised as a meal plan constructed to reach specific daily targets in grams of protein, CHO, and fats without a restriction on food source [184, 185]. Given this, IIFYM allows for more dietary inclusion and variety, and supports periods of weight gain, loss, or maintenance [184]. In the current study, IIFYM was paired with flexible dieting, the latter of which can be considered a distinct concept specific to weight loss. Cognitive restraint during phases of weight loss, to create a caloric deficit, is required on behalf of the dieter, and the approach to cognitive restraint has been characterised as an individual exerting more ‘flexible’ or more ‘rigid’ control, as scored on the three-factor eating questionnaire [189]. A rigid approach to dieting describes an all or nothing approach to eating behaviours and dieting, where ‘off-limit’ foods are avoided or eliminated and ‘diet’ foods are emphasised, narrowing the variability of foods consumed [190]. Flexible control represents a more moderate, balanced approach to dieting for weight loss that includes eating behaviours such as taking smaller servings of food than desired to regulate weight and including a variety of foods in limited quantities [186]. Thus, flexible dieting for

weight loss can be considered more consistent with, but conceptually different to, the IIFYM approach to organising the diet.

IIFYM emphasises reaching daily targets for macronutrients but does not necessarily consider micronutrient intakes and it is presently unknown whether powerlifters reach the recommended dietary allowance (RDA) for micronutrients with an IIFYM approach. Micronutrient intakes below the RDA have been reported in bodybuilders [191] but micronutrient intakes have not been quantified in powerlifters. Recently, in a cohort of bodybuilders, Ismaeel et al., [184] reported intakes of vitamins A, D, and E; potassium; and fibre below the RDA, with similar prevalence between males following a macronutrient-based diet and those following a more rigid, 'strict' diet. Additionally, while there was a low sample size of female bodybuilders, those following an IIFYM approach reported higher, but still inadequate, micronutrient values compared to strict dieting females, and all females reported iron intakes below the RDA [184]. The prevalence of iron deficiency is 15-35% in athletic, female populations [192]. Female athletes consuming lower EIs, practising vegan or vegetarian diets, and participating in endurance sports are notable factors in the prevalence of iron deficiency [193]; however, it is presently unknown to what degree female powerlifting athletes are affected. Future research is necessary to quantify the micronutrient intakes of powerlifters across specific competitive phases and identify any shortcomings in micronutrient intake in comparison to RDA.

5.6.2 Nutrition Practices Differ for Specific Competitive Phases

IIFYM/flexible dieting was most often followed during the competition preparation (Figure 5-3) and off-season phases (Figure 5-5). However, the findings for competition phase (day of competition and the 48 hrs prior) diet (Figure 5-4) indicate a variety of diet strategies, as the frequency of the five most popular diet selections were in the range of 20 – 40%. In addition, the diet strategies reported for the competition phase contrasted each other, as high and low-calorie diets were reported, and so were high and low (with high protein) CHO diets (Figure 5-4). Females more often reported than males implementing dietary approaches which were almost exclusively (90%) implemented to lose weight/body composition goals (Figure 5-4), such as restricted/low calorie or high protein with low

CHO diets. There were also competitive calibre sub-group differences, as powerlifters with 80+ IPF points more often than 79- IPF points reported IIFYM/flexible dieting and/or a restricted energy diet during the competition period (Figure 5-4). The results suggest that powerlifters following a high CHO and/or energy diet prioritise training performance in the days before competition, those following a restricted energy or high protein, low CHO diet prioritise weight loss/body composition, and those following IIFYM/flexible dieting perceive that this diet allows for them to maintain training performance and meet their weight loss/body composition goals. It should be noted that calorie restriction (possibly paired with fasting) and body water storage manipulation are common strategies used by powerlifters for inducing acute weight loss prior to the weigh-in that occurs on the day of powerlifting competition (2 hours before) [181]; thus, the findings for the competition phase in the present study likely capture some of these acute weight loss strategies.

5.6.3 Energy Intake Practices Differ by Sex

Several of the findings from the present study indicate that females more often males follow diets that restrict energy or do not allow for higher EIs. For example, long-term use of very high energy diets was reported less among female powerlifters (Figure 5-2) and more often reported following a restricted energy diet during competition preparation (Figure 5-3) and competition (Figure 5-4) than their male counterparts. The total energy expenditure associated with powerlifting training is likely lower compared to other forms of exercise (e.g., endurance); hence, dietary restriction is likely to feature as the primary strategy for achieving a desired body weight or composition [194]. While dietary restriction is common in weight class restricted sports, it is also frequently accompanied by disordered eating in such athletes [195]. More so, disordered eating behaviour is prevalent in female athletes competing in sports emphasising leanness and weight restricted sports [196], and female athletes more often report symptoms of disordered eating than males [197]. Given the weight-class categorisation of powerlifting and that body leanness and weight are key competition performance variables, powerlifting athletes may be at more of a risk of developing disordered eating behaviours.

Despite the likelihood that powerlifters are susceptible to disordered eating, there is minimal scientific inquiry investigating disordered eating in powerlifters (and other strength sports). In a qualitative analysis of disordered eating in competitive female powerlifters (n = 17), weight cutting behaviours were common and associated with disordered eating [198]. The weight class element of powerlifting may present a paradox for some female powerlifters, in which the desire to increase muscle mass (to aid performance) must be balanced against societal ideals for the female body (e.g., to decrease body weight and/or weight class) [198]. Indeed, in previous research, female athletes frequently diet to improve appearance, which was contrasted by males, who most often reported dieting for performance outcomes [199]. Future research is necessary to further elucidate the prevalence of disordered eating behaviours and eating disorders amongst powerlifters (including males [200]).

One possible consequence of disordered eating behaviours is low energy availability (defined as: EI – energy expenditure / FFM), which can occur without disordered eating behaviours (especially in high energy expenditure athletes) [201], but is often underpinned by disordered eating behaviours in female [197, 202] and male athletes [197, 203]. Impaired energy availability could potentially lead to adverse outcomes (e.g., reproductive and skeletal health) such as those included in the Female Athlete Triad [204] and Relative Energy Deficiency in Sports [205], that could foremost negatively affect general health, and training performance, recovery, and adaptation. A prolonged EI below an approximate threshold of < 30 kcal/kg of FFM/day is considered detrimental to physiological function in female athletes [206], although it is less clear whether this threshold is applicable to male athletes [207]. Importantly, a powerlifting athlete may be weight stable and at energy balance but be in a state of low energy availability and experiencing the associated symptoms due to suppressed physiological function [208]. Conversely, adequate EI to support physiological function may need to reach or exceed 45 kcal/kg of FFM/day in some cases [208]. Notably, while these recommendations provide a useful target for EI, a reliable estimation of dietary intake and body composition is needed to accurately implement them and assistance from a sport nutrition or dietetic and/or exercise physiology professional is recommended [204]. Dietary intake of powerlifting athletes could be assessed using dietary logs and food frequency questionnaires, but can be subject to error from underreporting, modified intake caused

by and during the measurement period, and inaccurate portion size estimation [209]. In athletic populations, body composition can be estimated with specialised technologies (e.g., dual x-ray absorptiometry, bioelectrical impedance) and field-based measures such as skinfolds [210]. Aided with this information, current recommendations are for physically active women to consume at least 45 kcal/kg of FFM per day to ensure adequate energy availability for physiological function, and between 30 and 45 kcal/kg of FFM per day during periods of intentional weight loss [194, 204].

The source of information informing nutrition practices should also be considered in the context of disordered eating behaviours. In the present study, the coach was the most often cited in-person source of information and females more often than males reported their coach as the source of information to inform hard training day nutrition practices. In previous research, coaches were identified as a prevalent source of information ahead of nutrition practitioners [211]. The coaching environment can increase or reduce risk of eating disorder [212]; thus, it may be beneficial for nutrition practitioners to educate powerlifting coaches on the importance of energy availability, the symptoms of low energy availability, and potential low energy availability management strategies (including the use of a multi-disciplinary team e.g., sport nutrition and mental health practitioners).

5.6.4 Harder Versus Easier Training Day Energy Periodisation

The energy cost associated with RT increases with greater training volumes and exercises that recruit more muscle mass [213]. Thus, athletes may modify their daily EI in accordance with the training demands on the day. For example, decreasing EI on lower volume training days or rest days may better manage EI during the weight cut before competition. Conversely, such a strategy may allow for an increased EI on harder, higher volume training days where the energetic demands of training are higher. Indeed, these strategies were observable in the present population as most powerlifters (71.8%, n = 219) reported intentionally and purposely eating more food/calories on all harder training days with higher training load the most often cited reason for this practice (87.6%, n = 192), compared to normal dietary intake. In contrast, most powerlifters reported not lowering their food/calorie intake on rest/easier training days compared to normal dietary intake (61%, n = 186) (Figure 5-7). Strategies to estimate EI

typically include dietary logs, questionnaires, and using smart phone dietary tracking applications [214]. While such estimates may contain notable error [209], they are likely preferred to making no such estimation. Another simple, less precise approach with potential utility is estimating energy expenditure from RT with the Metabolic Equivalent of Task method and the associated 2011 Compendium of Physical Activities [215]. When doing so, the energy expenditure of an activity in kilocalories = metabolic equivalent of the task x body weight in kilograms x duration of the activity in hours. Taken together, athletes and practitioners have several energy expenditure estimation tools at their disposal that, while limited, allow powerlifting athletes to tailor their EI to the energetic demands of their training.

5.6.5 Limitations

There are several limitations to the current study. Firstly, our analysis relies on self-reported nutrition practices, and the questionnaire described diet practices without defining concepts (e.g., IIFYM) or specific amounts required (e.g., what constitutes 'high' or 'low' CHO). It is unknown how much of a difference there is between reported dietary trends (e.g., high or low intakes) and actual intake in the current study, since previous work in endurance athletes has observed some discrepancies (up to ~35%) [216, 217]. These discrepancies may be explained by participant bias or because responses may reflect what the participants strive or perceive to achieve, rather than actual intake. In the present survey, participants were required to be at least 18 years old to be eligible for inclusion, which excluded younger sub-junior powerlifters (14 – 17 years old). While sub-junior (at least 18 years old) and junior (19 – 23 years old) powerlifters were pooled in the analysis, the findings may not generalise to sub-junior powerlifting competitors less than 18 years old. In addition, only 21% of participants (n = 65) were female, which may limit the generalisability of the results. Lastly, the large, global sample size in the current study enabled an exploration of nutrition practices across competitive calibre, and weight, sex, and age classes. However, since most participants (84%) in this study were from North America and Europe, the findings may not be representative of powerlifters in other regions. Various factors, including cultural and socioeconomic influences, among many others, could contribute to differences in food choice [218].

5.7 Conclusion

The current study characterises the general nutrition practices of competitive powerlifters. The key findings were that an IIFYM/flexible dieting approach is popularly used by powerlifters across the competitive cycle and where a special dietary approach was introduced for the competition preparation and off-season phases. The dietary approach chosen by powerlifters for the competitive cycle or competitive phase was not informed by a specific source of information. The findings of the present study indicate a trend in which female powerlifters are more cautious of EI than male counterparts. However, it is not clear whether this finding is connected to disordered eating behaviours, and little is known about the overall prevalence of disordered eating behaviours, and low energy availability, in powerlifters. Most competitive powerlifters reported eating more food/calories on harder training days to fuel for the higher training load. On the other hand, most competitive powerlifters reported not intentionally eating less on rest/easier training days, for the purpose of using the extra calories for muscle growth or recovery. Harder and easier training day nutrition practices were more commonly informed by a specific source of information, with having read/watched it somewhere, coaches, and sports nutritionists most often cited. Finally, powerlifters demonstrate an understanding of the need to achieve adequate fuelling to meet higher training demands by increasing EI on higher volume/intensity days but refrain from reducing EI on rest/easier training days where the training load is lower.

Chapter 6: Fuelling for and recovering from resistance training: The peri-workout nutrition practices of competitive powerlifters

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6.1 Preface

This chapter further develops the applied focus of the thesis by moving from general dietary practices across the training year (Chapter 5) to the specific peri-workout nutrition strategies used by competitive, drug-tested powerlifters. It characterises how athletes fuel before, during, and after key training sessions, their use of fasted training, and pre-exercise supplementation, across sex, age class, weight class, and competitive calibre. By describing these self-reported practices and situating them against contemporary RT sport nutrition guidelines, this chapter provides practical context for the acute CHO- and supplement-related mechanisms and effects explored in earlier chapters and identifies where current behaviour broadly aligns with, or potentially diverges from, current sport nutrition recommendations.

6.2 Abstract

6.2.1 Purpose

Nutrient timing is a concept that emphasises the intentional ingestion of whole or fortified foods, and dietary supplements, to adequately fuel for, and recover from, acute and chronic exercise. The nutrition strategies used by powerlifters around training sessions have not been previously investigated. This study explored the self-reported peri-workout (before, during, and after) nutrition practices of competitive powerlifters, including what, why, and information source that informed practice, with comparison to current sport nutrition guidelines.

6.2.2 Methods

Actively competing male (n = 240) and female (n = 65) powerlifters completed a cross-sectional online survey of self-reported peri-workout nutrition practices in the pre-, intra-, and post-exercise periods, fasted training, and supplementation. Data are presented as the number (n) and percentage (%) of all powerlifters practising a given strategy followed by a % of responses reporting various practices or beliefs within this strategy. Categorical sub-groups (sex, age, and weight class; and competitive calibre) were analysed with a chi-square test or Fisher's exact test and denoted where significant ($p \leq 0.05$).

6.2.3 Results

Most powerlifters reported paying specific attention to nutrition practices in the pre-exercise period (n = 261; 85.6%) by ingesting more CHO rich foods (n = 234; 89.6%) for the purpose of assisting in training performance (n = 222; 85.1%). Most powerlifters reported intra-exercise nutrition strategies (n = 211; 69.2%), of which most included ingesting more CHO rich foods (n = 159; 74.5%) for the purpose of feeling less hungry and/or boosting energy levels during training (n = 129; 61.1%). Most powerlifters reported paying attention to post-exercise nutrition (n = 244; 80%), by ingesting more protein rich foods (n = 182; 74.6%) for the purpose of recovering better for the whole day (n = 152; 62.3%) and enhancing the benefits of training (n = 149; 61.1%). Most powerlifters did not complete

training sessions in the fasted state (n = 262; 85.9%). Most powerlifters reported paying attention to supplementation before training (n = 237; 77.7%), of which pre-workout formulas (n = 137; 57.8%), energy drinks (n = 101; 42.6%), creatine (n = 88; 37.1%), and caffeine pills (n = 70; 29.5%) were most reported. Supplementation was used to assist in training performance (n = 197; 83.1%) and increase wakefulness/alertness (n = 183; 77.2%). Males reported more often than females that they informed multiple elements of their nutrition practices with the information they *read or watched somewhere* (p = 0.002 to 0.012).

6.2.4 Conclusion

The peri-workout nutrition practices used by competitive powerlifters followed current sport nutrition guidelines, by using CHO sources to fuel for training and ensuring the provision of protein post-exercise. Competitive powerlifters may wish to exert caution with supplementation, as there is a risk of harm or inadvertent doping.

6.3 Introduction

Powerlifting is a strength sport that includes three main lifts: the back squat, bench press, and deadlift. Powerlifters are distinguished in classes by weight, sex, and age, and whether they use supportive lifting equipment or not (equipped and classic, respectively). Performance is determined by the athlete with the greatest cumulative load lifted across the three lifts, in the respective class. In this regard, the primary goal of the powerlifter is to improve maximal strength via training and nutrition. RT, as completed by powerlifters, results in several adaptations favourable for maximal strength development, such as neuromuscular adaptation (e.g., increased motor unit recruitment, skill acquisition), changes in muscle architecture, and the accumulation of lean muscle mass (i.e., hypertrophy) [173, 219]. Of these, skeletal muscle hypertrophy is a strong predictor of performance in powerlifting [174, 220]. Accordingly, nutrition strategies are of interest longitudinally to support adaptation, and acutely, to adequately fuel and recover from individual training sessions. For instance, EI across the competitive calendar may be periodised depending on the phase of training (e.g., off-season or competition preparation) to optimise body composition (e.g., lean mass accumulation and body weight manipulation) [176]. On the other hand, acute nutrition strategies may include rapid weight loss for powerlifters in a weight class with an upper limit in the days/hours before competition [181], or the deliberate timing of macronutrients and/or supplements before, during, and after training or competition to aid performance.

Nutrient timing is the intentional ingestion of whole and fortified foods, and dietary supplements, to fuel for and recover from acute and chronic exercise [6]. Nutrient timing research typically considers CHO and protein of primary interest, as the role of timing dietary fat for athletes performing RT is not clear [6]. The timing of CHO is of consideration due to its role as an important fuel source during higher intensity exercise, of which CHO's stored form in skeletal muscle, muscle glycogen, is of particular importance for fuelling high intensity muscle contraction [3]. Indeed, the acute ingestion of CHO improves RT volume performance in some circumstances [118]. In addition, dietary protein is of interest as it is a trigger of, and substrate for, muscle protein synthesis, which is the incorporation of amino acids into bound skeletal muscle proteins (e.g., myofibrillar and mitochondrial

proteins) [221]. RT also triggers the synthesis of myofibrillar proteins [222], which – acting synergistically with essential amino acids derived from dietary protein [223, 224] – contribute to skeletal muscle mass accumulation. Overall, there is potential for the timed ingestion of macronutrients to affect training performance and chronic adaptation of competitive powerlifters.

In addition to the provision of key macronutrients, dietary supplementation around training is of interest to RT athletes both for its potential effects on acute training performance and chronic adaptation (i.e., strength and muscle gain). For example, there is robust evidence that daily creatine monohydrate supplementation improves strength and body composition indices [225-227] and caffeine ingestion improves outcomes of muscle strength, power, and endurance [228]. The efficacy of these supplements on exercise performance is reflected in the International Olympic Committee's (IOC) position statement on dietary supplements [229] and the International Society of Sport Nutrition's position stand on caffeine [230]. However, many dietary supplements often lack robust evidence supporting their effects on health and performance, may cause adverse side-effects, and can contain contaminants, underdosed primary ingredients, and banned substances [231-233]. Therefore, different acute nutrition strategies have the potential to either positively influence training performance and chronic adaptation, or in some cases undermine health and performance.

Previously, the general nutrition practices of powerlifters were reported [234], but to our knowledge, no previous study has explored the nutrition strategies used by powerlifters before, during, and after their training sessions. Therefore, we surveyed actively competing powerlifters on their current acute nutrition practices around training (pre-, intra-, and post-exercise) and use the term 'peri-workout nutrition' as an umbrella term to reflect these acute nutrition practices [235]. An exploration of the peri-workout nutrition practices used by competitive powerlifters allows for a current account of these athletes' practices, the reasoning for their practices, and a discussion of how current peri-workout nutrition practices relate to sport nutrition guidelines.

6.4 Methods

The methods of the present study were published in full previously [234]. An open invite, anonymous international survey was built using Qualtrics software (Seattle, WA, USA) and distributed via social media between November 2020 and February 2021 to investigate the self-reported nutrition practices and beliefs of competitive powerlifters. Participant inclusion criteria were to (a) be 18 years of age or older, and (b) have competed in a drug-free sanctioned powerlifting competition within the previous 18 months. The study protocol was approved by the Auckland University of Technology Ethics Committee (20/312).

6.4.1 Survey content

The questionnaire was split into ten sections, of which the last five (i.e., peri-workout nutrition practices) are of interest in this manuscript. In order of appearance, Section 1 covered participants' descriptive characteristics and training history. Sections 2 – 5 covered nutrition practices across the competitive cycle, within specific competitive phases (e.g., the offseason or competition phase), on harder training days, and on easier training days, respectively. The results for sections 1 – 5 were reported previously [234]. The last five sections (sections 6 – 10) covered pre-exercise nutrition, post-exercise nutrition, fasted training, intra-exercise nutrition, and supplementation practices, respectively. A full transcript of the questionnaire with display logic can be found in Appendix B Ch. 6 Supplementary File I.

Definitions for concepts were provided to participants in the survey. A hard training day was defined as a high volume and/or high intensity session. A rest/easier training day was defined as passive or active recovery or a lower volume accessory day where none of the three powerlifting lifts were completed. A key training session was defined as a high quality/intensity session consisting of at least one of the powerlifting movements (including variations/derivatives). Fuelling was defined as eating foods before training. Fasting was defined as the completion of a training session without eating food or calorie containing drinks in the 8 hours prior.

6.4.2 Statistical analysis

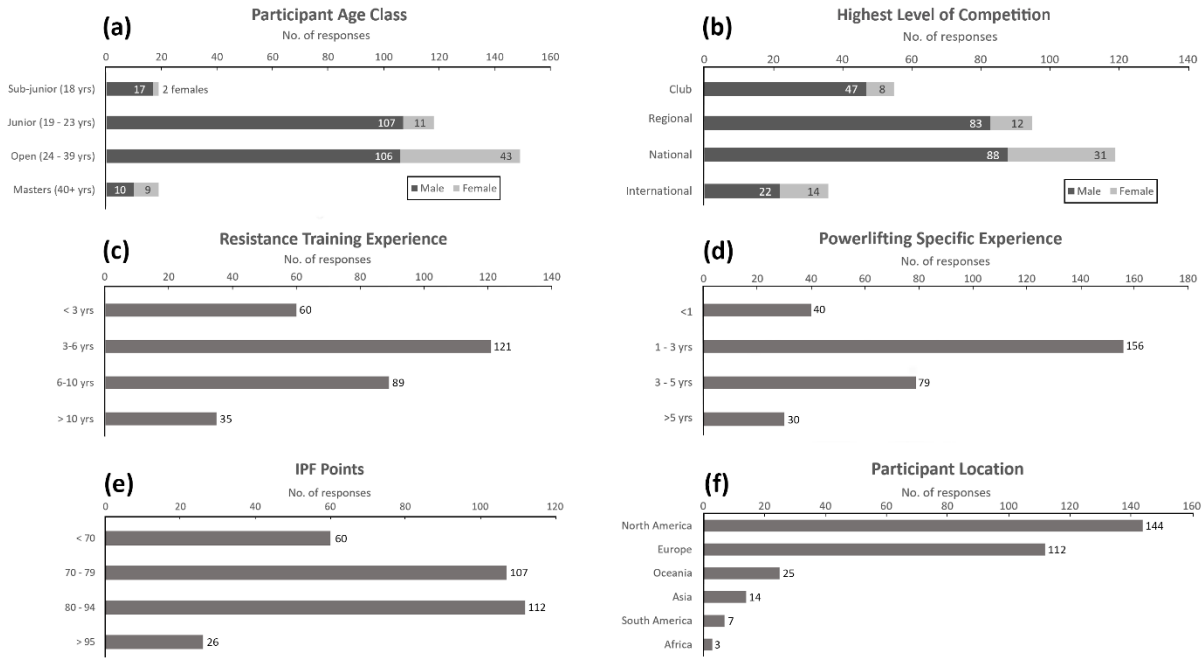
Only fully completed questionnaires were analysed. Missing data checks were performed to verify data integrity. Descriptive data were presented as number (*n*) and percentages (%). Categorical data were assessed by chi-square test and Cramer's V (φ_c). Where >20% of cells had an expected count of less than 5, Fisher's exact test was used. For the weight-class sub-group (4x2 contingency table), a follow-up individual chi-square test (or Fisher's exact test where the >20% expected count rule was violated) with Holm-Bonferroni correction was performed when a statistically significant result was observed. Cramer's V was interpreted as negligible (0.00 and under 0.10), weak (0.10 and under 0.20), moderate (0.2 and under 0.4), relatively strong (0.4 and under 0.6), strong (0.6 and under 0.8), and very strong association (0.8 to 1.0) [236]. Statistical significance was set at $p \leq 0.05$. Data were prepared and analysed in SPSS (version 27.0; IBM Corp, Armonk, NY), and follow-up chi-square and Fisher's tests were completed in R language for statistical computing (R Foundation for Statistical Computing, Vienna, Austria, 2021; Version 4.2.2) using the *Fifer2* package (https://github.com/dustinfife/fifer2/). The dataset and analysis code are available on the Open Science Framework: https://osf.io/xdu7s/.

Participants could select multiple answers for most questions; therefore, the percentage of responses for some questions could add up to more than 100%. Text answers to "other" responses were grouped into common themes/responses by the primary investigator (AK). Responses were analysed by sub-groups based on competitive division (males vs. females), age class (sub-juniors and juniors [SJ + J] vs. open and masters [O + M]), weight class (women's under 63, 57, 52, and 47kg classes [W63-] vs. women's under 72, 84 kg classes and 84 kg plus class [W72+] vs. men's under 83, 74, 66, 59, and 43 kg classes [M83-] vs. men's under 93, 105, 120 kg classes and 120 kg plus class [M93+]), and competitive calibre (i.e., IPF points where higher values indicate stronger powerlifters relative to bodyweight) from the best 3-lift total in competition (less than 80 IPF points [79- IPF] vs. 80 IPF points or more [80+ IPF]).

6.5 Results

Descriptive statistics for the participant sample are presented in Figure 6-1.

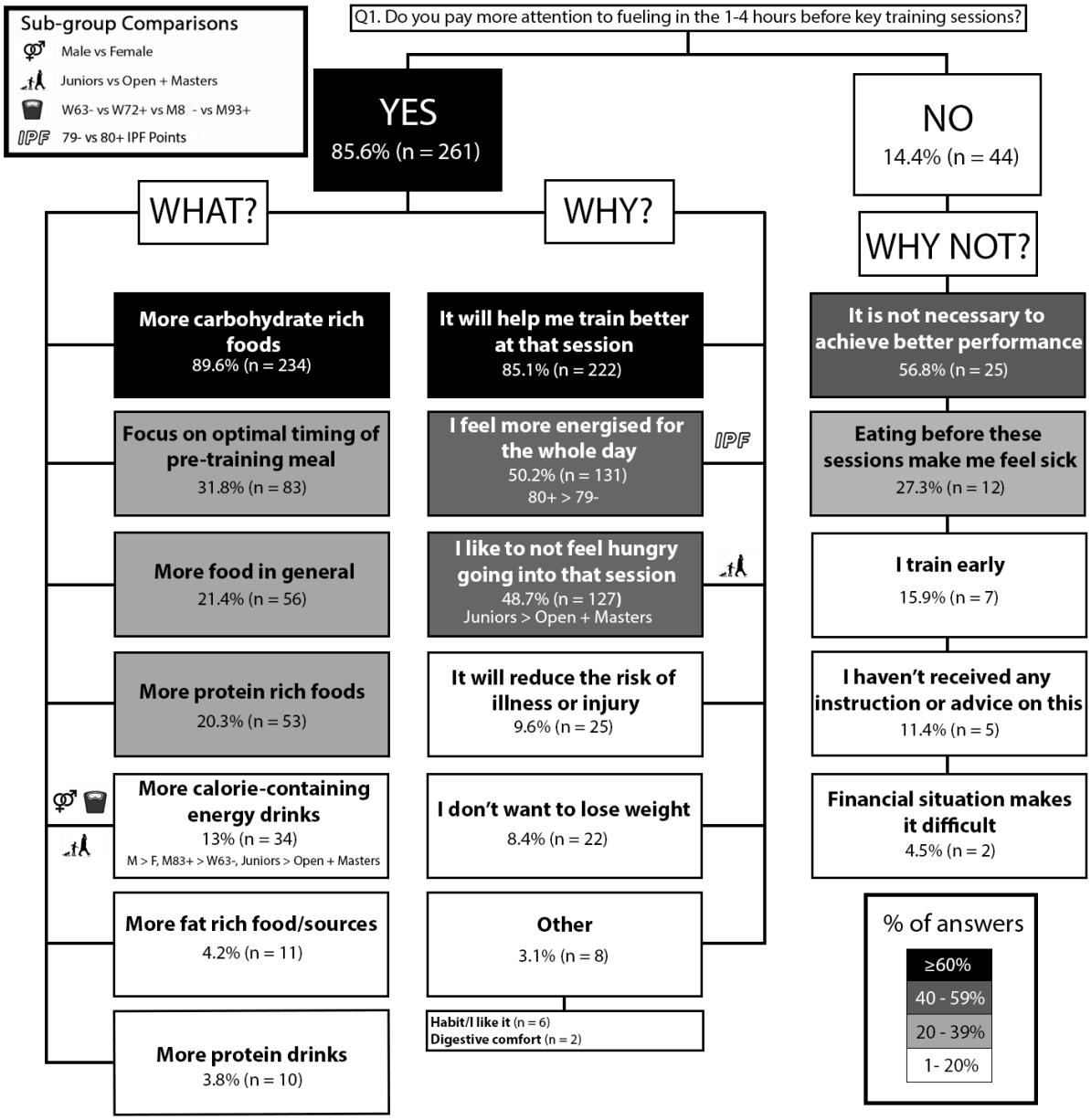
Figure 6-1: Descriptive participant characteristics of (A) age class, (B) competitive calibre, (C) resistance training experience in years, (D) powerlifting specific experience in years, (E) International Powerlifting Federation (IPF) points based on best total in competition, and (F) participants location. For (F), participants were from 47 countries, which were grouped by continent.



6.5.1 Question 1. Pre-exercise nutrition

Overall, 85.6% (n = 261) of participants reported paying attention to fuelling within 1-4 hrs before key training sessions, of which 89.6% (n = 234) ate more CHO rich foods and 85.1% (n = 222) reported paying attention to pre-exercise nutrition to assist with training performance. Males more often than females ($p = 0.020$; $\varphi_c = 0.133$), M83+ more often than W63- ($p = 0.026$; $\varphi_c = 0.218$), and SJ + J more often than O + M ($p = 0.036$; $\varphi_c = 0.120$), reported drinking more calorie containing drinks before training. Regarding why specific attention was paid to pre-exercise nutrition, 80+ IPF more often than 79- IPF reported feeling more energised for the day ($p = 0.013$; $\varphi_c = 0.143$) and SJ + J more often than O + M reported that they like to not feel hungry for the training session ($p = 0.005$; $\varphi_c = 0.160$). The detailed results for pre-exercise nutrition practices are presented in Figure 6-2.

Figure 6-2: Q1. Pre-exercise nutrition practices of 305 actively competing powerlifters. The prevalence of reported specific attention being paid to fuelling in the 1 to 4 h before a key training session, and the reason for following this practice. Percentages (%) are presented as the proportion of all participants that chose a specific answer (YES/NO), followed by a % of responses reporting various practices and reasons within these strategies. Number (n) of participants has been provided. Answer boxes and circles are colour coded based on the % of responses: ≥ 60%, black box with white font; 40 to 59%, dark grey box with white font; 20 to 39%, light grey with black font; < 20%, white box with black font. Symbols are used to indicate statistical significance from chi-square (or Fisher's Exact) test between sub-groups for sex (vector sex symbol), age class (human life cycle symbol), weight class (weight scale symbol), and IPF points (IPF symbol). Where significant differences were detected, the direction of difference is indicated in the corresponding box/circle (e.g., males reported more often than females would be indicated by M > F).



Males more often than females reported informing their pre-exercise nutrition practices by *reading or watching something* ($p = 0.004$; $\varphi_c = 0.167$) and from their *training partner* ($p = 0.032$; $\varphi_c = 0.122$). M83- ($p = 0.031$; $\varphi_c = 0.227$) and M93+ ($p = 0.031$; $\varphi_c = 0.228$) more often reported informing their pre-exercise nutrition practices by *reading or watching something* than W72+. The information sources used to inform pre-exercise nutrition practices are comprehensively presented in Table 6-1.

Table 6-1: Source of information informing peri-workout nutrition practices of powerlifters.

Question	**Answer**	**Source of Information (*n*)**									
		No specific source	*I read/ watched it*	*Coach*	*Sport Nutr.*	*Dietician*	*Scientist*	*Friend*	*Training Partner*	*Personal Trainer*	*Other*
Do you pay more attention to fuelling in the 1 to 4 hours **before** key training sessions?	Yes (n = 261)	79	119 †§	74	51	21	26	19	16 †	7	18
	No (n = 44)	37	3	4	2	1	0	0	0	0	1
Do you consume food and/or calorie containing drinks **during** training?	Yes (n = 211)	96	74 †	37 ‡	28	10	16	10	14	5	8
	No (n = 94)	78	8	5	4	3	2	0	0	0	1
Do you pay more attention to your nutrition **after** key training sessions?	Yes (n = 244)	73	114 †‡ǁ	70	48	16	19 ¶	14	14 †	8	14
	No (n = 61)	43	16 #	3	3	2	3	0	1	1	2
Do you intentionally complete training sessions in the **fasted state**?	Yes (n = 43)	33	6	2	0	1	0	0	1	0	2
	No (n = 262)	163	62 †	33	28	12	18	8	10	8	6
Do you pay attention to **supplementation** in the 2 hours preceding training sessions?	Yes (n = 237)	85	106 †	54	39	17	34	20	20 †‡	13	9
	No (n = 68)	49	15	3	3	1	5	1	1	0	2

Sport Nutr Sport Nutritionist

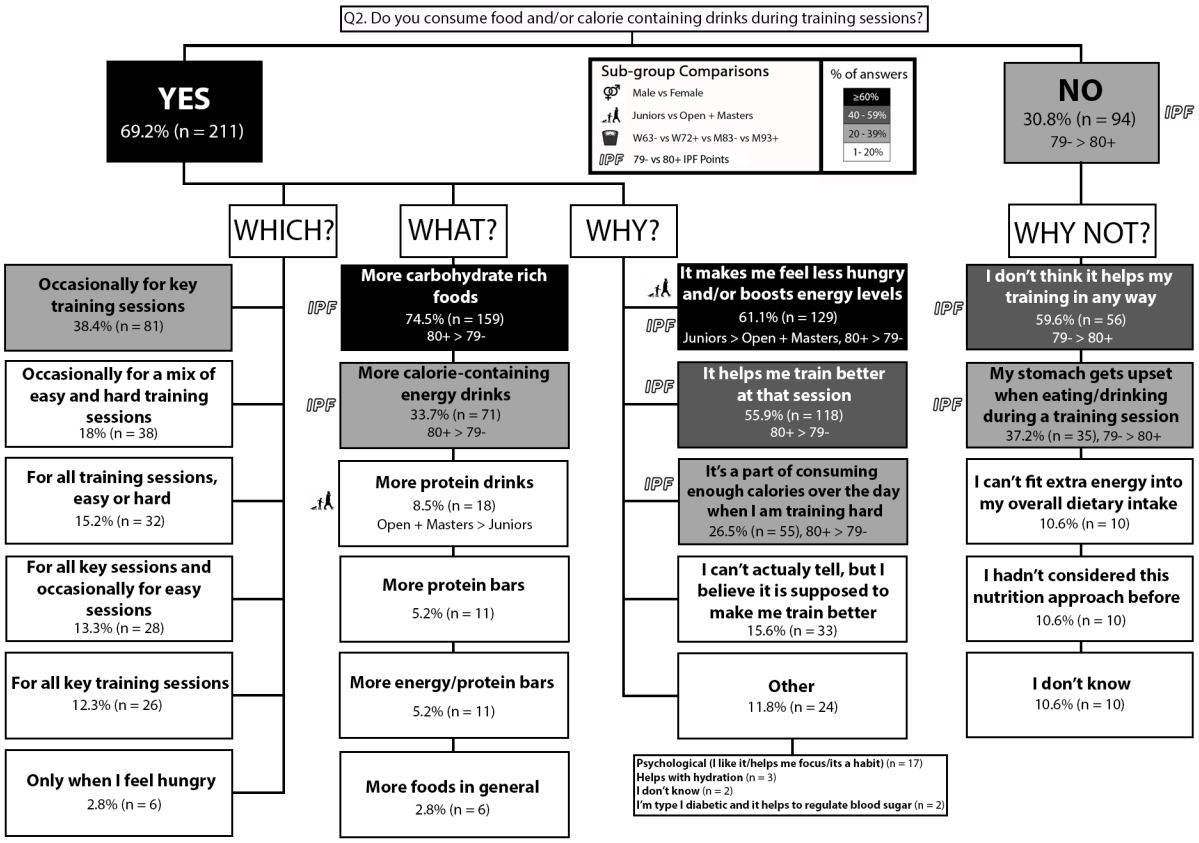
"*Other*" includes medical doctor, physiotherapist, and family member. Data are presented as numerical frequencies.

Significant differences ($p < 0.05$) of chi-square (or Fisher's Exact test) marked as: † male > female; ‡ Juniors > Open + Masters; ¶ Open + Masters > Juniors; § M83- & M93+ > W72+; ǁ 80+ IPF Points > 79- IPF Points; # 79- IPF Points > 80+ IPF Points

6.5.2 Question 2. Intra-exercise nutrition

Overall, 69.2% (n = 211) of participants reported consuming food and/or calorie containing drinks during training. CHO rich foods were most common (74.5%, n = 159) and their consumption was more often reported by 80+ IPF than 79- IPF ($p < 0.001$; $\varphi_c = 0.212$). 80+ IPF more often than 79- IPF reported consuming more calorie-containing energy drinks ($p = 0.032$; $\varphi_c = 0.123$). O + M more often than SJ + J reported consuming more protein drinks ($p = 0.046$; $\varphi_c = 0.114$). Regarding the purpose of intra-session nutrition, 61.1% (n = 112) answered that it made them feel less hungry or boosted energy levels, which was reported more often by 80+ IPF than 79- IPF ($p = 0.044$; $\varphi_c = 0.115$) and SJ + J than O + M ($p = 0.035$; $\varphi_c = 0.121$). 80+ IPF more often than 79- IPF reported that intra-session nutrition is used to aid training performance ($p = 0.006$; $\varphi_c = 0.157$) and a part of consuming enough calories over the day to support hard training ($p = 0.004$; $\varphi_c = 0.164$). 79- IPF more often than 80+ IPF reported not consuming food during training ($p = 0.009$; $\varphi_c = 0.151$) because they felt it did not help training performance ($p = 0.002$; $\varphi_c = 0.176$) or that it caused digestive issues ($p = 0.035$; $\varphi_c = 0.121$). The detailed results for intra-exercise nutrition practices are presented in Figure 6-3.

Figure 6-3: Q2. Intraexercise nutrition practices of 305 actively competing powerlifters. The prevalence of consuming food and/or calorie containing drinks during training sessions (YES/NO), followed by the type of training session, what is consumed, and the reason for this practice. Description of how to interpret is in the Figure 6-2 caption.



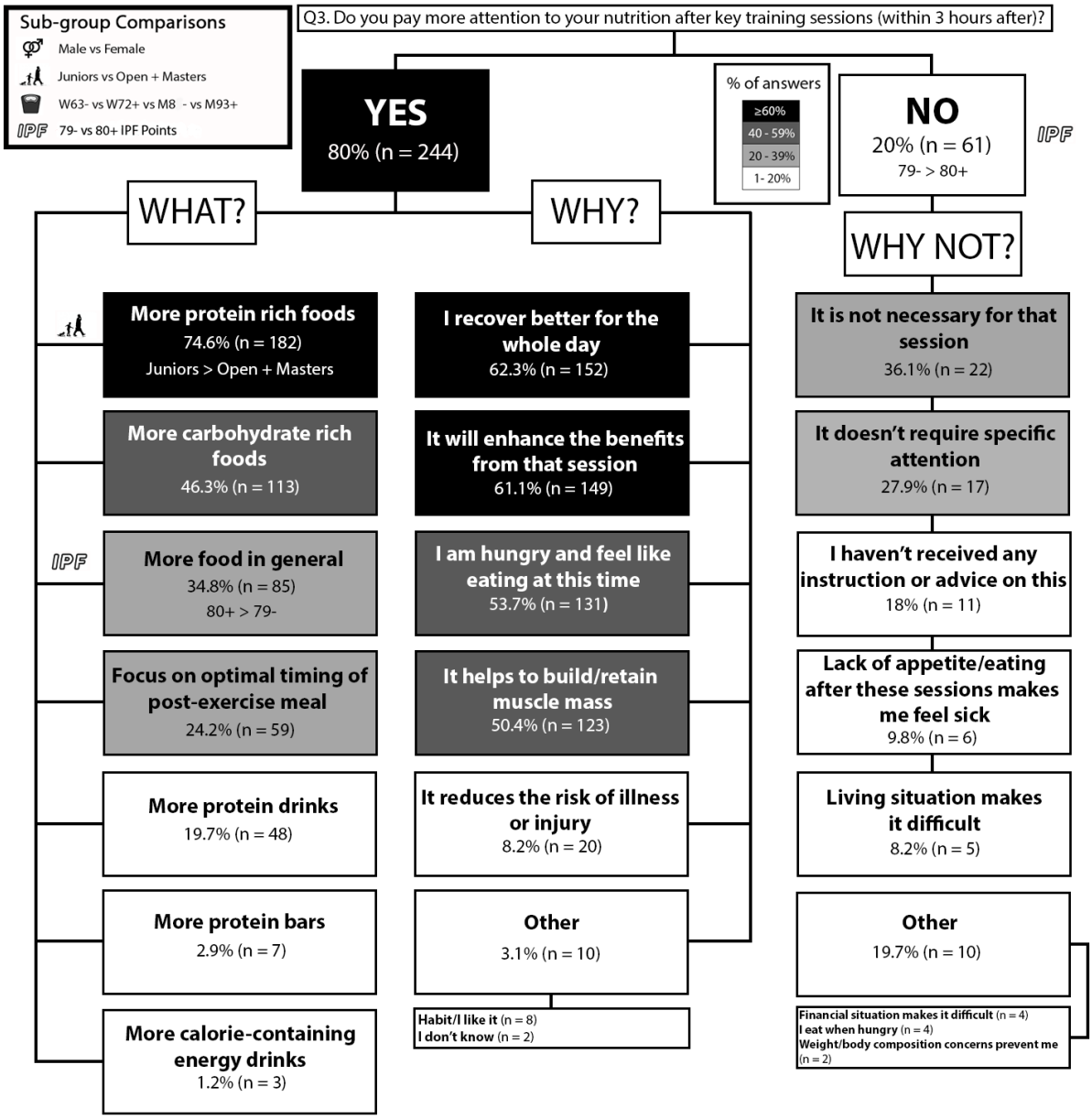
Males more often than females ($p = 0.002$; $\varphi_c = 0.179$) reported informing their intra-exercise nutrition practice by *reading or watching something*. SJ + J more often than O + M reported informing their intra-session nutrition practice from their *coach* ($p = 0.009$; $\varphi_c = 0.149$). The information sources used to inform intra-exercise nutrition practices are comprehensively presented in Table 6-1.

6.5.3 Question 3. Post-exercise nutrition

Overall, 80% (n = 244) of participants reported paying attention to post-exercise nutrition, of which 152 (62.3%) and 149 (61.1%) reported recovering better for the whole day and an enhancement of the benefits from the training session as the purpose, respectively. Protein rich foods were most popularly selected (74.6%, n = 182), which SJ + J more often reported than O + M ($p = 0.004$; $\varphi_c =$

0.165). 80+ IPF more often than 79- IPF reported eating more foods in general after training ($p = 0.007$; $\varphi_c = 0.155$) and 79- IPF more often than 80+ IPF reported not paying specific attention to post-exercise nutrition ($p = 0.029$; $\varphi_c = 0.125$). The detailed results for post-exercise nutrition practices are presented in Figure 6-4.

Figure 6-4: Q3. Postexercise nutrition practices of 305 actively competing powerlifters. The prevalence of reported specific attention being paid to nutrition after a key training session (within 3 h) (YES/NO), followed by what foods or calorie containing drinks are consumed, and the reasons for following this practice. Description of how to interpret is in the Figure 6-2 caption.

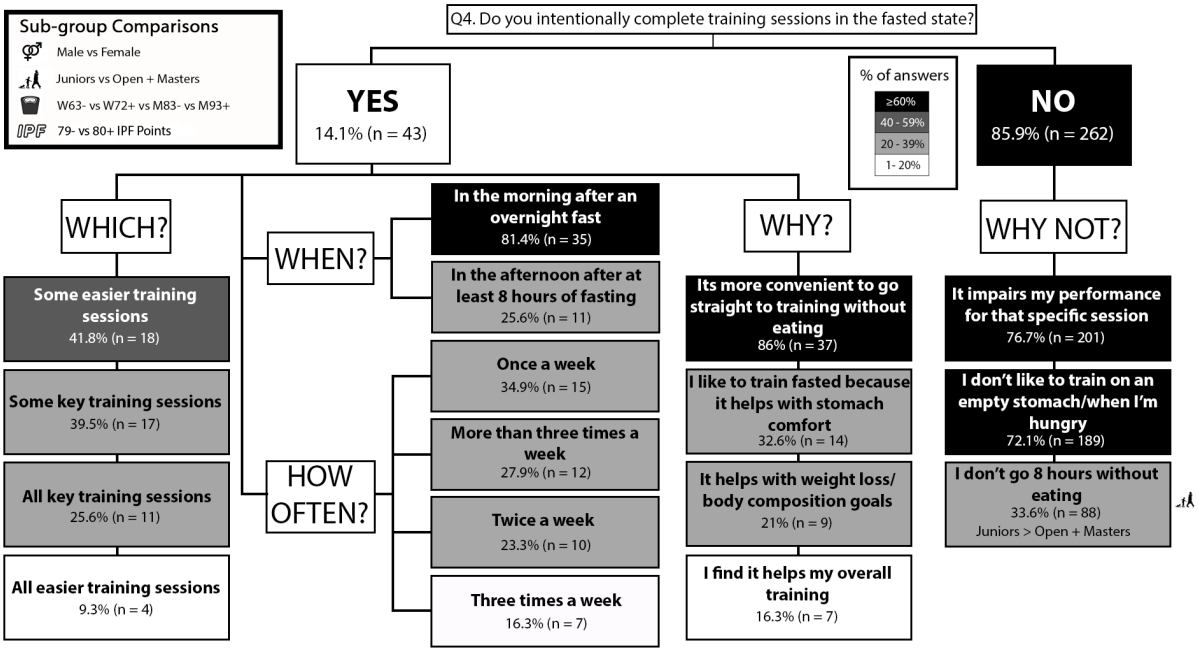


Males more often than females ($p = 0.003$; $\varphi_c = 0.170$), SJ + J more often than O + M ($p = 0.010$; $\varphi_c = 0.147$), and 80+ IPF more often than 79- IPF ($p = 0.025$; $\varphi_c = 0.128$) reported informing their post-exercise nutrition practice with information from *reading or watching something*. O + M more often than SJ + J reported *a scientist* as the source of information for their post-nutrition practice ($p = 0.031$; $\varphi_c = 0.124$). Males more often than females reported that their attention to post-exercise nutrition was informed from their *training partner* ($p = 0.046$; $\varphi_c = 0.114$). 79- IPF more often than 80+ IPF reported informing their practice of not paying specific attention to post-exercise nutrition with information from *reading or watching something* ($p = 0.007$; $\varphi_c = 0.155$). The information sources used to inform post-exercise nutrition practices are comprehensively presented in Table 6-1.

6.5.4 Question 4. Fasted training

Overall, 85.9% (n = 262) of participants did not complete any training sessions in the fasted state. The most common reasons were that fasted training impairs performance (76.7%, n = 201) and to avoid training while feeling hungry (72.1%, n = 189). SJ + J more often than O + M reported that they did not go eight hours without eating ($p = 0.031$; $\varphi_c = 0.123$). Of the participants (14.1%, n = 43) that completed at least some training sessions in the fasted state, fasted training most often occurred the morning after an overnight fast (81.4%, n = 35) and because it was more convenient to go straight to training than eat first (86%, n = 36). The detailed results for fasting practices are presented in Figure 6-5.

Figure 6-5: Q4. Fasted training nutrition practices of 305 actively competing powerlifters. The prevalence of reported intentional fasted training (YES/NO), and the reasons for following this practice. Description of how to interpret is in the Figure 6-2 caption.



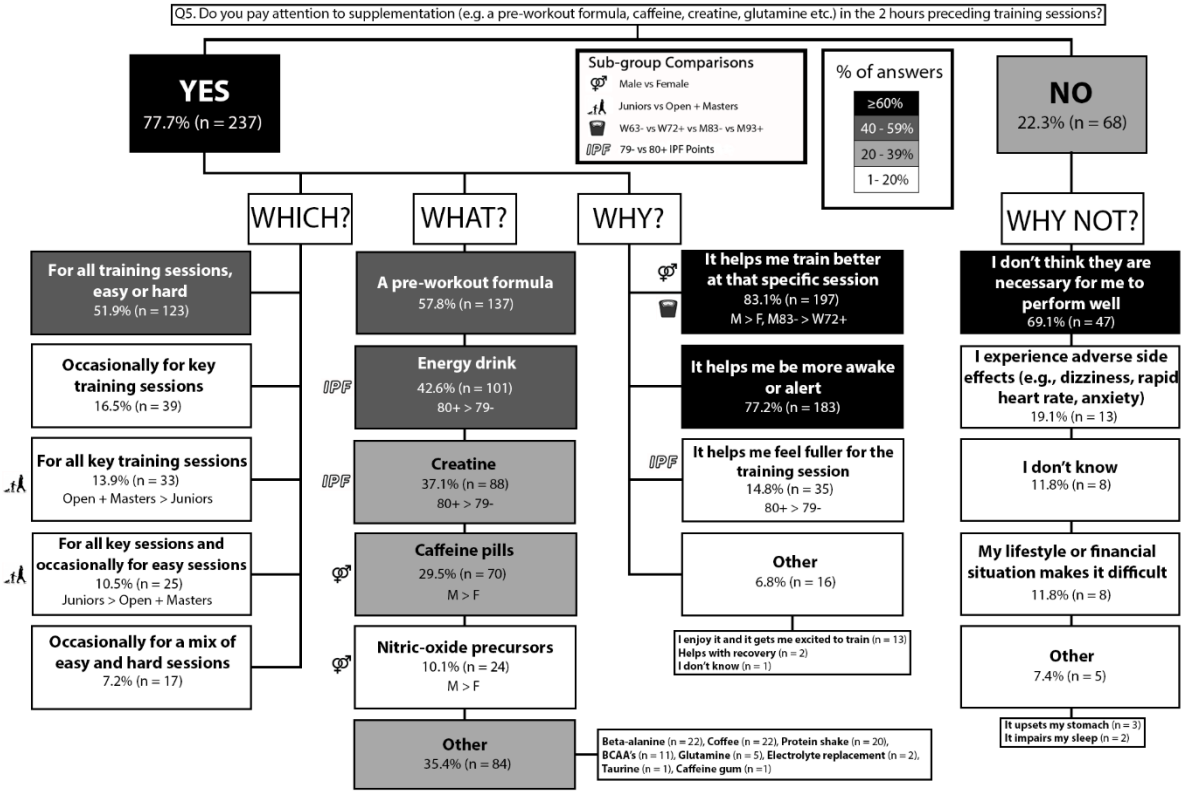
Males more often than females (p = 0.012; φ_c = 0.144) reported informing the practice of not completing fasted training with information from *reading or watching something*. The information sources used to inform fasting practices are comprehensively presented in Table 6-1.

6.5.5 Question 5. Supplementation

Overall, 77.7% (n = 237) of participants reported paying attention to supplementation in the 2-hrs preceding training. O + M more often than SJ + J reported paying attention to supplementation for all key sessions. SJ + J more often than O + M reported paying attention to supplementation for all key sessions and occasionally for easy sessions (p = 0.011; φ_c = 0.145). Regarding supplementation type, 80+ IPF more often than 79- IPF reported supplementing with an energy drink (p = 0.042; φ_c = 0.116) or creatine (p = 0.038; φ_c = 0.119). Males more often than females reported pre-exercise supplementation with caffeine pills (p = 0.021; φ_c = 0.132) and nitric-oxide precursors (p = 0.018; φ_c = 0.152). Regarding why supplementation is used, 83.1% (n = 197) reported using supplementation to assist in training performance which was more often reported by males than females (p = 0.009; φ_c =

0.150) and M83- than W72- ($p = 0.036$; $\varphi_c = 0.241$). 80+ IPF more often than 79- IPF reported that supplementation helped them feel fuller for the training session ($p < 0.001$; $\varphi_c = 0.210$). The detailed results for supplementation practices are presented in Figure 6-6.

Figure 6-6: Q5. Pre-exercise supplementation practices of 305 actively competing powerlifters. The prevalence of reported specific attention to pre-exercise supplementation (YES/NO), followed by which training session, what type of supplement, and the reasons for following this practice. Description of how to interpret is in the Figure 6-2 caption.



Males more often than females reported a focus on supplementation with information from *reading or watching something* ($p = 0.002$; $\varphi_c = 0.178$) and/or from their *training partner* ($p = 0.016$; $\varphi_c = 0.138$). SJ + J more often than O + M reported that their focus on supplementation was informed by their *training partner* ($p = 0.020$; $\varphi_c = 0.134$). The information sources used to inform supplementation practices are comprehensively presented in Table 6-1.

6.6 Discussion

The purpose of the current study was to explore the peri-workout nutrition practices of competitive powerlifters. There are several key findings: (1) Most powerlifters focus on the provision of CHO before and during training to aid training performance and boost energy levels; (2) most powerlifters do not complete training sessions fasted; (3) most powerlifters emphasise protein ingestion after training to aid in recovery and enhance the benefits of training; and (4) most powerlifters report using supplementation for at least some training sessions to aid performance and increase wakefulness/alertness. Regarding the source of information that informed peri-workout nutrition practice, there was a trend for males to report using information from *reading or watching something* more often than females. Various sub-group differences were detected, although there were no clear trends, and the associations were generally weak to moderate which limits the interpretation of the practical significance of the detected differences. Overall, these findings suggest that competitive powerlifters follow current sport nutrition guidelines.

6.6.1 Pre- and intra-exercise fuelling strategies

Most powerlifters reported paying more attention to fuelling in the 1-4 hrs before key training sessions, of which most reported emphasising CHO ingestion (Figure 6-2). Similarly, over two thirds reported consuming food and/or calorie containing drinks during at least some training sessions, of which most reported an emphasis on CHO provision (Figure 6-3). Along with phosphocreatine stores, CHO is an important metabolic fuel source during moderate to high-intensity exercise [2, 22], of which the stored form of CHO in skeletal muscle, muscle glycogen, is considered of particular importance for higher-intensity exercise [3]. CHO may also have an influence on exercise performance via central mechanisms in which receptors of the mouth sense the presence of CHO and relay messages to the regions of the brain associated with reward and motivation [237]. Current sport nutrition guidelines recommend consuming CHO solely or with protein before and during RT for the purpose of augmenting muscle glycogen stores (that may acutely improve training performance) and promoting positive nitrogen balance, respectively [6]. Indeed, CHO ingestion before and during RT improves total session

training volume performance for longer duration training sessions (> 45 mins), where the fast duration before training is longer (> 8hrs), and the ergogenic effect is larger when more sets are performed [118]. Thus, the pre-exercise (Figure 6-2) and intra-exercise (Figure 6-3) nutrition practices of competitive powerlifters reported in the current study agree with current sport nutrition recommendations.

6.6.2 Post-exercise nutrition practices

Most powerlifters reported paying more attention to nutrition within 3 hrs following training, of which most reported consuming more protein foods for the purpose of recovering better for the whole day and enhancing the benefits from training (Figure 6-4). Current sport nutrition recommendations advise athletes to ingest 0.3 g/kg body weight of protein post-exercise [17], as the essential amino acids derived from dietary protein are used to stimulate muscle protein synthesis and repair [238]. However, muscle protein synthesis is upregulated for at least 24 hrs following RT [239]; thus, it has been argued that a focus on protein intake in the few hours following training (referred to as the "anabolic window") is likely unnecessary if sufficient total daily dietary protein is consumed [240]. Indeed, there is no significant effect of protein timing on muscle hypertrophy where total daily protein intake is controlled for [241]. Thus, while the timing of protein may not be imperative, post-exercise protein ingestion may be prudent for powerlifters as a practical strategy that promotes adequate total daily protein intake across the day. Authors of recent meta-analyses recommend a daily protein intake ≥ 1.6 g/kg BM to optimise lean mass accretion with RT [242], but up to 2.2 g/kg BM for those wishing to maximise potential muscle gains [182]. Similarly, 1.5 g/kg daily total protein is sufficient to support strength gain with RT [243]. It should be noted that higher protein intakes are generally advised for RT athletes in a caloric deficit to aid in the preservation of lean mass [238], which is often used by powerlifters competing in weight restricted classes leading into competition. However, there are few trials [244-247] investigating the effects of higher versus lower protein intakes with RT on body composition outcomes, precluding firm recommendations for total daily protein intake during caloric deficit. Aiming for at least ~2.2g/kg BM daily protein during caloric deficit may be a simple strategy for powerlifters to employ. Overall, ensuring that at least 1.6 g/kg BM total daily protein is ingested supports strength

and lean mass accumulation for the powerlifting athlete, and higher intakes may be required for powerlifters undergoing caloric restriction (~2.2 g/kg BM).

In addition to protein intake, current sport nutrition recommendations also emphasise post-exercise CHO ingestion to facilitate the replenishment of glycogen stores, which is a key fuel source for high intensity exercise [6, 17]. Just under half (46.3%, n = 113) of powerlifters who reported emphasising post-exercise nutrition ate more CHO (Figure 6-4). Recommendations for post-exercise CHO ingestion aim to maximise the refuelling time after bouts of exercise that are highly dependent on CHO as a fuel source, especially in preparation for a second session later in the day (e.g., am and pm sessions). However, current post-exercise CHO recommendations are based on endurance exercise where multiple, potentially glycogen depleting, training sessions may be completed per day. RT induces a comparatively modest decrement in total muscle glycogen stores (24 – 40%) [20-22], and powerlifters often complete one session per day (which may not include the same muscle groups), making the applicability of common sport nutrition recommendations to strength sports less specific. Indeed, a post-exercise meal delivering 1.5 g/kg CHO was sufficient to mostly replenish (91%) muscle glycogen stores 6-hrs after exhaustive leg extension RT [23]. Thus, for the powerlifter performing one training session per day, personal preference can guide food selection and timing of post-exercise meals and snacks. This practice will likely be sufficient to meet training demands assuming athletes achieve a moderate intake of daily dietary CHO (3 – 7 g/kg body weight) to support glycogen replenishment, as outlined by current sport nutrition guidelines for strength/power athletes [5].

6.6.3 Supplementation

Most powerlifters reported paying attention to supplementation practices in the 2 hrs preceding training and just over half reported paying attention to supplementation before all training sessions (Figure 6-6). The most common reasons for supplementation were to assist with training performance and to help with wakefulness and alertness (Figure 6-6). Despite the ubiquity of supplements on the market, few have demonstrated robust effects on exercise performance. Current recommendations identify caffeine, creatine (monohydrate), nitrate, sodium bicarbonate, and possibly beta-alanine as

dietary supplements that directly improve sports performance [229], of which caffeine and creatine monohydrate have robust evidence that demonstrates an ergogenic effect relevant to RT performance [122, 248]. In the present study, powerlifters reported the use of caffeine as a single nutrient (caffeine pills) and in multi-ingredient products/drinks (pre-workout formulas, energy drinks, coffee) in the hours preceding training. Current recommendations are to ingest a caffeine dose of 3 – 6 mg/kg BM caffeine ~60 mins before exercise [229, 230]. However, lower doses of caffeine (1 – 2 g/kg BM or 1 – 2 cups of coffee) similarly confer a small ergogenic effect on RT performance as higher doses [249]. Caffeine is a stimulant, and higher doses of caffeine may cause adverse side-effects (e.g., loss of sleep, elevated HR, nervousness, abdominal discomfort) [230, 250]. Thus, it may be prudent for athletes to start with a lower dose of caffeine (i.e., 1 – 2 g/kg BM), which is then gradually increased to ascertain an appropriate ergogenic dose that considers individual response and tolerance. Unlike the acute effects of caffeine, the ergogenic effect of creatine arises with chronic supplementation that saturates intra-muscular creatine stores [19]. Current guidelines are for athletes to consume 3-5 g/day of creatine monohydrate, with higher doses for larger athletes (5 – 10g/day) [248]. Taken together, only a few supplements (i.e., caffeine and creatine) are backed by robust evidence, and those that are, confer small effects on training performance.

The term "supplementation" was not defined for participants in the current study, and the posed question emphasised acute ingestion before a training session and offered examples of what could be considered ergogenic supplements or sports foods [251]. The IOC defines a dietary supplement as: "A food, food component, nutrient, or non-food compound that is purposefully ingested in addition to the habitually-consumed diet with the aim of achieving a specific health and/or performance benefit" [229]. Supplementation may also be used by powerlifters outside of the pre-exercise timeframe and for a variety of purposes beyond training performance that may include medicinal, general health and well-being, and sponsorship reasons. These reasons and their prevalence require future exploration. Survey data generally indicate that supplement usage is more common in males than females, and usage increases with the level of training/performance and age [229, 252]. In the current study, there were no sub-group differences reporting yes/no to specific attention to supplementation in the hours preceding

training. SJ + J more often than O + M reported using supplementation occasionally for easy sessions in addition to all key sessions. This may reflect a greater frequency of use across all training sessions for younger powerlifters, although this sub-group difference was a weak association ($\varphi_c = 0.145$) and should be interpreted with caution. Females generally report using supplementation for health purposes; whereas, males more often report supplementation to enhance performance [252]. This agrees with the findings of the present study, as males reported using pre-exercise supplements for the purpose of training better at that specific training session more often than females.

It should be noted that while most powerlifters using supplementation did report a source of information informing their practice (n = 152, 64.1%), a minority reported *sport nutritionist* (n = 39, 16.2%) or *dietician* (n = 17, 7.2%) guidance in their decision making, with no sub-group differences (i.e., age, sex, and weight class, or competitive calibre) for nutrition professional informed decisions. Some supplements may contain underdosed active ingredients [229], or excessive doses of potentially toxic ingredients [253]. Indeed, adverse health effects associated with supplementation have been reported in the literature [254, 255]. In addition, anabolic androgenic steroids, ephedrine, and stimulants (or metabolites thereof) have been reported in dietary supplements [256, 257], and are highly prevalent in commercial sport nutrition supplements [258], which may increase the risk of inadvertent doping and a violation of anti-doping rules for powerlifters competing in drug-tested federations. Given these risks, the costs and benefits of supplementation need to be carefully weighed and lower risk supplements may wish to be sought. Third-party, independent testing (e.g., ConsumerLab, Informed Sport, Banned Substances Control Group) of supplements, identified by seals/markers on the product of the third-party company used, may provide some assurances regarding lower risk products [232]. There are also numerous online resources available for athletes, such as those established in the UK (http://sport.wetestyoutrust.com/), Germany (http://www.koelnerliste.com/), the Netherlands (http://macho.nl/nzvt), Australia (http://hasta.org.au/), and U.S. (http://info.nsf.org/Certified/dietary/). In addition, the "high risk list" curated by the U.S. Anti-Doping Agency provides examples of supplements that pose an anti-doping risk (http://www.usada.org/athletes/substances/supplement-

connect/high-risk-list/). Overall, dietary supplementation is not free of risk for the powerlifter but can be minimised with education and guidance from nutrition professionals.

6.6.4 Limitations

The current study has several limitations. Firstly, the analysis relies on self-reported nutrition practices that could be subject to recall errors and participant bias. Indeed, previous research on endurance athletes has observed discrepancies between participant reported dietary trends and actual intake [216, 217]. In addition, we could not assess reliability due to the anonymous nature of the survey. Secondly, we did not define all terms used in the questionnaire for the participants (e.g., supplementation or fasting), nor were quantities defined for potential answers (e.g., what constitutes a CHO/protein/fat rich food), although some examples were given. Participants were required to be at least 18 years old to be eligible for inclusion in the present survey, which excluded sub-junior powerlifters who were not yet 18 years old (14 – 17 years old). While we have pooled sub-junior (at least 18 years old) and junior (19 – 23 years old) powerlifters for the analysis, it should be noted that the results may not generalise to sub-junior powerlifters less than 18 years old. The large, international sample enabled sub-group analysis of sex, age, and weight class and competitive calibre. Most respondents (84%) resided in North America and Europe, which limits the generalisability of the results to different regions as various influences, such as cultural and socioeconomic factors, could contribute to different food choices [218]. However, we note that the sample was convenience based and our analysis should be considered descriptive and exploratory, rather than confirmatory. Only 21% of participants (n = 65) were female, which may limit the generalisability of the findings. Given the disparity in the number of female and male (n = 240) respondents, the sub-group analyses for weight class (i.e., W63-, W72+, M83-, and M93+) and competitive division (male or female) need to be interpreted with caution as these results may be spurious (i.e., false positive) or of limited practical significance.

6.7 Conclusion

The current study is the first to characterise the self-reported peri-workout nutrition practices of competitive powerlifters. The key findings were that competitive powerlifters rarely practiced fasted training and commonly use pre- and intra-exercise nutrition strategies that emphasise CHO ingestion to aid training performance and boost energy levels. Most powerlifters reported paying attention to post-exercise nutrition and emphasising protein rich foods. The most common reasons for post-exercise nutrition practices included recovering better for the day, enhancing the benefits of training, attenuating hunger, and helping to build/retain muscle mass. Supplementation in the hours before training was reported by most powerlifters, of which a source of caffeine (pre-workout formula, energy drink, caffeine pills, coffee) or creatine was most common. Given the prevalence of the use of formulated foods and multi- and single-ingredient products as supplements, competitive powerlifters should consider third-party tested supplements to minimise the risk of potential contamination with banned substances and underdosing of ergogenic ingredients. Overall, the findings suggest that competitive powerlifters implement nutrition strategies around their training sessions that are supported by current sport nutrition guidelines/recommendations.

Chapter 7: Isoenergetic Pre-Exercise Meals Varying in Carbohydrate Similarly Affect Resistance Training Volume Performance Compared to Placebo: A Cross-over Trial

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7.1 Preface

This chapter shifts from observational survey work (Chapters 5 - 6) to an experimental test of acute CHO ingestion in a controlled RT setting. Building on earlier mechanistic and meta-analytic evidence that acute CHO can enhance RT volume in some circumstances (Chapters 2 - 4), as well as the observation that RT-centric athletes commonly employ acute CHO strategies in practice (Chapters 5 - 6), this chapter examines whether a high-CHO pre-exercise liquid breakfast (HCHO) confers any advantage over a taste and texture matched isoenergetic, isonitrogenous low-CHO comparator (LCHO), or low-calorie placebo, before a high-volume, predominantly upper-body RT session. By matching energy and protein across CHO conditions, and assessing performance, blood metabolites, and subjective appetite, this cross-over trial directly addresses a key conceptual gap identified in Chapter 1: whether CHO dose *per se* is a determinant of session volume under ecologically realistic conditions, or whether perceived feeding and general energy provision may be sufficient to support performance in this context.

7.2 Abstract

7.2.1 Purpose

CHO is an important fuel during moderate-to-high-intensity exercise. We hypothesised that pre-exercise CHO ingestion would improve RT volume performance.

7.2.2 Methods

In a cross-over design, sixteen resistance-trained participants (male = 13, female = 3) performed 3 sets of back squats, bench press, prone row, and shoulder press to repetition fatigue at 80% of 1-RM (~90min). Two hours prior, in randomised order, participants ingested HCHO (1.2g/kg BM), LCHO (0.3g/kg BM), or low-calorie PLA, taste and texture matched liquid breakfasts. Linear mixed models were used to analyse volume performance, subjective appetite ratings, and BG and BL.

7.2.3 Results

There were no significant differences between conditions for repetitions completed per session ($p = 0.318$) or exercise ($p = 0.973$). Pre- and post-exercise hunger was similar between conditions ($p = 0.155$). Satiation was greater in HCHO and LCHO versus PLA post-breakfast ($p = 0.007$ and $p = 0.002$, respectively) and pre-exercise ($p = 0.001$ and $p = 0.002$). Fullness was greater in HCHO and LCHO versus PLA post-breakfast ($p = 0.001$ and $p = 0.001$, respectively) and pre-exercise ($p < 0.001$ and $p < 0.001$). BL was greater mid- ($p < 0.001$) and post-exercise ($p < 0.0001$) and was similar between conditions ($p = 0.897$). BG significantly increased 30-mins after breakfast in HCHO versus LCHO and PLA ($p < 0.001$) and was similar between conditions post-exercise ($p = 1.000$).

7.2.4 Conclusion

The macronutrient or energy composition of a pre-exercise meal does not enhance upper-body dominant RT volume.

7.3 Introduction

Dietary CHO is an important fuel source for moderate to high intensity exercise and the provision of CHO before and/or during exercise is recommended by current sport nutrition guidelines [6, 17]. Dietary CHO is stored in the liver and skeletal muscle as glycogen, which are important energy sources for high intensity exercise [3]. Standard RT volumes induce modest muscle glycogen store decrements (24 – 40%) [20-23], and greater RT volumes cause greater decrements [24]. Skeletal muscle contains several distinct muscle glycogen depots (e.g., intramyofibrillar, intermyofibrillar, and subsarcolemmal) [25]. Intramyofibrillar glycogen stores are associated with Ca2+ release from the sarcoplasmic reticula during contraction and these stores become selectively depleted after standard RT volumes [29]. The combined impact of a modest decrease in total muscle glycogen and the depletion of intramyofibrillar stores may induce fatigue and limit exercise performance during RT [26-28, 259]. In addition, during periods of fasting, such as the overnight fast, liver glycogen becomes progressively depleted while muscle glycogen stores remain stable [30, 31]. Nonetheless, CHO feeding can modestly increase muscle glycogen stores (10 – 15%) after an overnight fast [33, 34] and acute CHO feeding before RT may augment glycogen stores in preparation for RT.

While there are recommendations for peri-workout nutrition for endurance training that intend to augment glycogen storage, there is less evidence to establish RT-specific recommendations. Acute CHO ingestion improved RT volume performance as reported in a recent meta-analysis [118], where the pre-exercise fast and session duration were longer (≥8 hrs and ≥45 mins, respectively), and the ergogenic effect of CHO was greater as more volume was completed, compared to low or zero energy placebo. In addition, several recent trials reported the potential impact of acute CHO feeding on RT volume performance via psychological (i.e., expectancy) and appetite suppression mechanisms [74, 75].

No previous trial investigating the effect of acute CHO feeding on RT performance has used a comparator placebo condition while equating EI within CHO conditions. Where energy is not matched between conditions, an ergogenic effect of CHO feeding may be due to energy provision itself, rather

than any specific metabolic influence of CHO on performance. In this sense, energy provision in general could provide varying fuel sources for exercise, a psychological effect (e.g., placebo), or an effect on subjective appetite not necessarily exclusive to CHO that could affect RT volume performance. Thus, we designed a randomised, double-blind cross-over trial investigating the effect of two iso-energetic and isonitrogenous pre-exercise meals with higher (1.2g/kg BM) and lower (0.3g/kg BM) CHO content, and a low-calorie placebo, on volume performance during a high-volume, full body, yet ecologically valid RT session. Given the established role of CHO in exercise performance, we hypothesised that HCHO would improve volume performance compared to LCHO and PLA.

7.4 Methods

7.4.1 Participants

Using previously published data for session squat repetitions completed [74], an *a priori* power analysis was completed using Power Analysis and Sample Size (PASS; version 15.0.5) software, which revealed 15 participants would be required to achieve a power of 0.8, an effect size of $f = 0.28$, an alpha $\alpha = 0.05$, and correlation $\rho = 0.7$. The correlation assumption was checked by a statistician separate to data collection after the first six participants had completed all trials, which was robust ($\rho = 0.78$).

Resistance trained males (n = 13) and females (n = 3) were recruited via advertisement (posters, social media, and University courses). Their descriptive characteristics are presented in Table 7-1. Twenty-six participants were initially screened for participation, of which n = 16 were deemed eligible and volunteered to participate in the trial. All participants provided written consent before commencing the study and completed testing with no dropouts. The CONSORT participant flow diagram is presented in Figure 7-1. The study protocol was approved by the University Ethics Committee (20/312). To be eligible for inclusion, potential participants must have been (a) able to squat 1.5 and 1.25 x bodyweight for males and females, respectively; (b) able to bench press 1.0 and 0.75 x bodyweight for males and females, respectively; (c) between 18-40 years in age; (d) a habitual consumer of breakfast (>5 times per week); (e) not have a pre-existing injury, metabolic disease or condition, or medical condition that would contraindicate safe participation in exercise; (f) not reportedly using ergogenic insulin-like

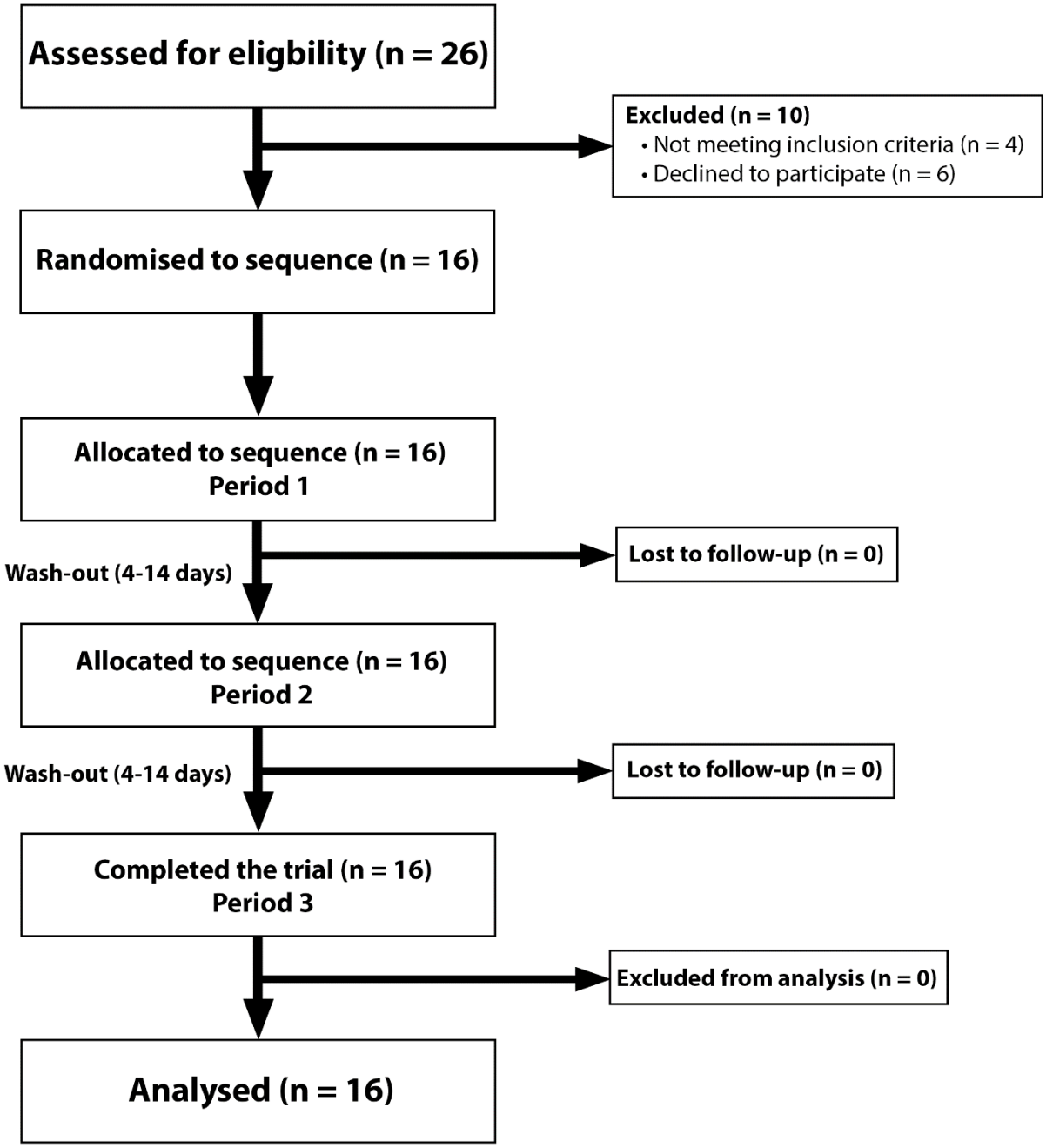
substances and/or anabolic/catabolic steroids, prohormones, or hormones known to affect muscle mass; (g) not reporting dietary requirements contraindicating the ingestion of a breakfast (e.g., reactions or aversions to ingredients); and (h) not previously privy to the contents of the pre-exercise meals (i.e., volunteers who pilot tested were aware of the nutritional composition).

Table 7-1: Participant descriptive characteristics (n = 16).

	Participants
Age (years)	26 ± 4
Height (cm)	176.6 ± 7.5
Body mass (kg)	83.68 ± 15.1
Resistance training experience (years)	4.8 ± 2.24
Relative squat strength (1-RM/body mass)	1.81 ± 0.4
Relative bench press strength (1-RM/body mass)	1.26 ± 0.3

Data is presented as mean ± standard deviation. *1-RM* = 1-repetition maximum.

Figure 7-1: CONSORT participant flow diagram through each stage of the randomised cross-over trial.



7.4.2 Design

This study was a double-blind, randomised, counterbalanced, cross-over trial consisting of, in order, two familiarisation sessions, one 1-RM session, and three experimental high-volume RT sessions. For each experimental session, participants arrived in the morning after an overnight fast (>10 hrs) and consumed one of three pre-exercise liquid breakfasts which were taste, texture, colour, and volume matched in pilot testing in randomised order (A) high CHO (HCHO; 1.2 g/kg BM CHO), (B) an isoenergetic and isonitrogenous low CHO (LCHO; 0.3 g/kg BM CHO), or (C) a low-calorie placebo (PLA) liquid breakfast. HCHO and LCHO primarily contained vanilla Super Mass Gainer (Dymatize, NC, U.S.) and vanilla KetoMeal (KetoLogic, NC, U.S.), respectively. HCHO and LCHO also contained water (350 – 500mL), Butter Powder (Garden of Life, FL, U.S.), and pure maltodextrin (NZ Starch, Auckland, NZ), of varying amounts depending on BM. PLA contained water, guar gum (Ceres Organics, Auckland, NZ), and vanilla FlavDrops (MyProtein, Manchester, UK). The sample average liquid breakfast nutrition values are presented in Table 7-2. The participants were told during familiarisation that the three conditions contained the same amount of total energy but differed in macronutrient composition. After the third experimental session was completed, participants learned of the true study design and were asked if they could confidently identify which trial was PLA.

Two hours after consuming the liquid breakfast, participants completed three sets of back squats, bench press, prone row, and shoulder press with 80% 1-RM, with repetitions completed to fatigue. Participants were randomised according to the Latin-square method. Possible sequences (i.e., ABC, ACB, BCA, BAC, CAB, CBA) were placed in individual sealed, opaque envelopes. A researcher independent from all data collection kept the sealed envelopes in a locked drawer and during participant sign-up, selected an envelope, assigned the sequence to the participant, then discarded the sequence. Once all six possible sequence combinations were assigned, a new block of six envelopes was generated. All testing was completed between April 2021 and May 2022. This trial was not prospectively pre-registered on a public registry.

Table 7-2: Average nutritional content of pre-exercise breakfasts (n = 16)

	High CHO (1.2 g/kg BM)	**Low CHO (0.3 g/kg BM)**	**Placebo**
Total energy (kJ)	2438 ± 478	2412 ± 505	11 ± 0
Relative total energy (kJ/BM)	29 ± 1	29 ± 1	0.1 ± 0
CHO (g)	103 ± 20	25 ± 5	0 ± 0
Protein (g)	20 ± 5	21 ± 4	0 ± 0
Fats (g)	10 ± 2	44 ± 9	0 ± 0
Water intake (mL)	1699 ± 608	1653 ± 719	1805 ± 747

CHO carbohydrate, *BM* body mass

7.4.3 Familiarisation (visit 1 & 2)

Participants' height (cm) and weight (kg) were recorded using a stadiometer (Seca Ltd, Hamburg, Germany) and digital calibrated scale (Tanita HD366, Tanita Corporation, Tokyo, Japan). Participants were verbally informed of the testing protocol for the 1-RM and experimental sessions. Participants were familiarised with the RT specific RPE/repetitions in reserve [260] and subjective appetite (hunger, satiety, and fullness) visual analogue [261] scales, and the instruction to lift as fast as possible during concentric phases (with self-selected eccentric tempo), which was implemented for all sessions, with feedback after each set during familiarisation. Participants were also instructed to take at least a momentary pause, but no longer than 2 seconds, between repetitions. Participants were asked what their best, most recent set of each exercise (or closest variation) was, to be used with the Lombardi prediction equation [262] to estimate a conservative 1-RM for 1-RM testing.

Participants performed a standardised dynamic warm-up and completed sets of 5, 3, and 1 repetition with 20, 40, and 60% of the estimated 1-RM, in the back squat, bench press, prone row, and shoulder press, with self-selected rest. After a mandatory 3-minute rest, participants completed 10 repetitions with 60% estimated 1-RM. A 20-kg barbell (Rogue, Columbus, Ohio, USA) and calibrated weight plates (Viking, Wellington, NZ) were used in all sessions. The squat and bench press were performed in accordance with IPF regulations using only approved "unequipped" lifting material aids

(i.e., knee sleeves and weightlifting belt). Briefly, the back squat required a depth where the hip crease passed the top of the knee when viewed laterally. For bench press, the necessary contact points were maintained (head, upper back, buttocks, and flat feet). The prone row and seated shoulder press were performed as outlined previously [263]. The chest had to maintain contact with the bench and the barbell to touch the bottom of the bench for the prone row, during which participants always wore lifting straps (VersaGrips, Maine, USA). The seated shoulder press was performed off safety pins in a squat rack and required the buttocks and upper back to remain in contact with the chair throughout the movement. A successful seated shoulder press repetition required the participant to raise the barbell off the safety pins to full elbow extension overhead, before controlling the eccentric movement of the barbell back onto the safety pins. All participants completed two familiarisation sessions, which were separated by at least 72 hrs.

7.4.4 Pre-trial standardisation

The participants were asked to track and record their daily food intake using the My Fitness Pal (various versions). During the two familiarisation sessions, the participants were provided a digital food scale, downloaded My Fitness Pal, practised inputting various food selections into My Fitness Pal, and received verbal instruction from a researcher on best practice for weighing/measuring and recording daily food intake. The participants were instructed to consume a daily CHO (4 – 7 g/kg BM) and protein (at least 1.6 g/kg BM) intake in line with current sport nutrition recommendations for RT athletes [5, 182] during participation in the study. Participants were not instructed regarding food selection but were provided food suggestions where necessary to enable adherence to the daily CHO and protein intakes. In addition, participants were instructed not to intentionally increase or decrease their total daily EI and to maintain their current supplement habits (i.e., not to introduce or stop taking supplements, and to maintain the dose). Where the participant was habituated to pre-workout supplementation, they were asked to consume the same dose of supplement, at the same time-point, prior to all sessions in the study. This was co-ordinated with a researcher and required the supplement to be low in total energy (<10 kcal). Participants were required to meet the daily CHO and protein recommendations for at least three days preceding each experimental trial, which was verified by a researcher who had access to the

participants' My Fitness Pal logs. Participant' water intake was not quantified during the pre-trial period. Participants were asked to maintain their normal training habits between each experimental trial and to refrain from physical activity for 48-hrs preceding 1-RM and experimental trials. Experimental sessions were separated at least 4, and up to 10 days, to provide adequate recovery and time to meet the standardised pre-trial nutrition requirements between experimental sessions.

7.4.5 1-RM (visit 3)

The 1-RM protocol consisted of 3 repetitions at 20, 40, and 60%; 1 repetition at 80% and 90%, followed by up to five 1-RM attempts [264, 265]. Mean concentric velocity, as measured by linear position transducer (Gymaware Kinetic Performance, Canberra, Australia), was used in concert with participant reported RPE/RIR to guide attempt selection. If a 1-RM attempt was successful, the load was increased 1 to 12.5kg in consultation with the participant. A 1-RM was recorded if the participant successfully completed the lift at 10 RPE or successfully completed an attempt at a lower RPE but failed a subsequent attempt. Three minutes and 3-5 mins rest were given between submaximal sets and 1-RM attempts, respectively. Barbell velocity feedback was not provided to participants during the 1-RM session, or at the subsequent experimental sessions. Constant verbal encouragement was provided by researchers. 1-RM for all four exercises were completed on the same day.

7.4.6 Experimental trials (visits 4-6)

After an overnight fast (>10 hrs), participants arrived at the laboratory at the time they habitually ate breakfast (all participants were between 0700 and 0900). The elected start time was kept consistent for each participant. Upon arrival, participants verbally confirmed adherence to the overnight fast (>10 hrs) and abstinence from physical activity (48-hrs), then BM was recorded. Thereafter, participants consumed the pre-exercise meal within 15-mins, which was prepared and delivered in an opaque container by a researcher independent from all data collection. To aid with blinding, participants were asked not to look in the opaque container and were required to wear a nose peg during its ingestion and for 2-mins following. A 10-sec water mouth rinse was performed after its ingestion, which was expectorated. Participants remained in the seated position for 2-hrs after completing the meal. Water

was provided *ad libitum* throughout each experimental trial, which was measured and recorded by a researcher.

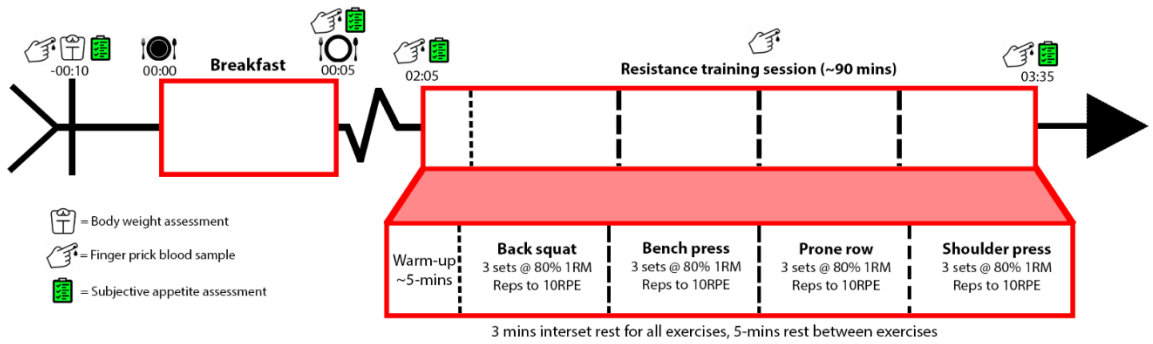
Two hours after the pre-exercise meal, participants began the RT session. Participants completed the same standardised warm-up before completing 3 sets of back squats, bench press, prone row, and seated shoulder press with repetitions completed to 10RPE (i.e., no repetitions left in reserve) at 80% of 1-RM. Exercise order was consistent for all participants and experimental trials. Rest before and between 10RPE sets was 3-mins. Rest between exercises was 5-mins. Each exercise was preceded by exercise specific warm-ups of 5, 3, and 1 repetition with 50, 70, and 90% of working load with 60-90 secs interset rest. Music was permitted at the discretion of the participant, and the same playlist and volume was used for all experimental sessions. Participants were reminded by researchers to complete the concentric muscle action as fast as they could for all lifts and standardised verbal encouragement was given to participants throughout all experimental sessions.

Performance outcomes of interest were total session repetitions completed, and total repetitions completed per exercise, which were silently counted by a researcher. Secondary outcomes were BG and BL, and subjective appetite (hunger, satiety, and fullness). The researcher that recorded all performance, metabolic, and subjective appetite values did not provide verbal encouragement to the participant.

BG was recorded at baseline (PREbreakfast) and 30 (POST30mins), and 60 (POST60mins) mins after the liquid meal; and before (POST120mins) and after (POST210mins) the RT session. BL was recorded immediately before (PREexercise), midway (MIDexercise; after bench press), and at completion (POSTexercise) of the RT session. Capillary BG and BL were drawn and analysed using a glucose (StatStrip Xpress2, Nova Biomedical, Germany) and lactate (Lactate Pro 2 LT-1730, Arkray, Japan) meter, respectively; and recorded by a researcher not providing verbal encouragement.

Subjective appetite (hunger, satiety, and fullness) was recorded before and after breakfast (PREbreakfast and POSTbreakfast, respectively) and RT session (PREexercise and POSTexercise, respectively). An overview of the experimental session is illustrated in Figure 7-2.

Figure 7-2: Experimental session overview. Note that the times are approximations. 1-RM = 1-repetition maximum, RPE = the resistance training repetitions in reserve/rating of perceived exertion scale.



7.4.7 Statistical analyses

All data were normally distributed as determined by graphical inspection and conventional value ranges for skewness and kurtosis [266-268]. Descriptive data are presented as mean ± standard deviation. Outcomes of interest were total number of repetitions completed per set and session; perceptual ratings of hunger, satiety, and fullness; and measures of BG and BL. To examine the effect of condition (i.e., HCHO, LCHO, and PLA) on the outcome of interest, linear mixed effect models were used. Condition (3 levels) and exercise (four levels) were treated as fixed effects; participants were treated as random effects. Random slopes were introduced to the models when their inclusion did not result in convergence error. Given the incorporation of both fixed and random effects, restricted maximum likelihood estimation was used to fit the models. Hedge's g effect sizes were calculated and the magnitude of difference was determined by standard thresholds: small (0.2 – 0.49), moderate (0.5 – 0.79), and large (>0.8) [92].

Multi-collinearity was checked by inspecting the variance inflation factors for all predictor parameters included in the linear mixed-effects model. The independence of observations was confirmed by performing autocorrelation diagnostics. For all linear models, a Gaussian distribution was assumed. Goodness of fit was checked by assessing the approximate normal distribution of model

residuals. Plotted residuals were checked to ensure homoscedasticity before applying the results of the model, to ensure all assumptions were met.

All statistical analysis was conducted in R language and environment for statistical computing [85] using the *lme4* [269], *emmeans* [270], and *ggeffects* [271] packages. Model assumptions were checked using the *performance* [272] and *DHARMa* [273] packages. The custom-written R script and associated dataset are available on the Open Science Framework repository (URL: https://osf.io/sc2up/). The figures in this manuscript present condition (i.e., HCHO, LCHO, and PLA) means with 95% CIs; however, if the reader is interested in individual responses across conditions, these are available on the repository.

7.5 Results

7.5.1 Baseline nutrition, session duration, and breakfast perception

Average 3-day protein (HCHO: 175 g/day; LCHO: 170 g/day; PLA: 168 g/day; p = 0.545), fat (HCHO: 94 g/day; LCHO: 97 g/day; PLA: 96 g/day; p = 0.929), CHO (HCHO: 363 g/day; LCHO: 355 g/day; PLA: 357 g/day; p = 0.739) and total energy (HCHO: 3042 kcal/day; LCHO: 3009 kcal/day; PLA: 2994 kcal/day; p = 0.843) intake between conditions produced a statistically non-significant result.

The average session duration was 93.4 ± 5.2 mins. *Ad libitum* water intake during the experimental trials produced a statistically non-significant result between conditions (p = 0.783).

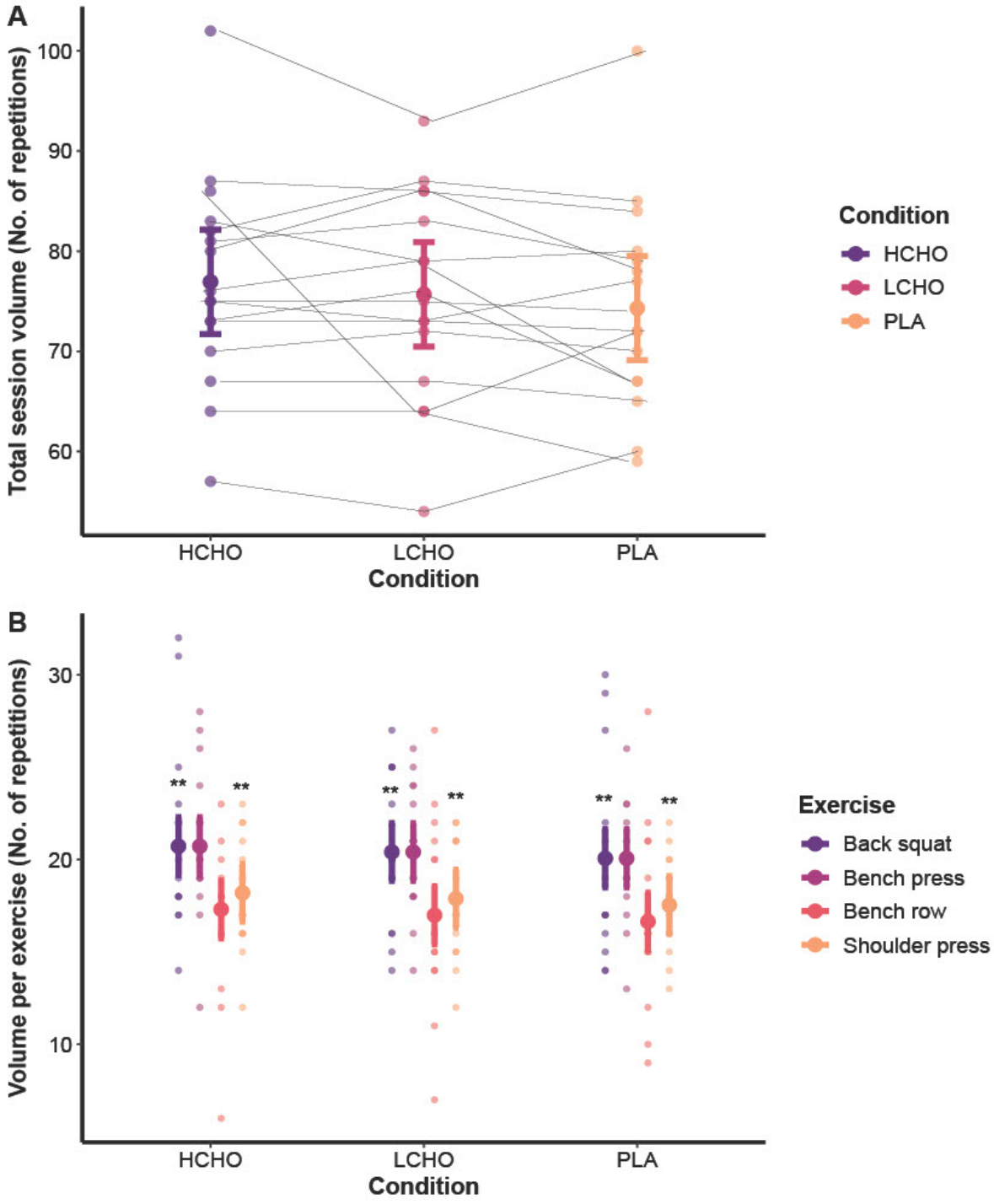
Nine of the 16 participants (56%) correctly identified which breakfast was PLA. Six stated that they could not identify which breakfast was PLA. One participant stated they could identify which breakfast was PLA but was incorrect.

7.5.2 Performance outcomes

There was no significant main effect of trial (trial 2: p = 0.57; trial 3: p = 0.06; compared to trial 1, respectively) or interaction between condition and trial (p = 0.35 – 0.84).

For total session repetitions completed, there was a non-significant result between conditions ($F = 1.192$; $p = 0.318$). For total session repetitions completed per exercise, there was a non-significant interaction between condition and exercise ($F = 0.208$; $p = 0.973$). There was a main effect of exercise on total session repetitions completed ($F = 6.84$; $p < 0.001$) as more squat repetitions were completed per session than prone row ($p < 0.001$; $g = 0.63$) and shoulder press ($p = 0.001$; $g = 0.5$). More bench press repetitions were completed per session than prone row ($p < 0.001$; $g = 0.83$) and shoulder press ($p = 0.001$; $g = 0.66$). Performance outcomes are presented in Figure 7-3.

Figure 7-3: Comparison between groups (HCHO, LCHO and PLA) for total session repetitions completed (Panel A) and repetitions completed per exercise (Panel B) after a high-volume resistance training session, as well as individual data points. Data were analysed using linear mixed models and are presented as mean and 95% confidence intervals. ** significantly greater than prone row and shoulder press ($p \leq 0.001$).



HCHO high carbohydrate breakfast, *LCHO* low carbohydrate breakfast, *PLA* placebo, *SQ* back squat, *BP* bench press, *SP* shoulder press.

7.5.3 Subjective appetite

7.5.3.1 Hunger

There was a non-significant interaction between condition and time-point (F = 1.594, p = 0.155). There was a significant main effect of time on hunger (F = 3.37, p = 0.027), as PREbreakfast was significantly greater than POSTbreakfast (p = 0.002). The results for hunger are presented in Figure 7-4 (A).

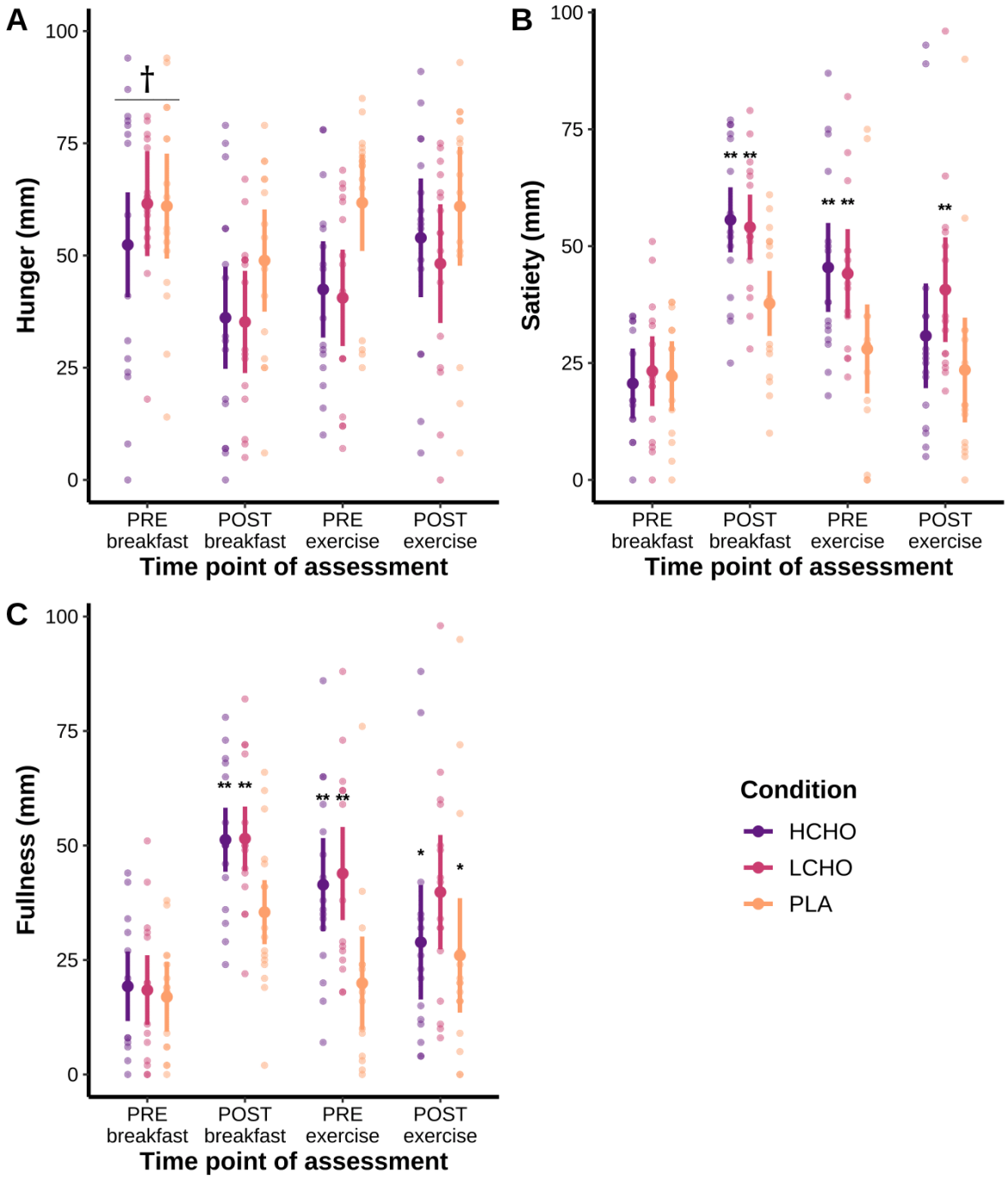
7.5.3.2 Satiety

There was a significant interaction between condition and time-point (F = 2.625, p = 0.02). Compared to PLA, satiety at the POSTbreakfast time-point was significantly greater in HCHO (p = 0.001, g = 0.68) and LCHO (p = 0.002, g = 0.69). Compared to PLA, satiety at the PREexercise time-point was significantly greater in HCHO (p = 0.001, g = 0.78) and LCHO (p = 0.002, g = 0.71). Compared to PLA, satiety at the POSTexercise time-point was significantly greater in LCHO (p = 0.001, g = 1.15), but not HCHO (p = 0.076, g = 0.37). The results for satiety are presented in Figure 7-4 (B).

7.5.3.3 Fullness

There was a significant interaction between condition and time-point (F = 3.672, p = 0.002). Compared to PLA, POSTbreakfast fullness was significantly greater in HCHO (p = 0.001, g = 0.63) and LCHO (p = 0.001, g = 0.63). Compared to PLA, PREexercise fullness was significantly greater in HCHO (p < 0.001, g = 1.13) and LCHO (p < 0.001, g = 1.33). POSTexercise fullness was significantly greater in LCHO when compared to HCHO (p = 0.026, g = 0.53) and PLA (p = 0.005, g = 0.72). The results for fullness are presented in Figure 7-4 (C).

Figure 7-4: Comparison between groups for subjective hunger (Panel A), satiety (Panel B), and fullness (Panel C) ratings after a high-volume resistance training session, as well as individual data points. Data were analysed using linear mixed models and are presented as mean and 95% confidence intervals. † significantly greater than POSTbreakfast ($p < 0.01$); ** significantly greater than PLA ($p \leq 0.001$); * Significantly lower than LCHO ($p \leq 0.05$)



HCHO high carbohydrate breakfast, *LCHO* low carbohydrate breakfast, *PLA* placebo

7.5.4 Metabolic markers

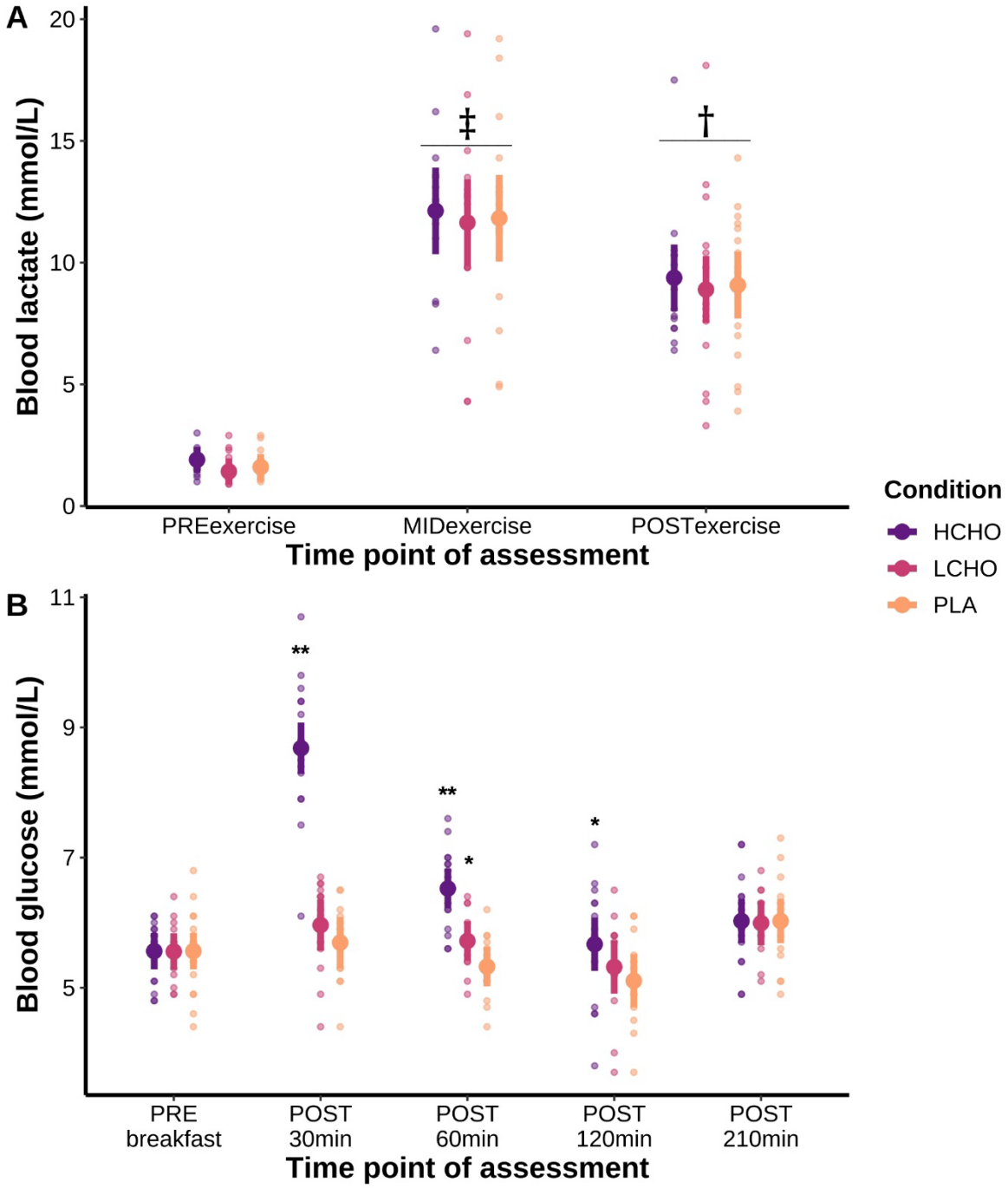
7.5.4.1 Lactate

There was a significant main effect of time for BL ($F = 51.03$, $p < 0.001$). BL at MIDexercise was significantly greater than PREexercise ($p < 0.001$, $g = 2.58$) and POSTexercise ($p < 0.001$, $g = 1.05$). BL at POSTexercise was significantly greater than PREexercise ($p < 0.001$, $g = 2.27$). The results for BL concentration are presented in Figure 7-5 (A).

7.5.4.2 Glucose

There was a significant interaction effect between condition and time-point ($F = 31.595$, $p < 0.001$). HCHO BG was higher than LCHO at POST30min ($p < 0.001$, $g = 2.46$) and POST60min ($p < 0.001$, $g = 1.35$), and higher than PLA at POST30min ($p < 0.001$, $g = 3.11$), POST60min ($p < 0.001$, $g = 1.94$), and POST120min ($p = 0.004$, $g = 0.59$). LCHO BG was higher than PLA at POST60min ($p = 0.025$, $g = 0.27$). The results for BG concentration are presented in Figure 7-5 (B).

Figure 7-5: Comparison between groups for blood lactate (Panel A) and glucose (Panel B) concentrations after a high-volume resistance training session, as well as individual data points. Data were analysed using linear mixed models and are presented as mean and 95% confidence intervals. † Significantly greater than PREexercise ($p < 0.001$); ‡ Significantly greater than PREexercise ($p < 0.001$) and POSTexercise ($p < 0.001$); ** significantly greater than PLA and LCHO ($p \leq 0.001$); * Significantly greater than PLA ($p \leq 0.05$)



HCHO high carbohydrate breakfast, *LCHO* low carbohydrate breakfast, *PLA* placebo

7.6 Discussion

The purpose of this study was to investigate the effect of higher and lower doses of pre-exercise CHO ingestion on RT volume performance in an ecologically valid exercise protocol, while controlling for total calories consumed. The main findings were, (a) RT volume performance was similar between

two isoenergetic, isonitrogenous pre-exercise meals differing in CHO dose and a low-calorie PLA, (b) participants were generally more full and sated, in HCHO and LCHO, compared to PLA, (c) pre-exercise BG was significantly higher in HCHO compared to PLA, but not LCHO, and post-exercise BG was similar between conditions, and (d) mid- and post-exercise BL increased compared to pre-exercise, with no interaction effect between conditions at any time-point.

The findings do not confirm our initial hypothesis. We hypothesised that a higher dose of CHO would improve volume performance over a lower dose (LCHO) and a low-calorie PLA due to the established role of dietary CHO as an important fuel source during high-intensity exercise [3]. RT induces modest decreases in total muscle glycogen (24 – 40%) [24] and stores of intra-myofibrillar glycogen in type II muscle fibres can become depleted during RT [29]. In some circumstances, CHO can be ergogenic for RT volume performance, such as where the training duration is longer (> 45 mins) and where the pre-exercise fast is longer (> 8hrs) [118]. Given the longer duration (~90 minutes) and higher volume performed to repetition fatigue (12 sets) in the RT session of the present study, we hypothesised an ergogenic effect of CHO ingestion. However, we found no significant effect of higher or lower CHO doses on RT volume performance, compared to a low-calorie PLA. Possible explanations for the lack of observed results may include exercise selection, training intensity, and the timing of CHO ingestion.

In the present study, three of the four exercises were for the upper body (i.e., bench press, prone row, and shoulder press), which were selected as a representative variety of exercises common to strength and hypertrophy type training. Previously, King et al. [118] reported that acute CHO ingestion had a clearer ergogenic effect on higher volume lower body RT and speculated that this trend may be due to lower body RT recruiting more muscle mass, producing more total work, and incurring greater metabolic fatigue. However, few studies have investigated the effects of acute CHO ingestion on higher-volume upper body RT. Krings et al. [49] reported an ergogenic effect of CHO ingestion on bench press repetitions completed to fatigue compared to a placebo, but no significant performance improvement in the bent-over row, incline press, or close-grip press. In addition, Smith et al. [50] reported no significant effect of a liquid CHO beverage on repetitions to fatigue in a ~60 min upper body RT session,

nor did the studies by Naharudin et al., [73, 74] report an ergogenic effect of pre-exercise CHO on bench press volume performance compared to water only or a viscous, energy-less placebo. Overall, the findings from the present study and previous literature suggest that CHO ingestion might be less important for volume performance in a higher-volume, upper body RT session, potentially due to recruiting relatively less muscle mass than lower body RT, resulting in less total work and metabolic fatigue. Future research is necessary to investigate whether isoenergetic pre-exercise meals similarly affect higher-volume, lower body RT.

It has previously been reported that hunger may influence RT performance. Naharudin et al. [74] reported no significant difference in repetitions to fatigue during 4 sets of back squat and bench press following viscous, semi-solid CHO containing and placebo pre-exercise meals. However, the CHO and placebo meals in Naharudin et al. [74] did improve volume performance compared to water only and the authors concluded that this may be due to psychological mechanisms (i.e., a placebo of ingesting, or nocebo of omitting, a pre-exercise meal). Indeed, the participants in that study [74] were hungrier and less full in the water only control, compared to the taste and texture matched CHO and placebo groups, and were similarly hungry and full following CHO and placebo. The findings of the present study are broadly in agreement with Naharudin et al. [74]. In a follow-up study [75], a viscous CHO containing breakfast improved subjective appetite and repetitions performed to fatigue, compared to a liquid CHO breakfast, suggesting hunger can influence RT performance. In the current study, there were no significant differences in hunger between conditions at the pre- and post-exercise timepoints. However, HCHO and LCHO had higher ratings of fullness and satiety at the pre-exercise timepoint, and satiety at the post-exercise timepoint, compared to PLA, indicating that the participants were generally less full and sated after ingesting PLA, compared to HCHO and LCHO. A greater magnitude in the difference of hunger/fullness between conditions of Naharudin et al., [74] may explain the differences in results compared to the current study. Nonetheless, the results from the current study suggest that lower subjective appetite may not always influence RT performance and that greater feelings of hunger may be requisite for pre-exercise feeding to influence volume performance. The discrepancy in results between our study and previous studies [74, 75] may be due to differences in the

magnitude of effect on subjective appetite (i.e., the previous studies elicited greater differences in appetite between conditions) and exercise protocol such as training duration, exercise selection (i.e., upper versus lower), and training intensity (i.e., %1-RM load) and the addition of pre-exercise supplement practices.

Training intensity (i.e., percentage of 1-RM) could have also affected the ability to detect an effect of CHO feeding in the present study. We selected a load of 80% 1-RM to lend ecological validity to the design, which resulted in an average of ~7 repetitions being completed in each set of each exercise. An increase of 1 repetition would be a ~14% increase in volume performance and though our power analysis was based on a 16% difference in volume performance, it's possible differences in study design led to non-significant results in volume performance. Several other studies using lower training intensities (approximately 55 – 75% 1-RM) and lower body exercise selection have reported an ergogenic effect of CHO in comparison to water [73, 74] and an energy-less placebo [43, 47, 48]. Thus, it's possible that lower loads and higher repetitions may be required to detect an effect of pre-exercise feeding, though a recent meta-regression did not find an effect of load on the ergogenic effect of CHO [118].

The participants were told that all three breakfast meals contained the same amount of energy (despite PLA containing almost no calories). The breakfasts were taste and texture matched during pilot testing. Nine of the 16 participants were able to correctly identify the PLA breakfast which indicates modest success in masking the true design of the study to the participants. Positive expectancy from ingesting a pre-exercise breakfast which is perceived to contain energy may explain why there was no significant differences in volume performance in the current study. However, without a control condition that omitted the ingestion of anything but water, it is not possible to determine the magnitude of a placebo effect. Nonetheless, previous studies [73, 74] also indicate that psychological factors (i.e., positive, or negative expectancy) of feeding may play a role in mediating RT volume performance.

Another potential mediating factor that could explain the lack of influence of subjective appetite on performance in the present study is that half of the participants (n = 8) used their habitual pre-exercise

supplements, which could be sufficient to mask an effect of the pre-exercise meal, or to suppress/mitigate sensations of hunger. These supplements included caffeine (black coffee, n = 4; pre-workout formulation, n = 4), which has known ergogenic effects on indices of muscle strength and endurance [228] without clear evidence for an effect on appetite [274]. Future research should investigate whether habituation to pre-exercise supplementation mediates the effect of a pre-exercise meal on RT performance.

There are several limitations to the present study. We detected modest evidence that there was an order effect such that more repetitions were completed on trial 3 compared to trial 1 ($g = 0.86$, $p = 0.06$). An effect of trial order could mask a treatment effect. However, the study design included randomisation with counterbalancing to address a potential influence of a trial effect and there was no evidence that condition was systematically influenced by trial number ($p = 0.35 – 0.8$). The sample size calculation for the present study was based on detecting a moderate effect between a CHO and water only condition for squat repetitions reported in a previous study [74]. Thus, while the sample size of the present study is powered to detect an effect between HCHO and PLA conditions, it might be underpowered to detect a small effect between HCHO and LCHO conditions, if one exists. Commercially available products were used to prepare pre-exercise meals, and their nutritional composition was not verified. Several aspects of our study design could have influenced the results (e.g., supplementation, music) and masked the potential effect of a pre-exercise meal on RT volume performance. This adds external validity to our findings, since these aids are used in practice, and while they were kept consistent for each participant across trials, their inclusion prevents the true isolation of the effect of the pre-exercise meal on RT performance. A mixed-sex cohort of participants was recruited in the current study, and it is currently unknown if there are potential sex differences in the response to a pre-exercise meal and RT volume performance. Finally, we attempted to provide metabolic insight with blood measures but did not measure muscle glycogen; thus, future research is necessary to understand the effect of CHO ingestion on muscle glycogen (and its subcellular compartments) during RT.

7.7 Conclusion

The results provide evidence that for primarily upper-body RT volume performance, a higher or lower CHO dose produces comparable performance to a low-calorie placebo. These findings are of practical relevance, as they suggest the macronutrient composition of a meal may not matter per se, and that the perception of EI may be sufficient for RT volume performance (at least in the context of similar session lengths, volumes, and exercise selections).

Chapter 8: A case series on the effect of acute carbohydrate ingestion on high volume, lower body resistance training performance and glycogen's subcellular compartments

8.1 Preface

This chapter extends the thesis' investigation of acute CHO ingestion by retaining performance outcomes as the primary focus and additionally assessing direct muscle-level mechanisms. Building on the meta-analytic work in Chapter 2 and 3 and the upper-body centric trial in Chapter 7, it uses a high-volume, lower-body RT protocol under conditions where acute CHO ingestion previously had the greatest ergogenic potential (i.e., longer fast, longer session, large muscle mass involvement). This double-blind, randomised cross-over case series compares the effects of HCHO and LCHO isoenergetic pre-exercise meals on lower-body RT volume performance and muscle glycogen content changes. It quantifies not only whole-muscle glycogen but also its subcellular compartments (intramyofibrillar, intermyofibrillar, and subsarcolemmal) using transmission electron microscopy and AI-assisted image analysis – an approach not previously applied in an acute CHO–RT trial. This chapter links acute feeding strategies, performance outcomes, and subcellular glycogen distribution within the same experiment, providing a mechanistic context for interpreting existing, and informing future, sport nutrition guidelines for RT-centric athletes.

8.2 Introduction

CHO is an important fuel source during high-intensity exercise [2]. Acute CHO ingestion can improve RT volume performance where the pre-exercise fast is longer (>8 hrs) and session duration is longer (>45 mins) [118]. In addition, while most studies have not reported an ergogenic effect for upper body exercise volume [50, 73, 74], several report benefit during lower body exercise [44, 47, 48]. A mechanistic explanation for these findings remains unresolved but may be due to lower body exercise recruiting more muscle mass, producing greater total work and decreases in muscle glycogen.

Standard RT volumes reduce muscle glycogen by 24 – 40% [20-23]. CHO feeding may spare glycogen (i.e., by postponing glycogen depletion, promoting resynthesis, or providing additional BG to working musculature) and aid performance [275]. Support for a glycogen-sparing effect of acute CHO ingestion has been observed during endurance exercise, where a small but statistically significant attenuation of net muscle glycogen utilisation was observed [276]. While endurance and RT differ substantially in stimulus and energetic demands, this finding provides biological plausibility for glycogen-sparing as a potential mechanism through which acute CHO ingestion could influence exercise performance. A glycogen-sparing effect of CHO ingestion is relatively unexplored in RT research, with one study reporting a potential glycogen-sparing effect [44] and the other not [52]. Divergent results may be due to differences in training protocols, with higher volumes and longer session durations potentially inducing greater glycogen use [24].

Muscle glycogen is localised to several distinct depots within the muscle cell (i.e., intramyofibrillar, intermyofibrillar, and subsarcolemmal), which purportedly fulfil differing metabolic roles. The distribution of these depots, and their use during exercise, could affect muscle function, which critically depends on adequate concentrations of glycogen at these specific locations [25]. Specific to RT, type II fibres exhibit marked decreases in subcellular glycogen with some intramyofibrillar glycogen stores depleting entirely during standard volumes and exercises [29]. Given the non-uniform depletion of subcellular glycogen during RT, a glycogen-sparing effect may reside

within a particular subcellular compartment, which would be overlooked in previous analyses of total muscle glycogen.

While some athletes perform multiple daily training sessions, RT-centric athletes rarely perform more than one RT session per day. Given that current guidelines for these athletes are to consume a moderate daily intake of CHO (4 – 7 g/kg BM/day) [5], training is unlikely to occur in a glycogen-depleted state. Nonetheless, the augmentation of skeletal muscle glycogen stores occurs in rested individuals consuming a CHO-containing breakfast [33, 34] which may explain the ergogenic effect of CHO on RT volume performance during longer sessions, after longer fasts, and possibly with lower body exercise [118]. Therefore, this research will use a double-blind, randomised cross-over trial to investigate the effect of acute pre-exercise CHO feeding compared to an isoenergetic placebo on performance during an ecologically valid higher volume, lower body RT session. Additionally, we will quantify changes in muscle glycogen and its subcellular compartments to evaluate the metabolic effect of acute pre-RT CHO feeding.

8.3 Methods

8.3.1 Participants

The sample for this project was feasibility-based due to time and financial constraints dictated by the constraints of a PhD programme. We recruited as many participants throughout the 2025 calendar year as possible. Four participants were recruited and completed the study; their descriptive characteristics are presented in Table 8-1. All participants provided written consent before commencing the study. Ethics approval was granted by the Auckland University of Technology Ethics Committee (24/318).

Table 8-1: Individual participant' descriptive characteristics (n = 4).

Participant ID	***Sex***	***Age (years)***	***Height (cm)***	***Body mass (kg)***	***Sport***	***RT experience (years)***
1	M	21	178.2	112	Rugby	4
2	F	20	166.6	65	Swimming	3
3	F	20	167.3	79	Netball	3
4	F	38	170.2	66	Powerlifting	9

M male, *F* female, *RT* resistance training

Inclusion criteria required participants to (a) have been performing RT three times per week for the last six months, (b) be between 18 and 50 years of age, (c) not have a pre-existing injury, metabolic disease or condition, or medical condition, that would contraindicate safe participation in exercise; (d) not report ergogenic insulin-like substance and/or anabolic/catabolic steroid, prohormone, or hormone use known to affect muscle mass; and (e) not report dietary requirements contraindicating the ingestion of a breakfast (e.g., reactions or aversions to ingredients). To maximise statistical power for performance outcomes, participants were permitted to opt out of the microbiopsy component. These participants completed the same protocol with the omission of microbiopsy, where they remained seated during this period. This case series presents a subset of participants (n = 4) from a larger, pre-registered cross-over trial (n = ~15), for which the methods were pre-registered and uploaded to the Open Science Framework following pilot testing but before experimental data collection (https://osf.io/v9bxq/).

8.3.2 Design

This case series is part of a double-blind, randomised, counterbalanced, cross-over trial consisting of, in order, a familiarisation session, a 10-RM session, and two experimental sessions. For each experimental session, participants arrived at the laboratory in the morning after an overnight fast (>10 hrs). Upon arrival, participants began ingesting one of two feeding conditions: (1) high CHO (HCHO; 1.5 g/kg BM CHO) or (2) low CHO (LCHO; approximately 0.75g/kg BM protein and 0.75 g/kg BM fat). HCHO comprised of low sweetness maltodextrin (Starch NZ, Auckland, New Zealand), LCHO of vanilla whey protein isolate (Kiwi Nutrition, New Zealand) and butter powder (Garden of Life, FL, U.S.), and both were mixed with water (350 – 500 ml), guar gum (Ceres Organics, Auckland, New Zealand), and Vanilla FlavDrops (MyProtein, Manchester, UK). Varying ingredient amounts were used depending on participant body mass. Water volume was consistent within-participants (i.e., between the HCHO and LCHO conditions). Participants were informed of the true design of the study (i.e., a comparison between HCHO and an isoenergetic LCHO) during familiarisation and were asked after study completion: “Do you think that you can confidently identify which trial was HCHO and which was LCHO?”.

Regarding nutrient timing, two thirds of the total energy in each condition (1g/kg CHO in HCHO; 0.5g/kg protein and 0.5 g/kg fat in LCHO) was ingested upon arrival following baseline measures (BG and BL, subjective appetite). An hour and a half after initial feeding, participants ingested the remaining energy (0.5g/kg CHO in HCHO; 0.25g/kg protein and 0.25 g/kg fat in LCHO). Two hours after completing the initial feeding (and 30 mins after the second feeding), participants commenced the RT session consisting of four sets of smith machine squat, leg press, and leg extension with 90%, 85%, and 80% of a 10-RM load, respectively.

Participants were block-randomised and counterbalanced via a permuted block randomisation with block size of 4 [277]. A researcher independent of all data collection assigned the allocations. To ensure allocation concealment, twenty-four opaque, sealed envelopes were prepared for the independent researcher and labelled with block number (1–6) and envelope number (1–4). Each block contained a balanced arrangement of two "AB" and two "BA" allocations, and the six blocks represent all possible balanced permutations. R code was prepared for the independent researcher that (1) randomly assigned A and B to the HCHO or LCHO conditions for the duration of the study, (2) randomly assigned block (1–6) for participant allocation as each block of 4 participants enrol in the study, and (3) is available on the Open Science Framework (https://osf.io/v9bxq/). Once a block was used, it was excluded from future randomisation until all six blocks were assigned. Upon participant sign-up, envelopes were irreversibly assigned to that participant. Given this preliminary case series reports n = 4, these first 4 participants represent a completed block of allocations, which allowed the primary researcher to unblind the condition to complete this case series for the thesis, while protecting allocation concealment and blinding for future assigned participants within the larger, ongoing cross-over trial.

8.3.3 Familiarisation (visit 1)

Participants' height (cm) and weight (kg) were recorded using a stadiometer and digital calibrated scale (Seca Ltd, Hamburg, Germany). Participants were verbally informed of the 10-RM and experimental protocols. Participants were familiarised with the RT specific rating of perceived exertion (RPE)/repetitions in reserve [260], Perceived Recovery Status (PRS) [278], and subjective appetite

(hunger, satiety, and fullness) [261] and gastrointestinal distress [279] scales, and the instruction to lift as fast as possible during concentric phases (with controlled but not slowed eccentric tempo), implemented for all sessions, with mean repetition velocity feedback after each set during familiarisation. Participants were also instructed to take at least a momentary pause, but no longer than 2 seconds, between repetitions, which was implemented for all sessions. Participants were asked what their best, most recent set of each exercise (or closest variation) was, which was used to inform warm-up loads for the RM session. To aid in 10-RM estimation and familiarisation, enrolled participants completed an "introduction week" consisting of two self-directed training sessions. On the first day, participants performed two sets of Smith machine squat, leg press, and leg extension for 8–12 repetitions at RPE 7. On the second day, they performed three sets of the same exercises for 8–12 repetitions at RPE 8–9.

Participants performed a standardised dynamic warm-up followed by 3 sets of 1 repetition of isokinetic smith squat (1080 Motion Quantum Synchro Pro, Västerås, Sweden) at 1.00 and 0.25 m/s with the instruction to push at 50, 75, and 100% of maximum effort during the concentric phase. Then, participants completed three practice sets of 10 repetitions with 50, 70, and 90% of the estimated 10-RM for each exercise. Foot and seat position were recorded and standardised for all sessions. For the Smith machine squat, participants were required to squat to a depth where the hip crease passes the top of the knee when viewed laterally, aided by a resistance band set at this depth, which they were required to touch with their hamstrings before ascending. For the leg press, a goniometer was used to establish 90° of knee flexion. Participants were required to reach at least 90° of knee flexion and were instructed to increase knee flexion (and decrease the knee joint angle lower than 90°) if necessary to achieve their habitual range of motion, before returning to the start position. Safety catches were placed as close as possible to the participant' full range of motion position for standardisation. Participants were instructed to touch but not rest or bounce the load on the safety catch for each repetition. For the leg extension, the participants started with ~80° of knee flexion and extended the knee until full extension was reached, before returning to the start position. Participants were instructed to control, but not slow, the eccentric

phase of all movements. Lifting material aids approved by the IPF (e.g., knee sleeves and weightlifting belt) were permitted at the participants' discretion and replicated for all sessions in the study.

8.3.4 Pre-trial standardisation

For 3-days before the RM and experimental sessions, participants were asked to record their daily food intake using MyFitnessPal. During familiarisation, participants practised inputting various food selections and received verbal guidance on best practice for dietary tracking. Participants were instructed to consume a daily CHO (4 – 7 g/kg BM) and protein (at least 1.6 g/kg BM) intake, aligned with current sport nutrition recommendations for RT athletes [5, 182, 242]. Participants were provided food suggestions where necessary to facilitate adherence but did not receive specific instructions on food selection. Participants were instructed not to purposefully increase or decrease their habitual EI. Participants were instructed not to take any new supplements and maintain their current supplement habits (e.g., daily creatine use). After the overnight fast preceding experimental trials, participants were instructed not to ingest food or supplements outside of the study protocol. Participants had to report following the CHO and protein requirements for at least 3-days prior to experimental trials, verified by a researcher with access to the participant's MyFitnessPal logs. Between trials, participants were instructed to keep their normal training habits and refrain from physical activity for 48 hrs before the 10-RM and experimental trials. Experimental trials were separated by at least 4 days to allow for fatigue dissipation and nutrition adherence but could last up to 10 days for scheduling flexibility without degrading protocol familiarisation.

8.3.5 10-RM session (visit 2)

The 10-RM protocol consisted of 10, 8, and 5 repetitions with 50, 75, and 90% of the estimated 10-RM, respectively, followed by up to five 10-RM attempts. Mean concentric velocity, as measured by a linear position transducer (Gymaware, Braddon, ACT, Australia) was used with participant-reported RPE/RIR to guide attempt selection. If a 10-RM attempt was successful, and the participant reported an RPE/RIR less than 10, load was increased by 2.5 to 25 kgs in consultation with the participant. A 10-RM was recorded if the participant successfully completed the set at 10RPE or at a

lower RPE but failed a subsequent set. Sets completed with 10 ± 1 repetition were recorded as the successful 10-RM load (i.e., sets completed with 9, 10, or 11 repetitions at 10RPE were accepted as the 10-RM load). To avoid fatigue accumulation, 10-RM attempts where the participant would clearly exceed the 10-RM repetition range (i.e., 9 – 11 repetitions) were terminated early and the load was increased for the next attempt. Three minutes and 3-5 mins rest were provided between submaximal sets and 10-RM attempts, respectively. Constant verbal encouragement was provided. 10-RM for all three exercises was completed on the same day in experimental session order (i.e., smith machine squat, leg press, and leg extension).

8.3.6 Experimental session (visits 3 and 4)

After an overnight fast (>10 hrs), participants arrived at the laboratory. The elected start time was kept consistent for each participant and coincided with their habitual breakfast time. Participants confirmed adherence to the overnight fast (>10 hrs) and abstinence from physical activity (48 hrs). Thereafter, baseline measures of body weight, subjective appetite, BG and BL, and gastrointestinal symptoms were recorded. Participants then began ingesting the assigned feeding protocol, which was delivered in an opaque container by a researcher separate from all data collection. To aid blinding, participants were asked not to look in the opaque container and wore a nose peg during its ingestion. Following ingestion, participants completed three, five second mouth rinses with water before the nose peg was removed two minutes after the mouth rinses. Participants remained seated until RT began. Approximately 15 minutes prior to RT, the pre-exercise muscle biopsy was obtained. Water was provided *ad libitum* throughout experimental trials and recorded.

Two hours after the initial feeding and ~30 mins after the second feeding, participants began RT. Participants completed the same standardised warm-up before completing four sets of Smith machine squat, leg press, and leg extension at 90%, 85%, and 80% of 10-RM, respectively. For the Smith machine squat and leg press, the first two sets were completed to an individualised 3 RIR mean velocity cut-off based on participant data from the 10-RM session. Once the mean velocity cutoff was exceeded, sets were terminated. The velocity cut-off approximately elicited 8RPE/2RIR. Based on pilot

testing, the rationale for the velocity cutoff was to manage gastrointestinal distress that could nullify the intervention effect or completion. The last two sets of the smith machine squat and leg press, and all four sets of leg extension, were completed to a 10 RPE (i.e., no repetitions in reserve). Exercise order remained consistent for all trials. Rest before and between 10RPE sets was three mins. Rest between exercises was five mins. Preceding the four working sets of each exercise, participants completed five and three repetitions with 60 and 90% of the working load with 60-90 secs interset rest. Participants were reminded to perform the concentric muscle action as fast as possible for all lifts. Standardised verbal encouragement was provided in all sessions.

After RT, participants performed 1 repetition of isokinetic smith machine squat (1080 Motion Quantum Synchro Pro, Västerås, Sweden) pushing maximally against 1.00 and 0.25 m/s, to resemble a movement velocity in the back squat of trained individuals close to maximum mechanical power [280] and 1-RM [281], respectively. PRS was recorded after the last warm-up set of each exercise. Subjective appetite (hunger, satiety, and fullness) was recorded at baseline, immediately after the initial feeding, 90-mins after initial feeding (i.e., immediately before the second feeding), pre-exercise, and post-exercise. Symptoms of gastrointestinal distress were recorded at baseline, and pre- and post-exercise. Blood samples were drawn at baseline, pre-exercise, and post-exercise, using the finger prick method and analysed using a glucose (StatStrip, NZ Medical and Scientific) and lactate (Lactate Pro2 LT-1730, Arkray) meter. Personnel otherwise not involved in data collection read and recorded BG values, which were provided to the researchers at the end of all data collection. Muscle biopsies were obtained approximately 15 minutes before and ten minutes after the RT session. Music was permitted during 10-RM and experimental sessions, but the order of songs and volume remained consistent across all sessions.

8.3.7 Muscle biopsies

Biopsies were obtained in the supine position. Local anaesthesia (5 - 10mL of 2% lidocaine) was applied to the skin and superficial muscle fascia, after which a microbiopsy needle was inserted mid-belly in the vastus lateralis to ~2cm depth to extract ~20mg of muscle tissue using a spring-loaded

mechanism (14G Ultimate Biopsy, Zamar Care, Croatia). Left (X) and right (Y) legs were counterbalanced (i.e., if participant 1 was XY, then participant 2 was YX) using a random generator in R. The midpoint of the line between the greater trochanter and tibial tuberosity was marked. To avoid obtaining damaged or regenerating muscle tissue from the pre-exercise biopsy, pre- and post-session samples were obtained 2cm proximal and distal to the marked midpoint, respectively. Distal (X) and proximal (Y) muscle sampling was also randomly counterbalanced.

8.3.8 Muscle glycogen assay

Muscle tissue (~10mg) was isolated from the initial specimen, immediately placed in microtubes in dry ice, and then frozen at -80°C for total glycogen assessment. Homogenised samples were incubated in the presence (positive) and absence (negative) of amyloglucosidase for 1 hour at 50°C, before centrifugation at 16,000 rcf, 4°C [282]. The resulting soluble glucose was then measured spectrophotometrically against a standard curve of known D-glucose concentrations. Amyloglucosidase hydrolyses glycogen into glucose monomers, and muscle glycogen content was determined by subtracting free glucose concentration from the negative sample from total glucose concentration of the positive sample.

8.3.9 Transmission electron microscope analyses

Subcellular glycogen quantification (i.e., intramyofibrillar, intermyofibrillar, and subsarcoplasmic) followed the protocol of Jensen et al. [283]. Immediately after the microbiopsy, a small specimen (~3-5mg wet weight) was isolated and placed in primary fixative solution (2.5% glutaraldehyde in 0.1 M sodium cacodylate buffer (pH 7.3)). The muscle sample stayed in the primary fixative solution for 24 hrs at 5°C and was then washed four times in 0.1 M sodium cacodylate buffer, with 15 minutes between each wash. Thereafter, samples were post-fixed and stained with 1% osmium tetroxide (OsO_4) and 1.5% potassium ferrocyanide ($K_4Fe(CN)_6$) in 0.1 M sodium cacodylate buffer for 120 mins at 4°C. After post-fixation, specimens were rinsed twice in room temperature double distilled water and then dehydrated by submerging at room temperature in graded series of alcohol (ethanol) at the following concentrations: 70% (10 min), 70% (10 min), 95% (10 min), 100% (10 min), and 100%

(10 min). After dehydration, specimens were infiltrated with graded mixtures of propylene oxide and epossidic resin at room temperature using the following volume ratios (propylene oxide/epossidic resin) and durations: 1/0 (10 min), 1/0 (10 min), 3/1 (45 min), 1/1 (45 min), 1/3 (45 min), 0/1 (overnight). The following day, the specimens were embedded in 100% fresh episodic resin in moulds and polymerised at 60°C for 48 hrs. Ultra-thin sections (~60-70 nm) were cut longitudinally using an ultramicrotome (EM UC6, Leica Microsystems, Wetzlar, Germany) and contrasted with uranyl acetate (0.5% in distilled water; 20 mins) and lead citrate solution (1% in distilled water; 5 mins). Sections were photographed in a transmission electron microscope (Tecnai 12, FEI Company, Oregon, US) using a Ultrascan 1000 CCD camera (Gatan Ametek, California, US). Approximately ten fibres were imaged, with 24 images per fibre. Glycogen granule quantification from transmission electron microscope images was completed using the artificial intelligence model provided by Rios et al. [284]. External validation against manual particle counts using Bland-Altman analysis [285] demonstrated acceptable agreement for total and intermyofibrillar glycogen (mean bias = 0.57 glycogen volume units normalised to fibre length; 95% limits of agreement: -3.44, 4.5), whereas agreement for intramyofibrillar glycogen was lower (mean bias = 0.44 glycogen volume units normalised to fibre length; 95% limits of agreement: -1.23, 2.17), and this limitation was considered in the interpretation of intramyofibrillar results.

8.3.10 Analysis plan

As this is a small, interim sample analysis from an ongoing project (n = 4 of a planned 15), to avoid potentially misleading inferential conclusions, we elected not to perform group-level statistical analyses specified in pre-registration for this thesis chapter. Instead, data are presented descriptively with qualitative interpretation, aligned with contemporary guidance on case study reporting [286]. The pre-registered, group-level statistical analysis plan will be implemented once the full sample is completed post-thesis submission.

For the purposes of the present thesis, the primary researcher (AK) – an outcome assessor during data collection – was unblinded to treatment allocation for the first randomised block of four

participants to enable complete data description and interpretation while protecting future participant allocation blinding. Importantly, this unblinding of treatment allocation occurred after all data collection and data processing (including glycogen imaging) had been completed.

Raw descriptive data are presented alongside the total number of session repetitions and total muscle glycogen content and its subcellular locations (i.e., intramyofibrillar, intermyofibrillar, and subsarcolemmal). Secondary outcomes of interest are total repetitions completed by exercise; average and peak concentric force (at 0.25 and 1.00 $m \cdot s^{-1}$ on the Quantum Synchro); BG and BL; and total and subcellular glycogen.

8.4 Results

Three participants completed all study procedures, including pre- and post-exercise muscle biopsies. One participant (ID = 4) elected not to undergo the biopsy procedures; therefore, their data are reported for all outcomes except total and subcellular muscle glycogen.

8.4.1 Volume performance

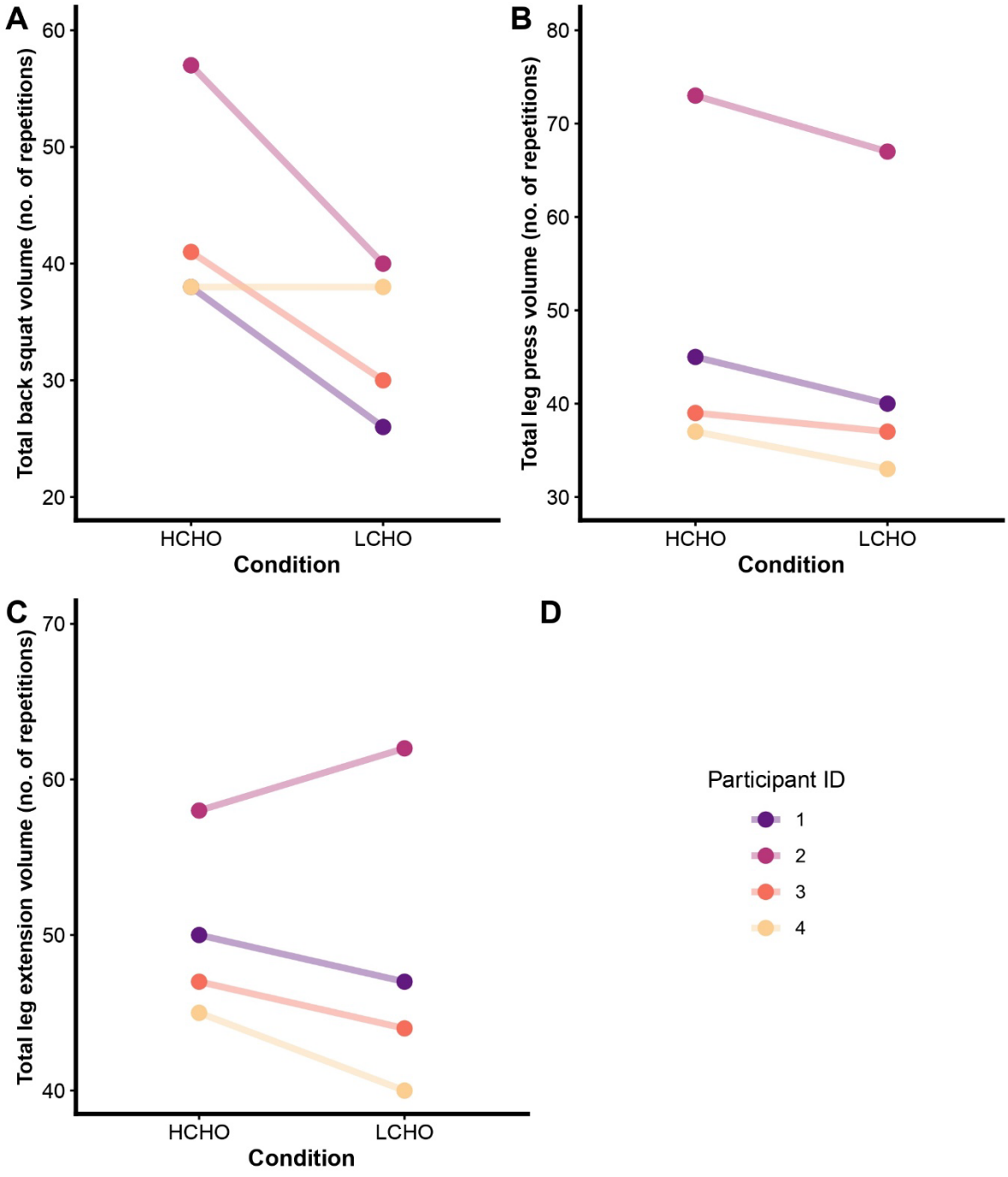
Raw data for repetitions completed per exercise and session for all four participants are presented in Table 8-2. Repetitions completed per exercise and session for all four participants are visualised in Figure 8-1 and Figure 8-2, respectively.

Table 8-2: Raw data for repetitions completed per exercise and session for all four participants.

ID	*Condition*	*Total repetitions completed*			
		Back squat	*Leg press*	*Leg extension*	*Total session*
1	HCHO	38	45	50	133
	LCHO	26	40	47	113
2	HCHO	57	73	58	188
	LCHO	40	67	62	169
3	HCHO	41	39	47	127
	LCHO	30	37	44	111
4	HCHO	38	37	45	120
	LCHO	38	33	40	111

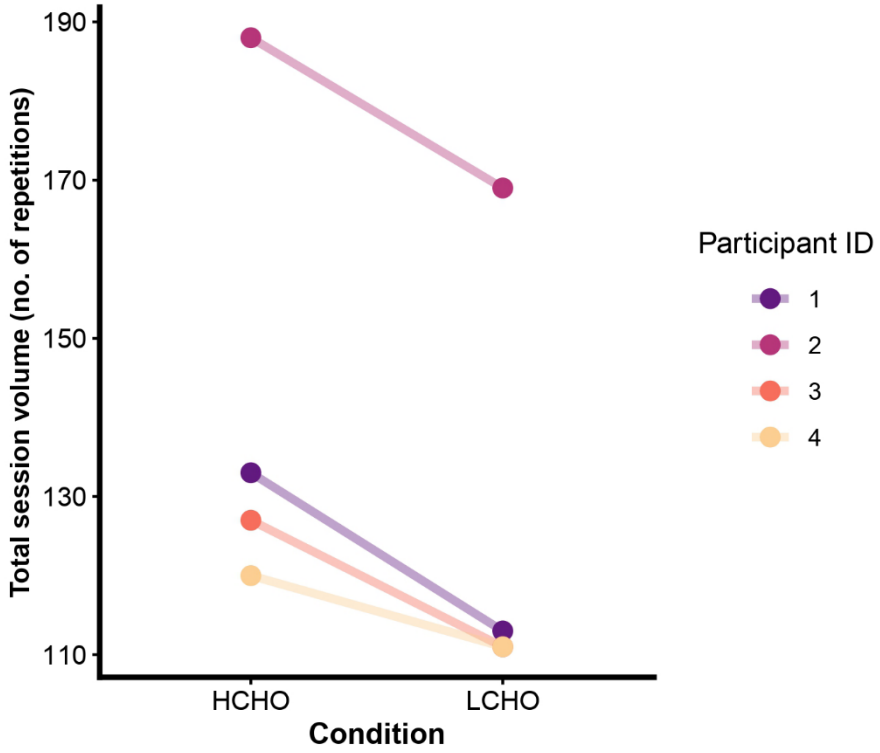
HCHO high carbohydrate breakfast, *LCHO* low carbohydrate breakfast

Figure 8-1: Repetitions completed per exercise between groups (i.e., HCHO and LCHO) with individual participant datapoints (n = 4).



HCHO high carbohydrate breakfast, *LCHO* low carbohydrate breakfast

Figure 8-2: Total repetitions completed per session between groups (i.e., HCHO and LCHO) with individual participant datapoints (n = 4).



HCHO high carbohydrate breakfast, *LCHO* low carbohydrate breakfast

8.4.2 Isokinetic peak and average force at 0.25m/s

Raw data for peak and average isokinetic force at 0.25 m/s are presented in Table 8-3 and Table 8-4, respectively. Peak and average isokinetic force values at 0.25 m/s are visualised in Figure 8-3.

Table 8-3: Peak isokinetic force (N) at 0.25m/s.

ID	*Condition*	*Peak force (N) at 0.25m/s*			
		Pre-EX	*Post-SQ*	*Post-LP*	*Post-EX*
1	HCHO	1305	936	903	963
	LCHO	1245	1207	1006	1179
2	HCHO	1049	1126	1032	1177
	LCHO	1382	1189	1054	1047
3	HCHO	1446	1138	860	992
	LCHO	1391	878	898	1051
4	HCHO	1420	1373	1173	1281
	LCHO	1537	1273	1471	1124

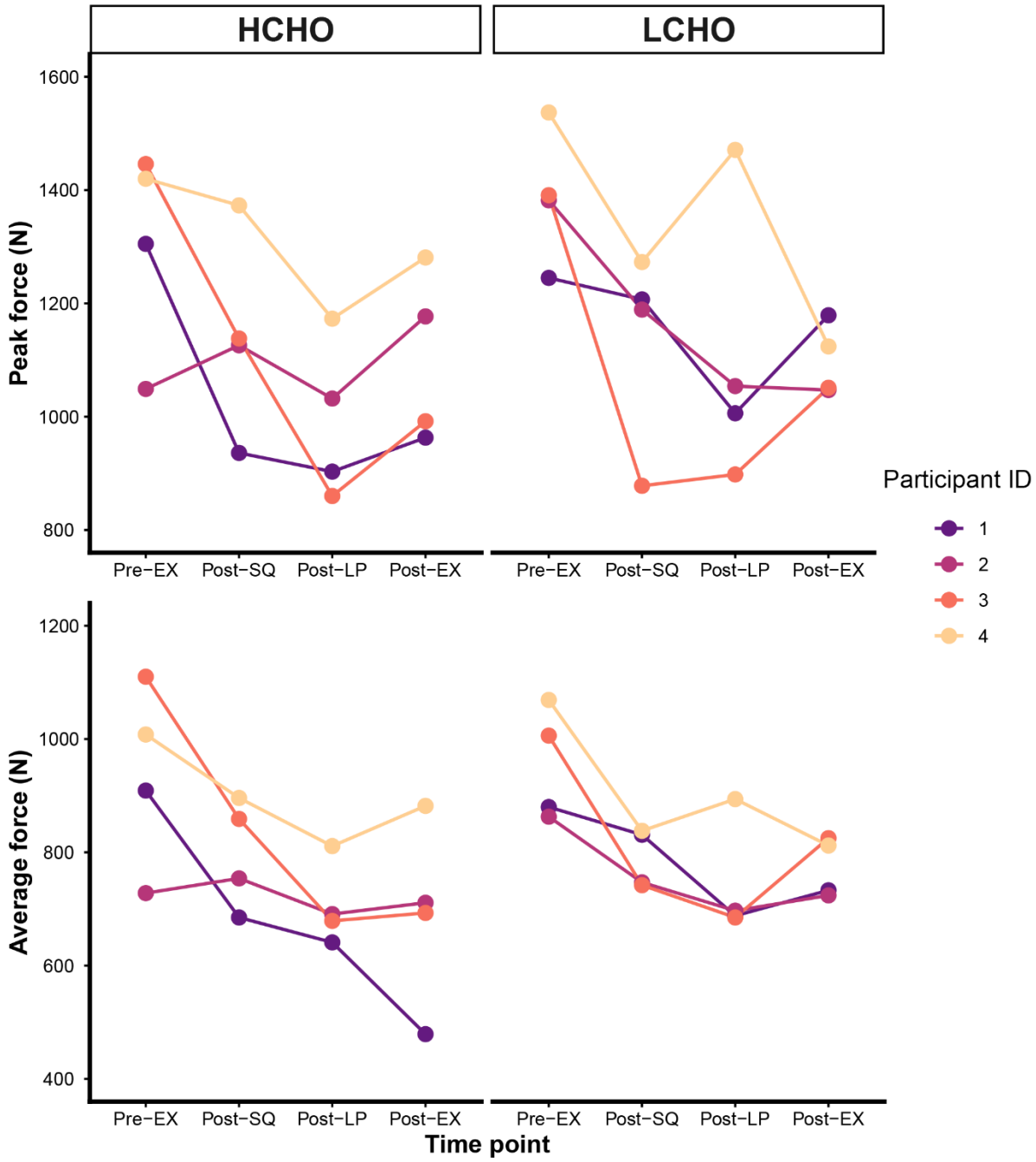
HCHO high carbohydrate breakfast, *LCHO* low carbohydrate breakfast, *EX* exercise, *SQ* squat, *LP* leg press

Table 8-4: Average isokinetic force (N) at 0.25m/s.

ID	*Condition*	*Average force at 0.25m/s*			
		Pre-EX	*Post-SQ*	*Post-LP*	*Post-EX*
1	HCHO	909	685	641	479
	LCHO	880	831	688	733
2	HCHO	728	754	691	711
	LCHO	863	747	697	724
3	HCHO	1110	859	679	693
	LCHO	1006	742	685	825
4	HCHO	1008	896	811	882
	LCHO	1069	838	894	812

HCHO high carbohydrate breakfast, *LCHO* low carbohydrate breakfast, *EX* exercise, *SQ* squat, *LP* leg press

Figure 8-3: Isokinetic peak and average force at 0.25 m/s between groups (i.e., HCHO and LCHO) with individual participant datapoints (n = 4).



HCHO high carbohydrate breakfast, *LCHO* low carbohydrate breakfast, *EX* exercise, *SQ* squat, *LP* leg press

8.4.3 Isokinetic peak and average force at 1.00m/s

Raw data for peak and average isokinetic force at 1.00 m/s are presented in Table 8-5 and Table 8-6, respectively. Peak and average isokinetic force values at 1.00 m/s are visualised in Figure 8-4.

Table 8-5: Peak isokinetic force (N) at 1.00m/s.

ID	*Condition*	*Peak force (N) at 1.00 m/s*			
		Pre-EX	*Post-SQ*	*Post-LP*	*Post-EX*
1	HCHO	800	499	580	501
	LCHO	847	593	555	538
2	HCHO	784	691	646	575
	LCHO	731	632	645	655
3	HCHO	1080	759	745	754
	LCHO	1003	718	647	662
4	HCHO	850	639	618	620
	LCHO	930	661	602	588

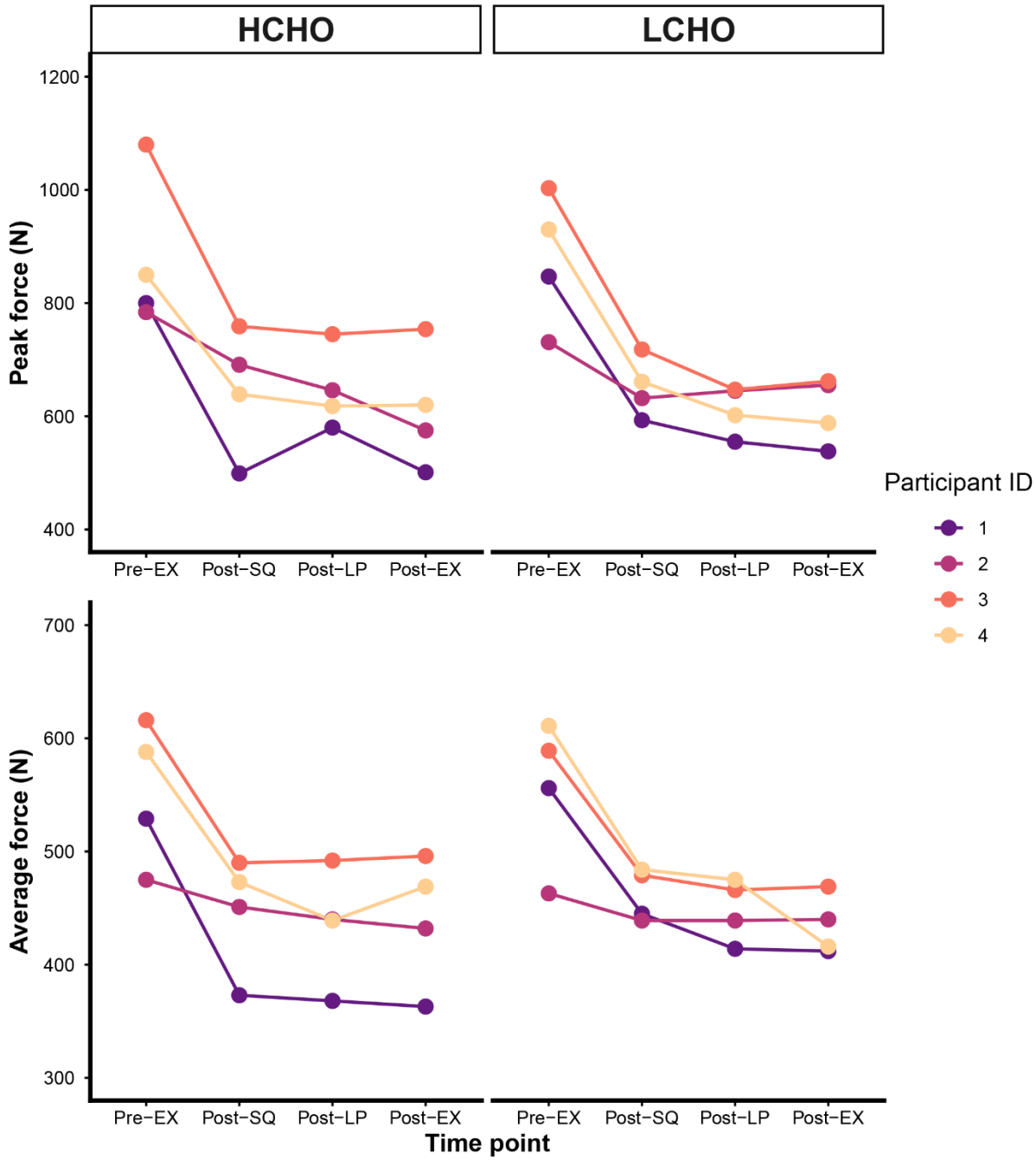
HCHO high carbohydrate breakfast, *LCHO* low carbohydrate breakfast, *EX* exercise, *SQ* squat, *LP* leg press

Table 8-6: Average isokinetic force (N) at 1.00m/s.

ID	*Condition*	*Average force at 1.00m/s*			
		Pre-EX	*Post-SQ*	*Post-LP*	*Post-EX*
1	HCHO	529	373	368	363
	LCHO	556	445	414	412
2	HCHO	475	451	440	432
	LCHO	463	439	439	440
3	HCHO	616	490	492	496
	LCHO	589	479	466	469
4	HCHO	588	473	439	469
	LCHO	611	484	475	416

HCHO high carbohydrate breakfast, *LCHO* low carbohydrate breakfast, *EX* exercise, *SQ* squat, *LP* leg press

Figure 8-4: Isokinetic peak and average force at 1.00 m/s between groups (i.e., HCHO and LCHO) with individual participant datapoints (n = 4).



HCHO high carbohydrate breakfast, *LCHO* low carbohydrate breakfast, *EX* exercise, *SQ* squat, *LP* leg press

8.4.4 Total muscle glycogen

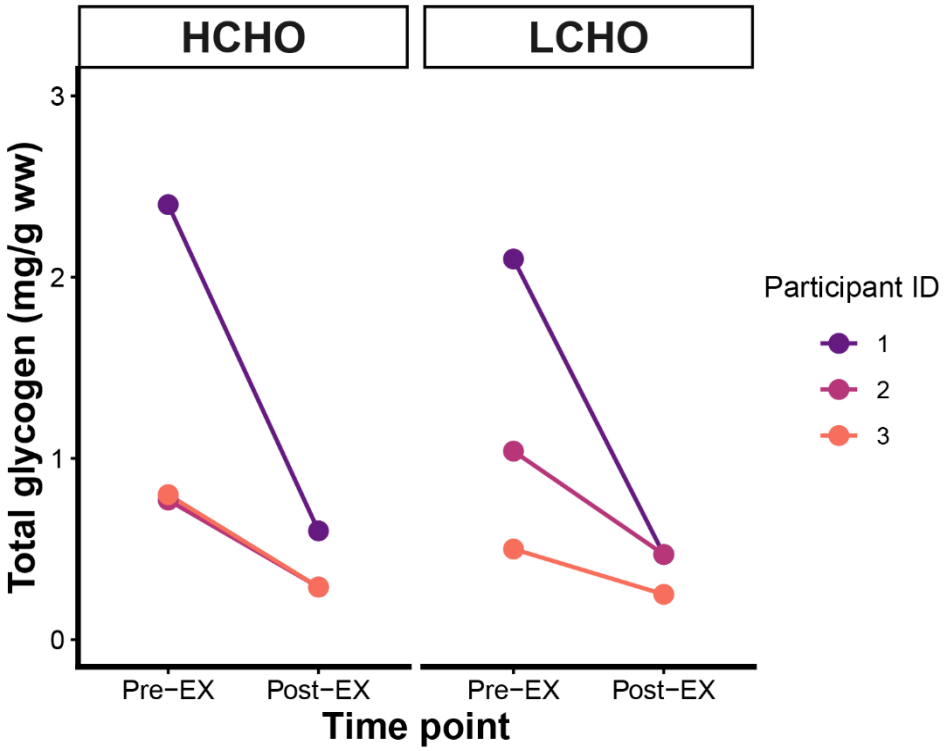
Raw data for total muscle glycogen is presented in Table 8-7. Data for total muscle glycogen are visualised in Figure 8-5.

Table 8-7: Raw data for total muscle glycogen (mg/g ww)

ID	*Condition*	*Total muscle glycogen (mg/g ww)*		
		Pre-EX	*Post-EX*	*Relative decrease (%)*
1	HCHO	2.4	0.6	-76
	LCHO	2.1	0.47	-77.6
2	HCHO	0.77	0.29	-62.3
	LCHO	1.04	0.47	-54.8
3	HCHO	0.8	0.29	-63.8
	LCHO	0.5	0.25	-50

HCHO high carbohydrate breakfast, *LCHO* low carbohydrate breakfast, *EX* exercise

Figure 8-5: Total muscle glycogen (mg/g ww) between groups (i.e., HCHO and LCHO) with individual participant datapoints (n = 3).



EX exercise, *HCHO* High carbohydrate breakfast, *LCHO* low carbohydrate breakfast

8.4.5 Subcellular muscle glycogen

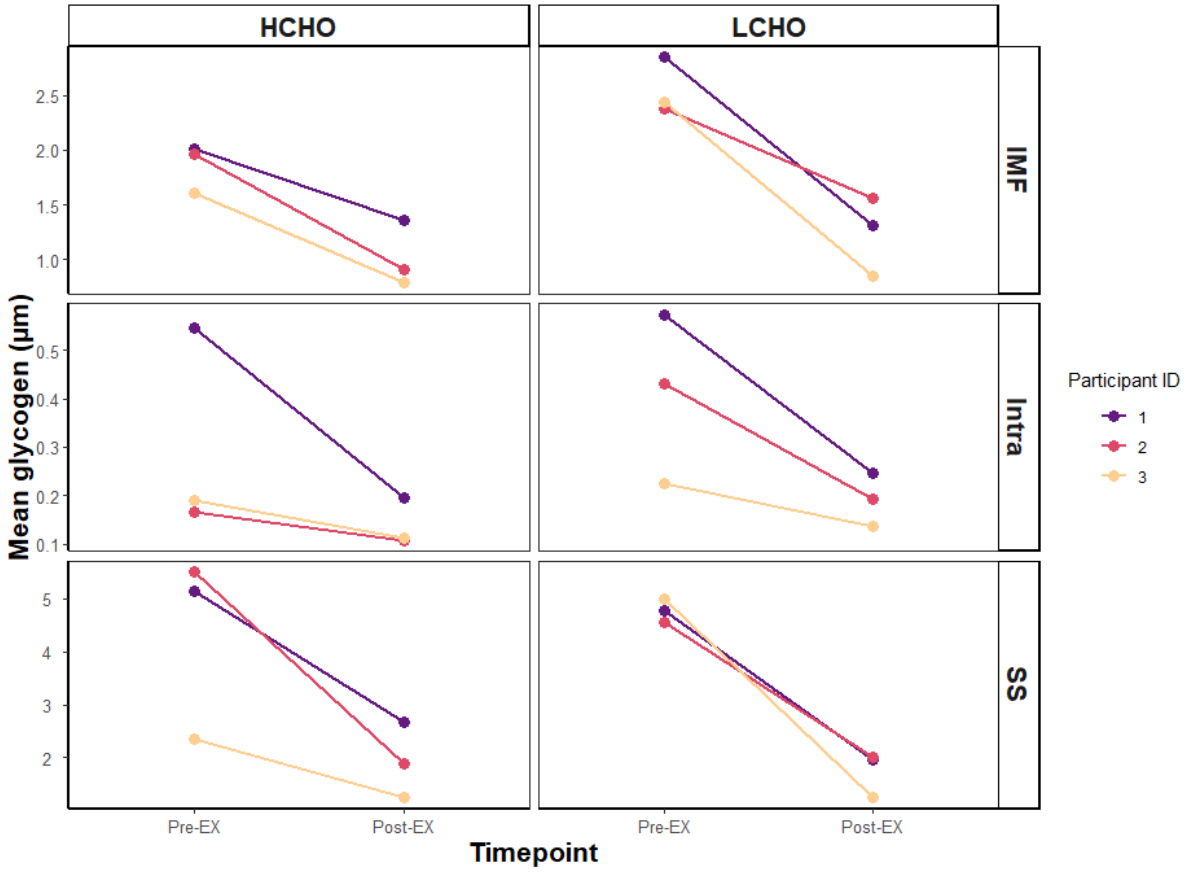
Raw data for subcellular muscle glycogen are presented in Table 8-8. Subcellular muscle glycogen results are visualised in Figure 8-6.

Table 8-8: Raw data for subcellular muscle glycogen. Glycogen content is expressed as glycogen volume normalised to fibre length (100 × µm³ per µm² myofibrillar area). Values represent means across 8–10 fibres per biopsy.

ID	*Condition*	*Subcellular glycogen stores (100 × µm³ per µm² myofibrillar area) by depot*								
		IMF			*Intra*			*SS*		
		Pre-EX	*Post-EX*	*Relative decrease (%)*	*Pre-EX*	*Post-EX*	*Relative decrease (%)*	*Pre-EX*	*Post-EX*	*Relative decrease (%)*
1	HCHO	2.02	1.35	-33.2	0.55	0.2	-64.2	5.13	2.66	-48.2
	LCHO	2.85	1.31	-54	0.57	0.25	-57.1	4.78	1.97	-58.8
2	HCHO	1.97	0.91	-53.8	0.17	0.11	-35.9	5.5	1.88	-65.8
	LCHO	2.38	1.55	-34.9	0.43	0.19	-55.1	4.56	2.00	-56.1
3	HCHO	1.61	0.78	-51.3	0.19	0.11	-41.4	2.35	1.25	-46.8
	LCHO	2.44	0.85	-65.2	0.22	0.14	-39.3	5.00	1.25	-75

IMF intermyofibrillar, *Intra* intramyofibrillar, *SS* subsarcolemmal, *HCHO* High carbohydrate breakfast, *LCHO* low carbohydrate breakfast

Figure 8-6: Participant-level subcellular glycogen responses from pre- to post-exercise in high-carbohydrate and low-carbohydrate conditions (n = 3). Glycogen content is expressed as glycogen volume normalised to fibre length (100 × µm³ per µm² myofibrillar area). Values represent means across 8–10 fibres per biopsy.



HCHO high carbohydrate breakfast, *LCHO* low carbohydrate breakfast, *EX* exercise, *IMF* intermyofibrillar, *Intra* Intramyofibrillar, *SS* Subsarcolemmal

8.4.6 Blood glucose and blood lactate

Raw data for BG and BL for all four participants are presented in Table 8-9 and Table 8-10. BG and BL results for all four participants are visualised in Figure 8-7.

Table 8-9: Raw data for blood glucose (mmol/L).

ID	*Condition*	*Blood glucose (mmol/L)*		
		Baseline	*Pre-EX*	*Post-EX*
1	HCHO	5.8	6.3	5.4
	LCHO	6.1	6.0	6.9
2	HCHO	5.4	4.9	4.9
	LCHO	4.8	5.1	5.3
3	HCHO	5.5	5.6	5.8
	LCHO	6.3	4.6	5.8
4	HCHO	5.3	5.7	5.3
	LCHO	5.4	4.8	5.4

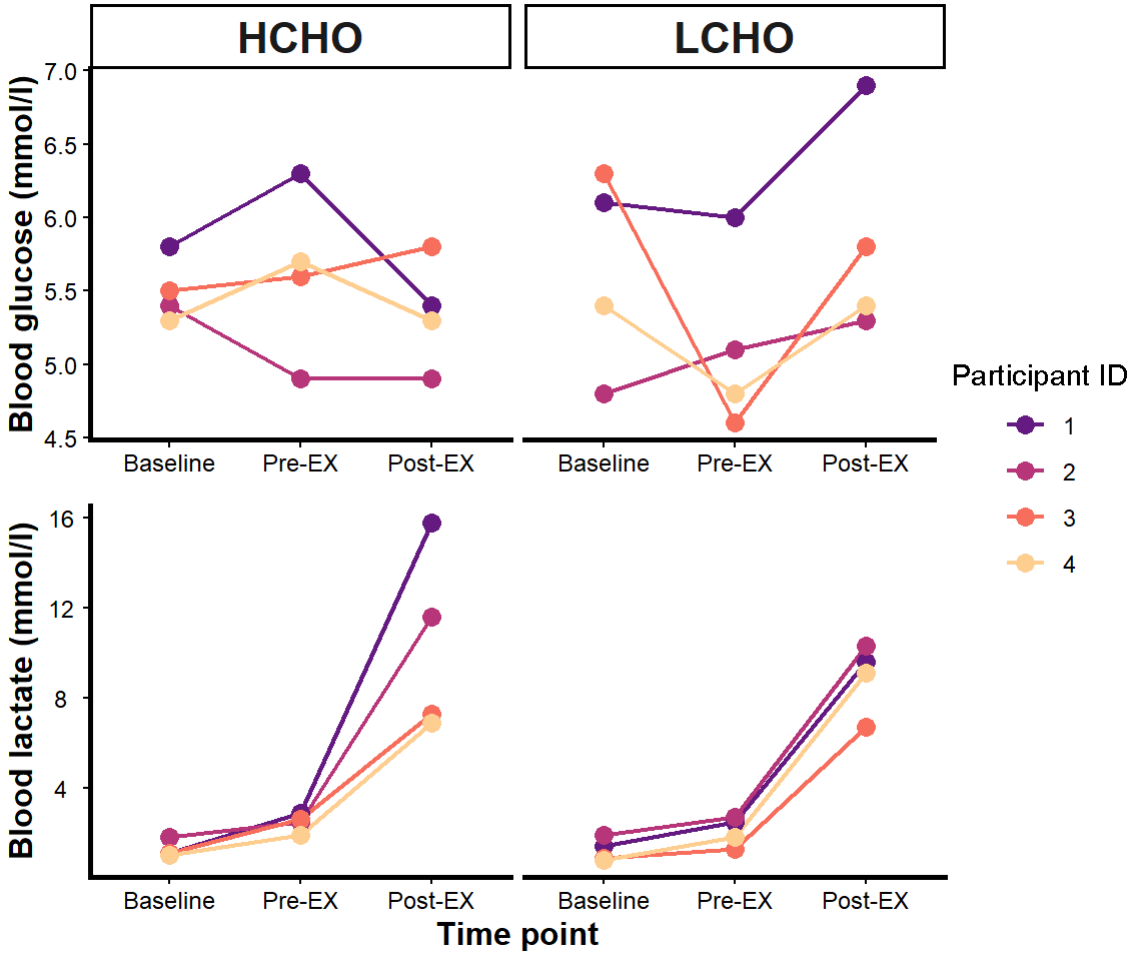
HCHO high carbohydrate breakfast, *LCHO* low carbohydrate breakfast, *EX* exercise

Table 8-10: Raw data for blood lactate (mmol/L).

ID	*Condition*	*Blood lactate (mmol/L)*		
		Baseline	*Pre-EX*	*Post-EX*
1	HCHO	1.1	2.9	15.8
	LCHO	1.4	2.5	9.6
2	HCHO	1.8	2.5	11.6
	LCHO	1.9	2.7	10.3
3	HCHO	1.1	2.6	7.3
	LCHO	0.9	1.3	6.7
4	HCHO	1.0	1.9	6.9
	LCHO	0.8	1.8	9.1

HCHO high carbohydrate breakfast, *LCHO* low carbohydrate breakfast, *EX* exercise

Figure 8-7: Blood glucose and blood lactate between groups (i.e., HCHO and LCHO) with individual participant datapoints (n = 4).



EX exercise, *HCHO* High carbohydrate breakfast, *LCHO* low carbohydrate breakfast

8.5 Discussion

This case series presents the first data examining the effects of acute CHO ingestion on RT volume performance alongside assessments of total and subcellular muscle glycogen. Results are reported descriptively and interpreted qualitatively. Collectively, we observed (a) greater exercise-specific and total session volume completed with HCHO compared to LCHO, (b) reductions in average and peak force output from pre-exercise to post-exercise across both conditions, (c) substantial decrements in total muscle glycogen from pre- to post-exercise (approximately 50–77%) with minimal differences between conditions, (d) similarly large pre- to post-exercise reductions across

intramyofibrillar, intermyofibrillar, and subsarcolemmal glycogen depots, with no consistent pattern of glycogen sparing between HCHO and LCHO, (e) BG values within normal physiological ranges between conditions and across the RT session, and (f) a marked increase in BL from pre- to post-exercise that was nominally higher for three of four participants.

8.5.1 Volume performance

Greater total session repetitions were completed in the HCHO condition. In general, the higher session volume observed with HCHO was not driven by a marked reduction in repetitions within a single exercise under LCHO. Modestly fewer repetitions were typically completed across exercises, which cumulatively resulted in lower total volume. Except for one participant who completed the same number of back squat repetitions between conditions, the between-condition difference in total repetitions was most pronounced during the back squat (8 – 17 repetitions) relative to the other exercises (2 – 7 repetitions). One participant completed substantially more total repetitions than the other three participants, as well as more repetitions within each exercise. While speculative, this may reflect a difference in habitual training, as her primary sport (swimming) is more endurance-oriented, possibly conferring a greater capacity to sustain work at a given load.

CHO has a small ergogenic effect on RT volume performance relative to a calorie-less placebo [287], consistent with the descriptive pattern of greater total session repetitions completed with HCHO observed in the present case series. One strength of the current case series is that an energy-equated liquid breakfast (i.e., LCHO; ~50% calories protein, ~50% calories fats) was used as the comparator relative to the CHO liquid breakfast (i.e., HCHO; 100% of calories from powdered maltodextrin). The liquid breakfasts were taste and texture matched and delivered in opaque bottles, aiding blinding.

The ergogenic role of acute CHO ingestion on RT performance may be moderated by several factors such as sessions duration, fast duration, and exercise selection [118, 287]. The present RT protocol incorporated a prolonged fast (>10 h), a relatively long session duration (~75 – 90 min), and lower-body exercise selection, all of which align with conditions under which acute CHO ingestion may exert greater effects. Additionally, lower absolute loads permitting a higher total number of

repetitions may place greater demands on glycogen-related substrate availability, potentially increasing the utility of CHO manipulation. While load has not been clearly associated with a greater SMD of volume performance with CHO ingestion [118, 287], a greater accumulation of repetitions may be necessary to detect relatively small performance differences. Group-level analyses are required once recruitment is complete to evaluate these observations more formally.

8.5.2 Isokinetic performance

We included a novel assessment of isokinetic force production during the back squat using the Quantum Synchro 1080 at velocities of 0.25 and 1.00 m/s. These velocities approximate the movement speeds of a repetition close to a 1-RM in trained individuals [281], and maximum mechanical power [280], respectively. These outcomes provide insight into changes in average and peak force which may reflect the development of neuromuscular fatigue [288].

At 1.00 $m \cdot s^{-1}$, average and peak force generally decreased from pre-exercise to post-squat across participants, with force remaining reduced for the remainder of the session. This pattern appeared broadly similar between the HCHO and LCHO conditions, with little indication of force production recovery following subsequent exercises. In contrast, patterns at 0.25 $m \cdot s^{-1}$ were less uniform. While most participants exhibited reductions in average and peak force from pre-exercise to post-squat, one participant demonstrated transient increases in force at post-squat under the HCHO condition only, followed by subsequent reductions later in the session.

Across both velocities, changes in force production varied substantially between participants, exercises, and force metrics. In some instances, reductions in peak and average force from pre-exercise appeared larger under the HCHO condition than under LCHO, which may reflect the greater training volume completed in that condition and a concomitant increase in neuromuscular fatigue. However, these patterns were not consistent across participants or velocities, and in some cases differed between peak and average force measures. As such, interpretations of condition-specific effects on isokinetic force production remain tentative, and group-level analyses with the forthcoming larger sample are needed to explore an effect of feeding condition, if one exists.

8.5.3 Total muscle glycogen

The three participants experienced decrements to total muscle glycogen in the range of 50 – 77% pre- to post-exercise. This is a larger decrement that has been previously reported in the literature, with standard volumes of RT incurring 20 – 40% total muscle glycogen depletion [20-22, 289]. Meta-analytic data further indicate an average reduction of 21% following RT, with larger decrements observed as the number of sets increases, session duration is extended, and training intensity is reduced [290]. The comparatively large glycogen decrements observed in the present case series are likely attributable to characteristics of the RT protocol employed. Specifically, the session involved a prolonged duration (~75 – 90 min), high total volume (12 working sets), relatively lower intensity (80 – 90% of 10-RM), and lower-body exercises (back squat, leg press, and leg extension) targeting the biopsied muscle. Collectively, these factors are consistent with conditions under which greater utilisation of intramuscular glycogen would be expected during resistance exercise.

The effects of acute CHO feeding on muscle glycogen before and after an RT session have not previously been investigated. Meta-analytic evidence from the endurance exercise literature suggests a small but practically relevant glycogen-sparing effect of CHO ingestion from pre- to post-exercise [276]. In the present case series, substantial between-participant variability was observed in baseline total muscle glycogen (0.5 - 2.4 mg/g wet weight), while post-exercise glycogen concentrations were low across all participants under both feeding conditions (0.25 - 0.6 mg/g wet weight). When expressed as relative change, the magnitude of glycogen depletion differed nominally between feeding conditions. Specifically, relative depletion was slightly greater under LCHO than HCHO for participant 1 (−77.6% versus −75%), whereas the opposite pattern was observed for participants 2 and 3, with nominally greater depletion under HCHO than LCHO (−62.3% versus −54.8% and −63.8% versus −50%, respectively). Collectively, the direction and magnitude of these differences were not consistent across participants, post-exercise glycogen concentrations were comparably low under both conditions. While speculative, a glycogen-sparing effect of CHO during RT – if one exists – is likely to be of small magnitude that will require group-level formal analysis.

8.5.4 Subcellular muscle glycogen

When examined at the subcellular level, glycogen depletion differed across subcellular depots and participants, with no consistent condition-dependent effect observed across depots. While subsarcolemmal and intermyofibrillar glycogen tended to exhibit greater relative depletion under LCHO in some participants, the direction and magnitude of these effects were not uniform. For example, participants 1 and 3 exhibited greater relative depletion of intermyofibrillar (−54% vs. −33% and −65% vs. −51%, respectively) and subsarcolemmal (−59% vs. −48% and −75% vs. −47%, respectively) glycogen under LCHO compared with HCHO, whereas participant 2 exhibited greater depletion of these depots under HCHO (intermyofibrillar: −54% vs. −35%; subsarcolemmal: −66% vs. −56%). Intramyofibrillar glycogen displayed a different pattern, with participants 1 and 3 exhibiting nominally greater depletion under HCHO compared with LCHO (−64% vs. −57% and −41% vs. −39%, respectively), whereas participant 2 exhibited greater depletion under LCHO relative to HCHO (−55% vs. −36%). A notable limitation is that the automated quantification model demonstrated acceptable agreement with manual counts for total and intermyofibrillar glycogen, but poorer agreement for intramyofibrillar glycogen.

There were also appreciable between-participant and between-condition variability in baseline subcellular glycogen content, despite standardisation procedures for pre-trial diet (i.e., 3 - 7 g/kg BM CHO per day during the study) and training (48 hr cessation), and biopsy timing. Intermyofibrillar glycogen was consistently higher pre-exercise under LCHO (~2.4 – 2.85 µg) compared with HCHO (~1.6 - 2 µg) across participants, suggesting that biological variability in glycogen storage and/or partitioning was present even under the controlled experimental conditions. Collectively, these inter-participant differences, depot-specific patterns of depletion, and limitations of the quantification model underscore the exploratory nature of the subcellular glycogen observations and suggest that whole-muscle glycogen depletion may arise via different subcellular contributions across individuals and feeding conditions.

8.5.5 Blood glucose

BG stayed within normal physiological ranges during all time points and conditions, indicating no RT-induced hypoglycaemia, consistent with meta-analytic evidence [287]. CHO feeding elicits a large effect on post-exercise BG that may be greater when CHO is ingested before *and* during RT, rather than just pre-exercise [287]. We opted to confine nutrient intake to the pre-exercise period, which may partly explain the absence of a clear condition- or time-dependent pattern in BG responses. The extent to which acute manipulation of BG availability influences RT performance remains an underexplored potential moderator of the ergogenic effects of CHO ingestion. Based on the descriptive findings of this case series, the role of BG dynamics in mediating acute CHO effects during RT remains unresolved and warrants further investigation.

8.5.6 Blood lactate

Regarding BL, concentrations were low at baseline and pre-exercise, before markedly increasing at post-exercise. Lactate is an important fuel source during exercise [291], is unlikely to be a central cause of fatigue [111], and is a useful correlate of metabolic and neuromuscular fatigue [112, 113]. Meta-analytic evidence suggests a small effect of CHO feeding on post-exercise BL [118, 287], likely due to the small ergogenic effect on RT volume performance that produces more total work and subsequent BL increases. In the present case series, post-exercise BL concentrations were nominally higher under the HCHO condition for three of four participants, although the magnitude and direction of individual, between-condition differences varied substantially. Taken together, post-exercise BL reflected the metabolic demands of the training session, with nominal between-condition differences that varied across individuals.

8.6 Conclusion

This case series provides the first preliminary examination of acute CHO feeding's effect on high-volume, lower-body RT performance alongside measurements of total and subcellular muscle glycogen. CHO ingestion was associated with greater exercise-specific and total session volume, while

average and peak force declined across training in both conditions. Substantial total muscle glycogen depletion occurred, which was similar across conditions, likely reflecting the prolonged duration, high volume, and lower-body exercise selection. At the subcellular level, glycogen depletion was evident across all depots; however, while the magnitude and pattern of depletion varied between participants, it remained broadly similar across feeding conditions. Collectively, these exploratory findings suggest that acute CHO feeding may support greater volume completion during high-volume, lower-body RT without clearly altering total, whole muscle glycogen utilisation.

Chapter 9: General summary, practical applications, and directions for future research

9.1 General summary

The overarching purpose of this thesis was to elucidate the role of acute CHO ingestion as a potential ergogenic aid for RT performance by integrating systematic evidence synthesis, an applied investigation of athlete nutrition practices, and experimental crossover trials. In doing so, the thesis sought to identify and address conceptual uncertainty, methodological limitations, and practical ambiguity surrounding CHO use in RT-specific contexts. Collectively, the chapters were designed to clarify whether, when, and how acute CHO ingestion may influence RT performance, placing these findings within applied practice, rigorous laboratory settings, and mechanistic understanding. The subsequent findings are directly relevant for athletes, coaches, and sport nutrition practitioners, as well as scientists seeking to advance and refine RT-specific nutritional recommendations and research.

Chapters 2 and 3 addressed the foundational question of whether acute CHO ingestion enhances RT performance through systematic review and meta-analysis. Chapter 2 provided the first quantitative synthesis of the literature examining acute CHO feeding and RT outcomes. Chapter 3 updated these findings, which demonstrate a small but potentially meaningful improvement in training volume, particularly when pre-exercise fasting (≥ 8 hrs) and session duration (> 45 mins) were longer. Importantly, Chapter 3 builds on Chapter 2 by improving effect size precision and reducing heterogeneity, while highlighting methodological weaknesses in the contemporary evidence, including inconsistent reporting regarding blinding and allocation concealment, and limited understanding of potential mechanisms. Together, these chapters established a conditional, rather than universal, ergogenic role for acute CHO ingestion on RT performance, which directly informed subsequent observational (Chapters 5 and 6) and experimental (Chapters 7 and 8) investigations.

Chapter 4 quantitatively synthesised the potential of centrally mediated ergogenic effects of CMR on RT performance. By identifying multiple CMR formulations (e.g., maltodextrin, maltose, and

glucose) alongside non-active comparator conditions (e.g., placebo rinses, water-only rinses, or no-rinse controls), this chapter simultaneously evaluated each via network meta-analysis. The findings indicated that CMR does not meaningfully influence maximal strength but may produce small and context-dependent improvements in peak force and total session volume. However, risk of bias, imprecision, and heterogeneity in effect estimates preclude conclusions beyond a low to very low certainty. Collectively, this chapter refines the evidence on CMR for RT performance by identifying where modest ergogenic effects may exist, while identifying methodological constraints that limit stronger inference.

Chapters 5 and 6 shifted the focus to applied nutrition by characterising the general and peri-workout nutrition behaviours of competitive, drug-tested powerlifters. Chapter 5 examined how athletes structure their energy and macronutrient intake across training phases, competitive periods, and varying training demands. Powerlifters commonly adopt an IIFYM/flexible dieting approach and frequently adjust EI in response to training demands, while avoiding deliberate energy restriction on rest or easier training days. Additionally, female powerlifters more frequently reported intentional energy restriction and dieting for body composition goals, compared to males. These are the first detailed descriptions of the general dietary practices in this population, highlighting several key trends relevant to athletes, coaches, and nutrition practitioners.

Chapter 6 continued by examining peri-workout nutrition practices, including pre-, intra-, and post-exercise feeding, fasted training, and supplementation in the same cohort of powerlifters. Most powerlifters prioritise pre- and intra-exercise CHO intake, rarely train fasted, and emphasise protein post-exercise. Supplementation with caffeine (e.g., pre-workout formulations and energy drinks) and creatine was most common before training, highlighting the need for powerlifters to consider third-party tested supplements to minimise risks of banned substance contamination and underdosing of ergogenic ingredients. Collectively, athletes' peri-workout practices are largely consistent with existing sport nutrition recommendations. Importantly, these survey chapters provide a practical backdrop for the experimental findings to be interpreted, bridging the gap between research and application.

Chapter 7 introduced a double-blind cross-over design to ascertain whether acute CHO ingestion enhances RT volume performance when total EI is held constant. This study compared isoenergetic pre-exercise meals differing in CHO content (i.e., 1.2 or 0.3g/kg BM CHO) with a low-calorie placebo before a predominantly upper-body high-volume RT session. No statistical differences were observed in RT volume performance between conditions, despite clear effects on BG and some differences in subjective appetite. Thus, under ecologically valid conditions, acute CHO dose *per se* may not be the primary determinant of RT performance, and the perception of EI may be sufficient (at least in the context of similar session lengths, volumes, and exercise selection).

The final research chapter (Chapter 8) presented preliminary case series data from an ongoing, pre-registered cross-over trial designed to investigate the effects of acute CHO feeding on high-volume lower-body RT performance and, with novelty to this field of research, on total and subcellular muscle glycogen utilisation. While full recruitment and group-level inferential analyses remain ongoing, the case series data indicated a general trend toward superior RT performance under HCHO compared with LCHO conditions. In contrast, both biochemical and ultrastructural glycogen analyses demonstrated substantial pre- to post-exercise reductions in total and subcellular muscle glycogen across participants, with similar between-condition depletion. By quantifying subcellular glycogen compartments via transmission electron microscopy and an AI quantification model, this Chapter and the future research that will arise from it, address a critical mechanistic gap identified throughout the thesis and represent an important step toward resolving how CHO availability may influence RT-induced fatigue at the cellular level.

Taken together, the studies comprising this thesis provide a coherent and progressive examination of acute CHO strategies in the context of RT. From systematic synthesis, through applied research, to controlled experimentation and novel mechanistic inquiry, the thesis advances understanding of acute CHO strategies in the context of RT beyond endurance-derived recommendations. This thesis supports a more nuanced, context-dependent view of CHO ergogenicity in RT, laying the foundation for refined practice guidelines and future research.

9.2 Practical applications

This thesis identified various findings of interest to athletes, coaches, nutrition practitioners, and researchers. These findings are categorised thematically into three primary domains:

9.2.1 When and how much acute CHO for RT performance?

- The small benefit of acute CHO feeding is more likely during longer (> 45 mins), higher-volume RT sessions and following longer pre-exercise fasts (≥ 8 hrs).
- Acute CHO intakes in the range of ~20–30 g consumed prior to or during RT confer small ergogenic effects on volume performance in some contexts. This range may serve as a pragmatic starting point, particularly during longer or higher-volume sessions, though responses are likely individual and context-dependent.
- For shorter session and pre-exercise fast durations, acute CHO provision is less likely to enhance RT performance.
- In the context of acute pre-exercise feeding, total energy availability may be as important as CHO content *per se*. Isoenergetic pre-exercise meals differing in CHO content produced comparable RT performance during a higher volume, predominantly upper-body RT session, suggesting perceived or actual energy provision – rather than CHO alone – may mediate performance.
- Upper-body dominant RT may be less sensitive to acute CHO availability due to less total muscle mass recruited. Compared with lower-body or whole-body RT, upper-body RT appears less likely to benefit from acute CHO feeding, potentially due to lower total work.

9.2.2 When and for whom might CMR be ergogenic for RT performance?

- CMR may confer small and moderate benefits for RT volume and pre- to post-exercise peak force production, respectively. While the certainty of evidence is low, this positions CMR as a potentially useful nutrition strategy that avoids CHO ingestion, such as in contexts where

athletes are undergoing energy restriction or where gastrointestinal symptom management is prioritised.

- CMR is unlikely to improve maximal dynamic strength.

9.2.3 How do the nutrition practices of RT-centric athletes align with acute CHO recommendations?

- Powerlifters commonly use an IIFYM/flexible dieting approach to support performance and body composition goals. This dietary strategy is compatible with acute CHO fuelling practices, as it allows athletes to flexibly adjust macronutrient intake around training demands without rigid dietary constraints.
- Powerlifters commonly increase EI on harder training days via more CHO-rich foods. Where higher training volumes or longer sessions are performed, this additional CHO may be strategically placed in the pre-exercise period to support volume performance, although the magnitude of any ergogenic effect is likely context-dependent (e.g., more likely for higher volume, lower body sessions).
- Female powerlifters more often follow energy-restricted diets. Chronic energy restriction may manifest as low energy availability, which can have performance, recovery, and health implications. In such contexts, acute CHO fuelling around training may represent a pragmatic approach to increasing CHO availability and total EI without requiring substantial changes to overall dietary structure.
- Powerlifters commonly emphasise acute CHO ingestion before and during training, which is more likely to have an ergogenic effect on volume performance during longer training durations, pre-exercise fasts, lower body exercise, and as more sets are completed.
- Powerlifters commonly prioritise protein and CHO intake in the post-exercise period to support recovery and adaptation. Post-exercise CHO ingestion may be particularly relevant for facilitating glycogen replenishment when multiple training sessions are performed within a day or when the same muscle groups are trained on consecutive days.

- In addition to acute CHO strategies, powerlifters commonly use ergogenic supplements such as creatine and caffeine-containing products (e.g., pre-workout formulations, energy drinks, or caffeine pills). Coaches and nutrition practitioners should encourage the use of third-party tested supplements to ensure accurate dosing and reduce the risk of inadvertent doping violation due to contamination or mislabelling.
- Acute CHO strategies should be individualised and context specific. Decisions regarding acute CHO ingestion or mouth rinsing should consider session duration, volume, exercise selection, fasting duration, habitual intakes, and athlete preference/goal, rather than being uniform.

9.3 Directions for future research

This thesis integrates evidence synthesis, applied nutrition research, and experimental investigation to examine the role of acute CHO availability in RT. While the novel findings incrementally advance understanding in this area, several important avenues for future research remain.

9.3.1 Acute CHO ingestion and RT performance

In Chapters 2 and 3, a small ergogenic benefit of acute CHO ingestion on RT volume performance was observed. Future research should:

- Employ protocols involving shorter training sessions (i.e., <45 min) and shorter fasting durations (<8 h), which may meaningfully improve the precision of effect size estimates.
- Examine additional RT performance outcomes (e.g., maximal dynamic strength, power output, and barbell velocity) and alternative modalities (e.g., CrossFit, Olympic weightlifting) currently underrepresented.
- Specifically investigate the dose–response relationship between acute CHO ingestion and RT volume performance.
- Explore potential moderators related to post-exercise BG, including the timing, dose, and type of CHO ingestion, to improve precision and reduce heterogeneity in effect estimates.

9.3.2 Mechanistic research

Mechanistic investigations represent a particularly important direction for future work. The preliminary incorporation of muscle biopsies and subcellular glycogen analyses in Chapter 8 demonstrates both the feasibility and potential value of examining total and depot-specific glycogen utilisation during RT. Future studies should:

- Replicate and extend these methods in larger samples to determine whether acute CHO feeding preferentially preserves, spares, or restores specific glycogen compartments (e.g., intramyofibrillar glycogen) during RT, and whether such effects are associated with meaningful differences in fatigue development, contractile function, and performance.
- Investigate the effects of CHO ingestion around RT on liver glycogen utilisation.
- Experimentally manipulate BG concentrations around RT to determine whether this influences RT performance.

9.3.3 CMR

In Chapter 4, CMR demonstrated a small ergogenic effect on RT session volume, a moderate effect on pre- to post-exercise peak force, and no effect on maximal dynamic strength. Future research should:

- Compare different CMR formulations to resolve network inconsistencies and clarify the relative efficacy of specific CHO types.
- Assess pre- to post-exercise peak force using RT protocols in resistance-trained and female participants.
- Further investigate mechanistic explanations for the enhancement of pre- to post-exercise peak force with CMR. Current evidence is limited to a small number of studies examining electromyographic outcomes (e.g., root mean square, maximal evoked potential, and mean fibre conduction velocity), with inconsistent findings.
- Examine the effects of CMR on total work performed to enable future quantitative synthesis.

Regarding maximal dynamic strength, the current evidence suggests CMR produces effects comparable to placebo. However, future studies could improve effect estimates and explore potential moderators by:

- Investigating untrained populations.
- Increasing the representation of female participants.
- Incorporating lower-body exercise selections.

9.3.4 Methodological considerations

Across the evidence syntheses presented in Chapters 2 - 4, several recurring methodological limitations were identified. Future research should:

- Clearly distinguish between allocation concealment and blinding in reported methods.
- Explicitly define what "double-blind" means by specifying who was blinded (e.g., participants, outcome assessors, data analysts, and manuscript writers).
- Provide transparent descriptions of how allocation concealment and assessor blinding were achieved (e.g., independent sequence generation, third-party preparation of supplements or mouth rinse solutions).
- Ensure sufficient washout periods, particularly when higher RT volumes are employed.
- Pre-register study protocols with clearly defined primary outcomes and analysis plans.

9.3.5 Applied nutrition practices in RT-centric athletes

Finally, the observational data examining nutrition practices of competitive powerlifters (Chapters 5 and 6) identified several trends and gaps that warrant further investigation, including:

- The nutrition practices of other RT-centric athletes (e.g., strongman competitors and Olympic weightlifters).
- Quantification of macronutrient and micronutrient intake across distinct competitive phases.
- The prevalence and implications of low energy availability among powerlifters.

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Appendices

Appendix A – Co-author contributions template

COAUTHORSHIP CONTRIBUTION TEMPLATE

From the AUT Co-Authorship Protocol:

An author is an individual who has made a significant intellectual or scholarly contribution to research and its output, and agrees to be listed as an author. A significant intellectual or scholarly contribution must include one, and should include a combination of two or more, of the following:

- Conception and design of the project or output;
- Acquisition of research data where the acquisition has required significant intellectual judgement, planning, design, or input;
- Contribution of knowledge, where justified, including Indigenous knowledge;
- Analysis or interpretation of research data;
- Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation.

For further details on the co-authorship guidelines and requirements, please refer to the AUT Co-Authorship Protocol.
For the definition of a 'manuscript' within a thesis please refer to the Postgraduate Handbook.

Co-authorship Contributions within this Thesis

Please copy the box below in to your thesis, repeated for each manuscript included in the thesis.

STUDENT AND SUPERVISOR APPROVALS

By signing you are confirming that the co-author contributions stated in the table(s) below are accurate.

Student Name	Andrew King	**Signature**		**Date**	28/12/25
Supervisor Name	Eric Helms	**Signature**		**Date**	28/12/25

Chapter Number:	**3**
Manuscript Title:	**An Updated Meta-analysis on The Ergogenic Effects of Acute Carbohydrate Feeding on Resistance Exercise Performance**

Publication Status:	**Submitted for Publication**
Reference if published:	**NA**

AUTHOR SURNAME: (order as per manuscript)	**CONTRIBUTION** (May copy from the guidelines above)
Andrew King	**Conceptualisation, data curation, formal analysis, investigation, methodology, project administration, software, writing – original draft, writing – review and editing.**
Eric Helms	**Conceptualisation, methodology, writing – review and editing, supervision**
Ivan Jukic	**Conceptualisation, data curation, investigation, methodology, supervision, writing – review and editing.**

Chapter Number:	**4**
Manuscript Title:	**The effects of carbohydrate mouth rinsing on muscle strength and endurance: A systematic review with network meta-analysis**
Publication Status:	**Submitted for Publication**
Reference if published:	**NA**

AUTHOR SURNAME: (order as per manuscript)	**CONTRIBUTION** (May copy from the guidelines above)
Andrew King	**Conceptualisation, data curation, formal analysis, investigation, methodology, project administration, software, writing – original draft, writing – review and editing.**
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Ivan Jukic	**Conceptualisation, data curation, investigation, methodology, supervision, writing – review and editing.**

Chapter Number:	**2**
Manuscript Title:	**The ergogenic effects of acute carbohydrate feeding on resistance exercise performance: a systematic review and meta-analysis**
Publication Status:	**Published**
Reference if published:	**King, A., Helms, E., Zinn, C., & Jukic, I. (2022). The ergogenic effects of acute carbohydrate feeding on resistance exercise performance: a systematic review and meta-analysis. Sports Medicine, 52(11), 2691-2712. https://doi.org/10.1007/s40279-022-01716-w**

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Caryn Zinn	**Conceptualisation, writing – review and editing, supervision**
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Chapter Number:	**5**
Manuscript Title:	**The general nutrition practices of competitive powerlifters vary by competitive calibre and sex, weight, and age class.**
Publication Status:	**Published**
Reference if published:	**King, A., Kwan, K., Jukic, I., Zinn, C., & Helms, E. (2023). The general nutrition practices of competitive powerlifters vary by competitive calibre and sex, weight, and age class. European Journal of Nutrition, 62(8), 3297-3310. https://doi.org/10.1007/s00394-023-03233-6**

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Kedric Kwan	**Conceptualisation, methodology, writing – review and editing.**
Ivan Jukic	**Conceptualisation, methodology, supervision, writing – review and editing.**
Caryn Zinn	**Conceptualisation, methodology, writing – review and editing, supervision**
Eric Helms	**Conceptualisation, methodology, writing – review and editing, supervision**

Chapter Number:	**6**
Manuscript Title:	**Fueling for and recovering from resistance training: The periworkout nutrition practices of competitive powerlifters**
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Reference if published:	**King, A., Kwan, K., Jukic, I., Zinn, C., & Helms, E. (2024). Fueling for and recovering from resistance training: The periworkout nutrition practices of competitive powerlifters. Nutrition, 122, 112389. https://doi.org/10.1016/j.nut.2024.112389**

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Kedric Kwan	**Conceptualisation, methodology, writing – review and editing.**
Ivan Jukic	**Conceptualisation, methodology, supervision, writing – review and editing.**
Caryn Zinn	**Conceptualisation, methodology, writing – review and editing, supervision**
Eric Helms	**Conceptualisation, methodology, writing – review and editing, supervision**

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Appendix B - Supplementary Files for all Chapters in this doctoral thesis

Supplementary Files for every Chapter in this thesis can be found on the Open Science Framework using this link. Supplementary Files are indexed by Chapter with corresponding Supplementary Files within the relevant Chapter folder.