Preparedness for Competition in Highly Trained Adolescent Swimmers: Integrated Nutrition and Physiology

By

Josh Newbury

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Abstract

Swimmers will undergo large training loads during early adolescence to develop the physical and technical characteristics for elite competition, therefore daily nutrition practices to support health and performance are important at this critical age.

Past research suggested that adolescent swimmers often consumed inadequate energy and carbohydrate intakes to support their training; though, whether this research remains accurate is questionable considering given that studies were mostly based on singular assessment time points prior to the COVID-19 pandemic. As such, Chapter 3 observed the current daily nutrition intakes of highly trained adolescent swimmers in the UK, showing this population adapted, yet achieved the macronutrient recommendations before (carbohydrate [CHO]: 5.4 ± 1.2 g·kg BM^{-1}; protein: 2.3 ± 0.4 g·kg BM^{-1}; fat: 1.6 ± 0.4 g·kg BM^{-1}), during (CHO: 3.5 ± 1.1 g·kg BM^{-1}; protein: 1.7 ± 0.4 g·kg BM^{-1}; fat: 1.1 ± 0.3 g·kg BM^{-1}), and after (CHO: 5.4 ± 1.4 g·kg BM^{-1}; protein: 2.1 ± 0.6 g·kg BM^{-1}; fat: 1.5 ± 0.6 g·kg BM^{-1}) a COVID-19 lockdown.

Since adolescent swimmers appeared to appropriately support their daily health and performance through dietary intake, attention was then turned to supplement use. Chapter 4 demonstrated that supplement use was highly prevalent across the swimming talent pathway, with swimmers at the development talent stage utilising approximately four different nutritional supplements (~3 sports foods, ~1 health supplement) that were mostly informed by parents/guardians (74%), whereas national-level swimmers used a wider range of supplements (~3 health, ~3 sports, ~2 ergogenic) following greater access to performance nutrition support (i.e., nutritionists informed 51% of supplement use). Despite the widespread supplement use, however, Chapter 5 showed that adolescent swimmers had low adherence to vitamin D supplement recommendations, resulting in 70% of the population developing an 'insufficient' circulating vitamin D (<75 nmol·L^{-1}) status between the autumn and winter training periods.

Indeed, adolescent swimmers were most likely to use supplements for performance (35%) rather than health (12%), even though ergogenic aids currently have unclear performance outcomes for competitive swimmers. Consequently, Chapters 6–8 sought to explore the effects of acute ergogenic aids during practical swimming scenarios, although the outcomes appeared to question their application in the real world.

Firstly, caffeine (3 mg·kg BM^{-1}) provided no benefits towards a simulated 100 m competition performance (59.5 ± 7.8 s vs. 59.9 ± 7.9 s, g = 0.07), nor did it appear to impair a repeated performance the next morning after sleep (59.7 ± 7.7 s vs. 60.2 ± 7.9 s, g = 0.06). The second ergogenic aid under scrutiny was sodium bicarbonate ($NaHCO_3$; 0.3 g·kg BM^{-1}), which was shown to produce highly individual time to peak blood bicarbonate (HCO_3^-) concentrations in Chapter 7a (between 75–180 min post-ingestion). Yet, when this individualised approach (IND) was compared to a standardised approach (STND; 150 min pre-exercise) in practice, neither $NaHCO_3$ approach improved 6 x 75 m swimming interval swimming (mean interval time: IND: 47.3 ± 5.1 s, STND: 47.8 ± 6.0 s, PLA: 48.0 ± 5.5 s, all g <0.20), nor a follow-up 200 m time-trial after a 30 min recovery period (IND: 2:11.0 ± 8.2 s, STND: 2:11.5 ± 7.1 s, PLA: 2:11.1 ± 7.1 s, all g <0.20). Finally, the ingestion of citrulline malate (15 g) was also unsuccessful at improving 6 x 300 m interval swimming versus a placebo supplement (3:32.0 ± 9.6 vs. 3:32.8 ± 7.7 s, g = 0.09), despite the proposed ergogenic mechanisms appearing to align with whole-body, repeated aerobic efforts.

Collectively, these studies suggest that highly trained adolescent swimmers should place emphasis on achieving the recommended daily energy and nutrient requirements to achieve optimal preparedness for swimming competitions, rather than relying on ergogenic aids. However, it should be noted that this thesis only considered a small proportion of supplements, dosing strategies, and practical scenarios; therefore, further research is required before the potential benefits of ergogenic aids are dismissed in this cohort.

Keywords: sport nutrition; supplements; vitamin D; ergogenic aids; performance.

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25(OH)D, 25-hydroxyvitamin D

ATP, adenosine triphosphate

Ca^{2+}, calcium

CAF, caffeine

CHO, carbohydrate

Cl^-, chloride

CM, citrulline malate

DEE, daily energy expenditure

DEI, daily energy intake

H^+, hydrogen ions

K^+, potassium

La^-, lactate

Na^+, sodium

$NaHCO_3$, sodium bicarbonate

NO, nitric oxide

O_2, oxygen

PLA, placebo

SID, strong ion difference

SWC, smallest worthwhile change

Chapter 1 – Introduction and Literature Review

1.1 Introduction

Swimming is an Olympic sport that has been included at every modern summer Games since Athens 1896. This sport involves athletes racing against one another in four swimming strokes (freestyle, butterfly, backstroke, breaststroke) across 50 m (~25–30 s), 100 m (~45–60 s), and 200 m (~2–3 min) distances; with the freestyle event also held over longer durations (400 m: ~4–5 min, 800 m: ~8–9 min, 1500 m: ~14–17 min). Swimmers may also compete in a medley event, which involves performing all four swimming strokes in the same race (i.e., 200 m medley: 4 x 50 m, 400 m medley: 4 x 100 m). Moreover, while swimming is mostly an individual sport, some competitions also involve team relays (same and mixed sex) where four swimmers race together in 4 x 100 m (freestyle and medley) and 4 x 200 m (freestyle) events. Competition formats are variable, such that open/qualifying meets typically hold all races over 1–3 days, whereas championships span over 3–7 days. This is because the more competitive meets can require swimmers to race in heats, semi-finals, and finals on the same day, which is particularly challenging for swimmers who specialise in multiple strokes and distances (e.g., Michael Phelps at the 2008 Olympic Games: 200 m freestyle 100–200 m butterfly, 200–400 m medley, 4 x 100–200 m freestyle, 4 x 100 m medley).

Swimmers typically begin formal training as a progression from ‘learn to swim’ programmes and enter their first races soon afterwards (aged 8–11 years). Once joining competitive swimming clubs, it is common for young swimmers to undertake large training volumes comparable to adults (1–3 sessions·day^{-1}, 6–10 sessions·week^{-1}), in order to develop optimal stroke techniques; physical attributes; and racing skills to compete at an elite standard during adolescence (Shaw et al., 2014). Indeed, many swimmers have become World and Olympic champions before reaching adulthood (e.g., females: 14–16 years, males: 16–18 years; Knechtle et al., 2016). Notable examples of this occurred in 2022, as 17-year-old David Popovici became the first ever swimmer to complete the 100 m freestyle event in under 47 s (46.86 s), whereas 15-year-old Summer McIntosh won ten international medals in two months, including four at the World Aquatic Championships (2 x gold, 1

x silver, 1 x bronze), followed by six at the Commonwealth Games (2 x gold, 3 x silver, 1 x bronze). In contrast, the large commitments to swimming training and education during adolescence can be overwhelming, often resulting in attrition if not winning competitions or consistently making performance improvements (Monteiro et al., 2017). Therefore, given the large training loads and importance of achieving competitive success from an early age, it is critical that adolescent swimmers are fulfilling daily nutritional requirements to ensure that optimal training adaptations, recovery, and growth can occur.

Competitive swimmers of all ages only require a peak performance once or twice per year at major competitions; hence, much of the swimming season is dedicated to maximising training adaptations (Mujika et al., 2014). For example, the training emphasis will change as the season progresses with more training sessions dedicated towards building general aerobic capacity and strength adaptations in the early season or early competition cycle (i.e., September to December: high-volume; low-to-moderate intensity; low specificity), and more training sessions dedicated towards specific race speed and preparation skills in mid-competition cycle (i.e., January to April: lower volume; higher intensity; including entry to domestic competitions) (Mujika et al., 2018; Pollock et al., 2019). Moreover, in the 1–2 weeks immediately prior to competitions, swimmers will undergo a taper period, consisting of a significant decrease in training volume and training sessions while maintaining a high intensity, in an attempt to dissipate fatigue and maintain adaptations during the competition period (i.e., April and August; Pollock et al., 2019; Stellingwerff et al., 2011). Subsequently, these training alterations within the season, and often within 3–4-month training cycles for adolescents, place a changing emphasis on a swimmer's fuelling and recovery needs (Burke & Mujika, 2014). Consuming a nutrition intake that provides adequate energy, macronutrients, and micronutrients is therefore essential for supporting daily training performances and maintaining athlete health throughout the year; and as such, optimising the capacity to make training adaptations in preparation for swimming competitions (Domínguez et al., 2017; Mujika et al., 2014). Thus, given the importance of nutrition, the first part of this literature review will critically discuss the research that has reported the daily nutrition intakes of

highly trained adolescent and young adult swimmers, as well as seek to identify whether the nutritional guidelines are currently being achieved.

While swimmers should eat a wide variety of foods to achieve their nutritional requirements, the adoption of a 'food only' approach to nutrition is likely to be detrimental to health and performance. Indeed, swimmers could have difficulty consuming all required nutrients through food alone, either because: (a) some nutrients are naturally scarce in the diet (e.g., vitamin D); (b) large or impractical portion sizes may be required to consume a sufficient intake (e.g., carbohydrate [CHO]); and/or (c) some nutrients might only abundant in foods that a swimmer does not/cannot eat due to intolerances or dietary preferences (e.g., vegan, vegetarian) (Close et al., 2022). As such, a 'food first, but not food only' approach to sport nutrition is thought to be optimal since supplements can offer a convenient provision of energy and macronutrients, while the ingestion concentrated vitamins and minerals can support health and offset potential deficiencies (Close et al., 2022). Moreover, once swimmers are consuming nutritional intakes that support their daily fuelling and recovery requirements, they might then turn their attention to more advanced nutrition strategies associated with marginal performance enhancements (Maughan et al., 2018). This includes nutritional ergogenic aids that can promote physiological adaptations that can delay fatigue and/or hasten recovery (Derave & Tipton, 2014), possibly giving swimmers an advantage over their competitors. Therefore, to give a complete overview of the nutritional practices required to optimise preparedness for swimming competitions, the second part to this literature review will focus on nutritional supplements; giving particular attention to identifying and critically analysing potential ergogenic aids that are suggested to enhance swimming performance.

1.2 Energy and Macronutrient Requirements

1.2.1 Energy

An adequate daily energy intake (DEI) is essential for the healthy functioning of all physiological processes, from muscle function and bone health to the synthesis of all hormones and enzymes (Mountjoy et al., 2018). For most of the competitive season, a swimmer's DEI should first aim to cover their daily energy expenditure (DEE), such that the energy consumed through food, drinks, and supplements matches the demands placed on the body through activity and physiological functions (i.e., basal metabolic rate) (Logue et al., 2018). Indeed, reaching this state of energy balance has been recommended to swimmers to support training and racing performances (Shaw et al., 2014); stimulate training adaptations (Mujika et al., 2014); promote post-exercise recovery (Burke & Mujika, 2014); and maintain health year-round (Pyne et al., 2014). However, as energy balance is also required for a stable body mass, swimmers may incorporate planned periods of energy surplus or deficit into their season to manipulate their body composition (Stellingwerff et al, 2011). An energy surplus provides an increased anabolic effect that could support muscle hypertrophy and power improvements (Garthe et al., 2013), but could also lead to increases in body fat that could negate performance if power-to-weight ratio and hydrodynamics are offset (Dopsaj et al., 2020). In contrast, energy deficits can be used to decrease body fat and increase relative power output for competitions; although, this strategy involves training with low energy availability (LEA) that increases the risk of poor performance, fatigue, illness, and injury if not managed correctly (Mountjoy et al., 2018). Therefore, due to the risks involved, most swimmers should strive to achieve energy balance across the swimming season, with changes in body composition only attempted under qualified supervision.

The importance of achieving energy balance is further enhanced in adolescents, who have higher energy requirements than adults due to growth and development (Norris et al., 2022). However, meeting these energy demands can be challenging, due to: (a) absolute food and drink intakes being impractical to consume (Berning et al., 1991; Simič & Mohorko, 2018); (b) limited time to prepare

and eat meals when balancing training, education, and/or work commitments (Desbrow, 2021); or (c) the development of disordered eating practices in response to societal and/or sporting pressures to sustain a lean physique (da Costa et al., 2013). This can be problematic since LEA during adolescence could have numerous health consequences that could delay growth and development, result in poor health, and reduce swimming performance (Desbrow et al., 2014; VanHeest et al., 2014). It is therefore critical that adolescent swimmers consume an adequate DEI, potentially requiring additional education and practical workshops (i.e., meal preparation, food shopping) alongside their support network (e.g., parents/guardians, coaches, sport science staff) to support adherence to this requirement (Shaw et al., 2014).

Establishing DEI guidelines is difficult considering that requirements should be individualised based on training, lifestyle, body size, and maturity status. Nonetheless, studies have sought to determine DEI thresholds for swimmers at each training stage, which are as follows: ≥40–75 kcal·kg BM^{-1}·day^{-1} in general/aerobic preparatory training (high-volume, low-to-moderate intensities); 35–65 kcal·kg BM^{-1}·day^{-1} in specific/race preparatory training (high-intensity, low-to-moderate volumes); 35–62 kcal·kg BM^{-1}·day^{-1} in tapers and competitions; and 29–43 kcal·kg BM^{-1}·day^{-1} in rest periods (Mujika et al., 2014; Shaw et al., 2014). Swimmers should be advised that these energy recommendations are only a guide, and it is possible that LEA can occur when consuming a DEI within these ranges. For example, Matsuda et al. (2018) observed intakes of ≥60 kcal·kg BM^{-1}·day^{-1} (~4300 kcal·day^{-1}) during a general preparatory training phase, but this intake was insufficient to achieve energy balance when DEE was considered (~5400 kcal·day^{-1}). Similarly, Montenegro et al. (2017) found that male swimmers consumed 42–48 kcal·kg BM^{-1}·day^{-1} throughout a competitive season, which seems appropriate based on the DEI guidelines, yet these intakes were insufficient to achieve energy balance on 63% of dietary assessments. Therefore, while these current guidelines may be useful, it is advised that swimmers base their DEI on their own individual DEE where possible. However, this may require some trial and error under the direction of qualified performance nutritionist as DEE is admittedly difficult to measure in practice.

Adolescent swimmers (particularly females) are often found to consume an energy deficit during the swimming season, though this should be interpreted cautiously as research has used variable methods to estimate DEI and DEE (Table 1.1). Berning et al. (1991) first identified an energy deficit in females (~500 kcal·day^{-1}), but not males, during an intensive training camp. However, swimming EE was calculated via this group's mean oxygen (O_2) uptake while swimming at 1.3 m·s^{-1} (i.e., 5 kcal·L^{-1}), and was added to an estimated EE for non-athletic adolescents. Therefore, DEE estimations in this study were not individualised to each swimmer and only accounted for the energy used at one exercise intensity. Similarly, Hawley and Williams (1991) suggested that female swimmers were consuming an energy deficit of ~800 kcal·day^{-1} during an in-season training phase; though, DEE estimations were based on the energy used by adult swimmers during a middle-distance race (366 m), and not adolescents in daily training. Hassapidou et al. (2002) followed these studies by showing that adolescent male and female swimmers achieved energy balance when DEE was estimated with a predictive equation (Schofield, 1985). However, the use of predictive equations for adolescents has recently been challenged, considering they can underpredict basal energy requirements for growth by up to 1100 kcal·day^{-1} (Hannon et al., 2020a). Finally, Collins et al. (2012) and Arachchi et al. (2015) both used physical activity records to estimate DEE, but then monitored DEI with collection methods prone to underreporting (food frequency questionnaire [FFQ] and 24-hour recall, respectively) (Magkos & Yannakoulia, 2003). Combined, these studies highlight the challenges of accurately assessing energy balance in adolescent swimmers at singular time points in a season, suggesting that longitudinal studies would be more effective as these can also monitor changes in body composition, growth, and wellness.

To date, only one study has attempted to compare DEI and DEE directly in adolescent swimmers; using indirect calorimetry (resting EE) and 24-hour heart rate monitoring (activity EE) to determine the DEE across a season (Alméras et al., 1997). While energy balance appeared to be achieved in the initial months, the female swimmers in this study displayed energy deficits (~500–900 kcal·day^{-1}) at

the eight- and 12-month time points compared to DEI. Despite this, body mass was increased at the end of the season, indicating that energy balance (or a surplus) had been achieved (Garthe et al., 2013). This may be explained since DEI and DEE were only measured for three days, and therefore the dietary scrutiny during this assessment window could have caused swimmers to alter or misreport their DEI (Magkos & Yannakoulia, 2003). A secondary finding was that DEI was not altered across the season to match the training phase, resulting in body fat accruement (+4.8 kg) during the off-season. Following this landmark study, two other longitudinal dietary assessments of adolescent swimmers have found a similar outcome: that adolescent swimmers adapt their DEI to match their changing energy demands (Kabasakalsis et al., 2007; Zietz et al., 2009). However, neither of these studies reported any consequence to hormone production, body composition, or 100 m swimming speed (Kabasakalsis et al., 2007; Zietz et al., 2009). This suggests that long-term energy deficiency might be overstated in adolescent swimmers, and the alternate problem lies in their ability to accurately record/recall their dietary intakes. Nonetheless, due to the individuality of each swimmer, and the possible occurrence of LEA and/or eating disorders (da Costa et al., 2013; VanHeest et al., 2014), it is important that DEI continues to be monitored in young swimming cohorts to best support their future health and performances.

Long-term dietary studies in adolescents have mostly investigated female swimmers, therefore a discussion of the most recent research in young adults (aged 19–25 years) is required to assess the possible sex-based differences (Montenegro et al., 2017). Similarly, this research reported that neither male nor female swimmers altered their dietary intakes across a 32-week period, resulting in males seemingly being in an energy deficit for 63% of the season, and females being in an energy deficit year-round. However, as this study only monitored dietary intakes for one day using an error-prone collection method (24-hour recall) (Burke, 2015), these results should be interpreted with caution. Indeed, despite apparent energy deficits, male swimmers did not change in body composition across the season, which is in accordance with other studies using more reliable methods (i.e., 3-day food diaries; Barr & Costill, 1992; Noland et al., 2001; Sato et al., 2011), and suggests that male swimmers

are also likely to underreport their dietary intakes. On the other hand, large reductions in body mass (~3 kg) were detected in female swimmers, but these were most noticeable during competition periods (Montenegro et al., 2017). While this implies that LEA was present, the timing of weight loss hints that body composition periodisation might have been utilised to improve performance (Stellingwerff et al., 2011). Past research has supported the notion that adult female swimmers decrease in body mass during the competitive season (1–2 kg loss, Noland et al., 2001; Petersen et al., 2006), though this is not always the case (1 kg gain, Sato et al., 2011). This potentially suggests that female swimmers require additional sport nutrition support compared to males, although due to both sexes seemingly being incapable of accurately reporting their DEI, further research is required.

Though adolescent swimmers have displayed an apparent inability to match (or accurately report) an appropriate DEI, this has been found to have little practical implications in research to date. However, no study has so far accounted for such large disruptions to training and daily routines as caused by the COVID-19 pandemic. Between March 2020 and December 2021, the rapid spread of COVID-19 caused governments to impose lockdown procedures, forcing the closure of all swimming facilities, the cancellation of all competitions, and resulting in swimmers training at home in isolation (Haddad et al., 2021). During these lockdown periods, young swimmers were potentially faced with greater psychological stress (particularly around performance and body composition) that may have instigated energy restriction/surplus practices; a tendency to consume poor quality foods; unfavourable eating patterns (i.e., skipping breakfast, late meals); and/or more sedentary attitudes towards exercise (Chandler et al., 2021; di Cagno et al., 2020; Fitzgerald et al., 2021; Pillay et al., 2020). Therefore, while previous research suggests that swimmers would not adapt their DEI in response to their decreased training loads, this was unknown under the pressures of COVID-19. Moreover, as potential dietary changes could have occurred during lockdown, it was no longer clear whether swimmers retained a capacity to spontaneously increase DEI following a return to sport. Hence, to provide an updated perspective on whether highly trained adolescent swimmers can consume an adequate DEI to support their performance and health, current studies should first consider the dietary effects that took

place before, during, and after the COVID-19 pandemic. This is especially important given that no information is currently available on these changes, and this research would support swimmers and their support staff to adequately prepare in the event of similar global pandemics in the future.

Table 1.1. An overview of studies that have reported the dietary energy intakes of highly trained adolescent and young adult swimmers.

Authors	Participants			Methods		Results		
	Sample size	Training status (nation)	Age (years)	DEE/DEI collection method	Time of season or volume	DEE (kcal·day^{-1})	DEI (kcal·day^{-1})	DEI (kcal·kg BM^{-1}·day^{-1})
Adolescents (aged 11–18 years)								
Alméras et al. (1997)	6 (all female)	International (Canada)	F = 17 ± 1	IC + PAR / Written food diary (3 days)	Pre-season 4 months 8 months 12 months 2-month rest	F = 2866 ± 740 F = 2866 ± 645 F = 3153 ± 573 F = 3033 ± 525 N/A	F = 2627 ± 788 F = 2507 ± 812 F = 2651 ± 717 F = 2197 ± 717 F = 2270 ± 905	F = 44 F = 42 F = 44 F = 36 F = 35
Arachchi et al. (2015)	38 (M = 16, F = 22)	National & international (Sri Lanka)	M = 17 ± 1 F = 17 ± 2	PAR / 24-hour recall (3 days)	6 days·week^{-1} 2 hours·day^{-1}	M = 3941 ± 585 F = 3876 ± 553	M = 3866 ± 605 F = 3371 ± 484	N/A
Berning et al. (1991)	43 (M = 22, F = 21)	National (USA)	M = 16 ± 2 F = 15 ± 2	IC / Written food diary (5 days)	Training camp 10 km·day^{-1}	M = 5167 F = 4025	M = 5222 ± 152 F = 3573 ± 147	M = 68 F = 61
Collins et al. (2012)	91 (M = 30, F = 61)	Mixed (USA)	14 ± 3	PAR (7 days) / FFQ (12-month recall)	N/A	2398 ± 784	M = 2570 ± 779 F = 2121 ± 881	M = 50 ± 19 F = 44 ± 20
da Costa et al. (2013)	77 (all female)	National (Brazil)	N/A (range: 11–19 years)	Written food diary (3 days)	N/A	N/A	$F_{<15}$ = 2032 $F_{<15(ED)}$ = 1966 $F_{\geq15}$ = 2534 $F_{\geq15(ED)}$ = 2112	$F_{<15}$ = 44 $F_{<15(ED)}$ = 37 $F_{\geq15}$ = 44 $F_{\geq15(ED)}$ = 37
Hassapidou et al. (2002)	35 (M = 20, F = 15)	National & international (Greece)	M = 16 ± 1 F = 16 ± 1	Equation / Weighed food diary (7 days)	In-season	M = 2718 F = 2317	M = 2861 ± 754 F = 2424 ± 650	M = 43 F = 40
Hawley & Williams (1991)	20 (M = 9, F = 11)	N/A (New Zealand)	M = 13 ± 1 F = 13 ± 2	Est. IC / Weighed food diary (4 days)	6 km·day^{-1} 6 days·week^{-1}	M = 2954 F = 2886	M = 3072 ± 732 F = 2130 ± 544	M = 55 ± 14 F = 40 ± 16
Kabasakalis et al. (2007)	9 (M = 4, F = 5)	International (Greece)	M = 18 ± 1 F = 17 ± 2	Written food diary (3 days)	Week 0: Pre-season	N/A	M = 3461 ± 459 F = 2090 ± 702	M = 46 F = 33

Table 1.1 continued

Authors	Participants			Methods		Results		
	Sample size	Training status (nation)	Age (years)	DEE/DEI collection method	Time of season or volume	DEE (kcal·day^{-1})	DEI (kcal·day^{-1})	DEI (kcal·kg BM^{-1}·day^{-1})
Adolescents (aged 11–18 years)								
Kabasakalis et al. (2007) *continued*	9 (M = 4, F = 5)	International (Greece)	M = 18 ± 1 F = 17 ± 2	Written food diary (3 days)	Week 10: 57 km·wk^{-1}	N/A	M = 3107 ± 614 F = 2549 ± 810	M = 42 F = 40
					Week 19: Minor taper	N/A	M = 2821 ± 480 F = 2369 ± 898	M = 37 F = 38
					Week 32: Major taper	N/A	M = 2861 ± 920 F = 2434 ± 838	M = 37 F = 38
Martínez et al. (2011)	36 (M = 22, F = 14)	Mixed (Spain)	M = 16 ± 1 F = 15 ± 1	24-hour recall (3 days)	30-36 km·wk^{-1} 6 d·wk^{-1}	N/A	M = 2845 ± 157 F = 1789 ± 103	M = 46 ± 3 F = 32 ± 2
Simič & Mohorko (2018)	19 (M = 6, F = 13)	International (Slovenia)	M = 16 ± 1 F = 14 ± 1	Weighed food diary (3 days)	In-season: 21 ± 3 hours·week^{-1}	N/A	M = 2738 F = 1576	M = 37 F = 28
VanHeest et al. (2014)	10 (F_C = 5, F_S = 5)	National (USA)	F_C = 16 ± 2 F_S = 17 ± 2	IC / Written food diary (3 days) & 24-hour recall	Week 0: Pre-season	F_C = 2394 F_S = 2225	F_C = 2481 ± 29 F_S = 1747 ± 49	F_C = 39 F_S = 27
					Week 2: General prep.	F_C = 2312 F_S = 2162	F_C = 2605 ± 29 F_S = 1772 ± 35	F_C = 42 F_S = 27
					Week 4: General prep.	F_C = 2332 F_S = 2333	F_C = 2667 ± 165 F_S = 1813 ± 37	F_C = 43 F_S = 28
					Week 6: Mixed prep.	F_C = 2568 F_S = 2602	F_C = 2660 ± 245 F_S = 1845 ± 51	F_C = 43 F_S = 28
					Week 8: Mixed prep.	F_C = 2686 F_S = 2393	F_C = 2565 ± 103 F_S = 1802 ± 46	F_C = 42 F_S = 28
					Week 10: Specific prep.	F_C = 2487 F_S = 2295	F_C = 2608 ± 87 F_S = 1801 ± 66	F_C = 43 F_S = 28
					Week 12: Taper	F_C = 2482 F_S = 2334	F_C = 2530 ± 291 F_S = 1821 ± 42	F_C = 41 F_S = 28
Zietz et al. (2009)	23 (all female)	Regional & national (Germany)	F = 14 ± 3	Written food diary (3 days)	Off-season	N/A	F = 5258 ± 1904	N/A
					General prep.	N/A	F = 5212 ± 1923	N/A
					Specific prep.	N/A	F = 4411 ± 1391	N/A
					Competition	N/A	F = 4714 ± 1674	N/A

Table 1.1 continued

Authors	Participants			Methods		Results		
	Sample size	Training status (nation)	Age (years)	DEE/DEI collection method	Time of season or volume	DEE (kcal·day^{-1})	DEI (kcal·day^{-1})	DEI (kcal·kg BM^{-1}·day^{-1})
Young adults (aged 19–25 years)								
Abood et al. (2004)	15 (all female)	Collegiate (USA)	F = 19 ± 2	Written food diary (3 days)	In-season	N/A	F = 1969 ± 414	F = 32
					8 weeks later	N/A	F = 1974 ± 473	F = 32
Barr & Costill (1992)	24 (M_S = 12, M_L = 12)	Collegiate (USA)	M = 19 ± 1	Written food diary (2 days)	Early season: 10 km·week^{-1}	N/A	M_S = 3609 ± 287 M_L = 3728 ± 215	M_S = 46 M_L = 52
					Mid-season: $_S$ = 22 km·week^{-1} $_L$ = 44 km·week^{-1}	N/A	M_S = 3227 ± 191 M_L = 4230 ± 215	M_S = 41 M_L = 59
					Late-season: 22 km·week^{-1}	N/A	M_S = 3155 ± 215 M_L = 3824 ± 167	M_S = 40 M_L = 53
de Carvalho et al. (2012)	8 (all male)	National (Brazil)	N/A (range: 18–25 years)	Written food diary (3 days)	Pre-season	N/A	M = 3663	M = 47
					General prep.	N/A	M = 4029	M = 52
					Taper	N/A	M = 3861	M = 49
Farajian et al. (2004)	31 (M = 20, F =11)	National & international (Greece)	M = 21 ± 4 F = 21 ± 4	24-hour recall (4 days)	7-17 km·day^{-1} 6 days·week^{-1}	N/A	M = 3408 ± 941 F = 2018 ± 559	M = 42 F = 31
Lukaski et al. (1989)	12 (all female)	National (USA)	N/A	Written food diary (7 days)	Pre-season	N/A	F = 2030 ± 96	F = 33
					Post-season	N/A	F = 2269 ± 104	F = 36
Lukaski et al. (1990)	29 (M = 13, F = 16)	National (USA)	N/A	Written food diary (7 days)	Pre-season	N/A	M = 3342 ± 176 F = 2193 ± 121	M = 43 F = 35
					Post-season	N/A	M = 3717 ± 200 F = 2329 ± 167	M = 48 F = 37
Lukaski et al. (1996)	10 (M = 5, F = 5)	National (USA)	N/A	Written food diary (3 days)	Specific prep./Taper	N/A	M = 3943 ± 132 F = 2085 ± 130	M = 51 F = 33
Matsuda et al. (2018)	13 (all male)	National (USA)	M = 20 ± 1	IC / Written food diary (3 days)	10 km·day^{-1}			
					Day 2	M = 5457 ± 629	M = 4385 ± 803	M = 65
					Day 3	M = 3579 ± 401	M = 3279 ± 817	M = 49
					Day 4	M = 5323 ± 529	M = 4279 ± 876	M = 63

Table 1.1 continued

Authors	Participants			Methods		Results		
	Sample size	Training status (nation)	Age (years)	DEE/DEI collection method	Time of season or volume	DEE (kcal·day^{-1})	DEI (kcal·day^{-1})	DEI (kcal·kg BM^{-1}·day^{-1})
Young Adults (aged 18–25 years)								
Mizugaki et al. (2021)	8 (M = 2, F = 6)	International (Japan)	M = 24 ± 1 F = 21 ± 2	Equation / Weighed food diary (3 days)	Training camp 12 km·day^{-1} Day 1 Day 2 Day 3	 3792 ± 1048 3157 ± 429 4780 ± 509	 3889 ± 1156 3803 ± 1128 4447 ± 1068	 61 59 69
Montenegro et al. (2017)	18 (M = 10, F = 8)	National & international (Brazil)	M = 20 ± 3 F = 20 ± 3	PAR / Week 1: written food diary (2 days); Weeks 6–32: 24-hour recall	Week 1: General prep. Week 6: Mixed prep. Week 9: Specific prep. Week 14: Competition Week 18: General prep. Week 24: Mixed prep. Week 28: Specific prep. Week 32: Competition	M = 3566 ± 146 F = 2784 ± 216 M = 3865 ± 260 F = 3076 ± 258 M = 3984 ± 367 F = 3077 ± 209 M = 3285 ± 216 F = 2676 ± 20 M = 4071 ± 188 F = 3156 ± 328 M = 3903 ± 202 F = 3107 ± 195 M = 4021 ± 181 F = 3239 ± 174 M = 3233 ± 146 F = 2575 ± 153	M = 3317 ± 389 F = 1921 ± 466 M = 3393 ± 480 F = 2027 ± 348 M = 3336 ± 139 F = 1792 ± 188 M = 3460 ± 389 F = 1905 ± 320 M = 3014 ± 257 F = 1670 ± 230 M = 3111 ± 195 F = 1763 ± 236 M = 3020 ± 271 F = 1750 ± 230 M = 3297 ± 403 F = 1523 ± 264	M = 46 F = 28 M = 48 F = 30 M = 47 F = 27 M = 48 F = 28 M = 42 F = 25 M = 43 F = 26 M = 42 F = 26 M = 45 F = 24
Noland et al. (2001)	21 (M = 9, F = 12)	National (USA)	M = 20 ± 0 F = 20 ± 0	PAR / Written food diary (3 days)	Week 1: 27 km·week^{-1} Week 4: 39 km·week^{-1} Week 9: 40 km·week^{-1}	M = 3600 ± 273 F = 2839 ± 118 M = 3897 ± 230 F = 3333 ± 226 M = 3992 ± 332 F = 3149 ± 130	M = 4530 ± 497 F = 2579 ± 156 M = 3704 ± 495 F = 2525 ± 140 M = 3062 ± 495 F = 2494 ± 137	M = 60 F = 42 M = 49 F = 41 M = 40 F = 41

Table 1.1 continued

Authors	Participants			Methods		Results		
	Sample size	Training status (nation)	Age (years)	DEE/DEI collection method	Time of season or volume	DEE (kcal·day^{-1})	DEI (kcal·day^{-1})	DEI (kcal·kg BM^{-1}·day^{-1})
Young Adults (aged 18–25 years)								
Ousley-Pahnke et al. (2001)	16 (all female)	National (USA)	F = 20 ± 1	Equation / Written food diary (4 days)	Taper: 4.3 km·day^{-1}	F = 2342 ± 158	F = 2275 ± 665	F = 34 ± 11
Paschoal & Amancio (2004)	8 (all male)	International (Brazil)	M = 19 ± 1	Written food diary (4 days)	3 hours·day^{-1} 6 days·week^{-1}	N/A	M = 3810	M = 53 ± 10
Petersen et al. (2006)	24 (all female)	National (USA)	F = 20 (median)	Photo food diary (3 days)	Pre-season	N/A	F = 2403 ± 864	F = 37
					Mid-season: 6.4–10 km·day^{-1}	N/A	F = 2356 ± 768	F = 37
Sato et al. (2011)	19 (M = 6, F = 13)	National (Japan)	M = 20 ± 1 F = 19 ± 1	IC + PAR / Photo food diary (3 days)	General prep. 3.5 km·day^{-1}	M = 2646 ± 146 F = 2085 ± 326	M = 3158 ± 773 F = 2710 ± 431	M = 48 F = 46
					Specific prep. 6–7 km·day^{-1}	M = 2932 ± 335 F = 2562 ± 372	M = 3322 ± 378 F = 2880 ± 408	M = 50 F = 49
Trappe et al. (1997)	5 (all female)	International (USA)	F = 19 ± 1	DLW / Written food diary (2 days)	Training camp 5–6 hours·day^{-1}	F = 5593 ± 495	F = 3136 ± 227	F = 48
Trindade et al. (2017)	19 (M = 11, F = 8)	National & international (Brazil)	M = 21 ± 3 F = 20 ± 3	PAR (7 days) / Written food diary (3 days)	General prep. 9 km·day^{-1}	M = 2908 ± 146 F = 2360 ± 138	M = 3328 ± 694 F = 2203 ± 501	M = 44 F = 34
Vallières et al. (1989)	6 (all female)	International (Canada)	F = 22 ± 1	IC + PAR / Written food diary (3 days)	3.3 km·day^{-1}	F = 2873 ± 577	F = 2497 ± 759	F = 40
					30 days later	F = 2511 ± 364	F = 2446 ± 693	F = 39
Van Handel et al. (1984)	27 (M = 13, F = 14)	National & international (USA)	M = 22 ± 3 F = 17 ± 2	Written food diary (3 days)	In-season	N/A	M = 4339 ± 1000 F = 2300 ± 840	M = 55 ± 11 F = 37 ± 8

All data are mean ± standard deviation. DEE = daily energy expenditure; DEI = daily energy intake. M = male swimmers; M_S/M_L = male sub-groups completing either 'short' (22 km·week^{-1}) or 'long' (44 km·week^{-1}) weekly distances. F = female participants; F_C/F_S = female sub-groups with either 'cyclic' or 'suppressed' menstrual function; $F_{<15}/F_{\geq 15}$ = female sub-groups either aged '<15 years' or '≥15 years'; $_{(ED)}$ = swimmers with a diagnosed eating disorder. DLW = doubly labelled water; IC = indirect calorimetry; PAR = physical activity record; FFQ = food frequency questionnaire. N/A = insufficient data reported.

1.2.2 Carbohydrate

Dietary CHO directly increases the concentration of muscle glycogen (Bergström et al., 1967): the primary fuel when exercising at intensities ≥65–75% of maximal O_2 uptake ($\dot{V}O_{2max}$) (Ivy, 1991). However, muscle glycogen stores can quickly deplete during swimming training of high intensities, or when swimming distances ≥5 km·day^{-1} (Costill et al., 1988b). As most highly trained swimmers will complete 1–2 swimming sessions·day^{-1}, consisting of training volumes between 5–10 km·day^{-1} (Pollock et al., 2019), it is essential that sufficient CHO is consumed daily. Indeed, inadequate CHO intakes have been associated with greater perceptions of fatigue, as well as a decreased capacity to complete high-volume and/or high-intensity training in swimmers (Costill et al., 1988a; Reilly & Woodbridge, 1999). Moreover, swimming with low glycogen availability can also increase circulating stress hormones and impair the immune system (Gleeson & Bishop, 2000), both of which increase the risk of contracting illnesses. Avoiding illnesses should be a key priority for swimmers as this can directly impair training performance and/or the ability to compete, either through attendance or performing poorly (Johnson, 2003; Pyne et al., 2005). Therefore, for swimmers to maintain their level of performance, training capacity, and health status throughout the season; it is important they consume sufficient daily CHO to support their energy demands.

The amount of daily CHO that should be consumed by swimmers is determined by training volume and intensity. Costill et al. (1988a) showed that swimmers who consumed ~5 g·kg BM^{-1}·day^{-1} CHO during a high-volume training period (9 km·day^{-1}) did not fully replenish muscle glycogen stores, leading to a reduction in exercise capacity; although, this effect was not observed in swimmers who consumed a CHO intake of ~8 g·kg BM^{-1}·day^{-1}. Importantly, the lower CHO intakes were also associated with energy deficiency (-1000 kcal·day^{-1}), which might infer that dietary CHO is equally as important for performance by sustaining energy balance during high-volume phases. This was corroborated by Lamb et al. (1990), who found no differences in training performance across a moderate-intensity training week when swimmers ingested energy matched diets of differing CHO

proportions (6 vs. 12 g·kg BM^{-1}·day^{-1}). However, caution must be taken since both studies (Lamb et al., 1990; Costill et al., 1988a) took place over a maximum duration of 10 days, and therefore did not investigate the long-term implications of consuming inadequate CHO. Nonetheless, based on this early evidence, it appears that a daily CHO intake between 6–12 g·kg BM^{-1}·day^{-1} may be required to meet energy and glycogen demands during moderate-to-high-volume training phases (Domínguez et al., 2017; Mujika et al., 2014); although, it should be noted that these were identified in adults and not adolescents. At present, there is little research to suggest an optimal CHO intake for low-volume or competition swimming phases, though intakes between 3–10 g·kg BM^{-1}·day^{-1} have been mooted depending on the individual's energy requirements and number of high-intensity efforts/races that will be completed (Mujika et al., 2014).

Given the lack of strong evidence in swimming, the following CHO guidelines have been suggested based on other power-endurance sports that require efforts greater than 100% of $\dot{V}O_{2max}$ for up to 10 min (Stellingwerff et al., 2011): 3–5 g·kg BM^{-1}·day^{-1} when training is low-intensity and skill-based; 5–7 g·kg BM^{-1}·day^{-1} for shorter duration training sessions (~1 hours·day^{-1} at moderate-to-high intensities); 6–10 g·kg BM^{-1}·day^{-1} when training once per day (1–3 hours·day^{-1} at moderate-to-high intensities); and 8–12 g·kg BM^{-1}·day^{-1} when training twice per day (4–5 hours·day^{-1} at moderate-to-high intensities). Whether adolescent swimmers require greater daily CHO intakes is currently unclear. Indeed, it is well established that children and adolescents have lesser developed glycolytic metabolism compared to adults (Boisseau & Delamarch, 2000), and often utilise less CHO at given exercise intensities (Martinez & Haymes, 1994; Rowland et al., 1987). However, such differences are typically observed in children and adolescents of low physical maturity and training status; hence, these results might not extrapolate to highly trained adolescents who have extensive training histories. Further research is therefore required to assess whether adolescent swimmers should deviate away from the CHO guidelines for adults, although this is not recommended at present (Desbrow, 2021; Hannon et al., 2020b).

Most research to date has only analysed the CHO intakes of adolescent swimmers at singular time points, finding inconsistent results (Table 1.2). In early work, for example, males consistently consumed CHO intakes ≥7 g·kg BM^{-1}·day^{-1}, whereas female swimmers reported more variable intakes (5.5–7.4 g·kg BM^{-1}·day^{-1}) (Berning et al., 1991; Hawley & Williams, 1991). However, these studies examined CHO intake during different training phases (6 vs. 10 km·day^{-1}), perhaps indicating that female swimmers were more capable of adjusting their daily CHO intakes compared to males. In a follow up investigation, both male and female swimmers were suggested to be consuming 'low' CHO intakes (≤5 g·kg BM^{-1}·day^{-1}); though, as this study did not provide training details, it was unclear whether these intakes were suboptimal for the training phase (Hassapidou et al., 2002). Later studies seemingly supported the notion that male swimmers consume higher CHO intakes (5.6–6.5 g·kg BM^{-1}·day^{-1}) than female swimmers (3.6–5.5 g·kg BM^{-1}·day^{-1}) (Collins et al., 2012; Martínez et al., 2011). Although, as both these studies used dietary collection method that relied on participant memory (24-hour recall and FFQ, respectively), it is plausible that a greater proportion of female swimmers instead misreported their intakes (Jonnalaggada et al., 2000). More recently, all male swimmers from the Slovenian junior national team reported consuming 6–10 g·kg BM^{-1}·day^{-1} CHO during a high-volume training phase (~21 hours·$week^{-1}$), whereas this intake threshold was only achieved by 69% of females (Simič and Mohorko, 2018). Collectively, these studies show that adolescent female swimmers are likely to report lower CHO intakes compared to males. Though whether these intakes were accurate or had practical implications is unclear, considering that each of these studies only assessed intakes once, and at varying points within the swimming season.

Few studies have assessed the CHO intakes of adolescent swimmers on a longitudinal basis, observing a lack of dietary periodisation. Alméras et al. (1997) first showed that female swimmers did not alter their CHO intake over a 13-month period (~6 g·kg BM^{-1}·day^{-1}), including during a two-month detraining period. However, while these intakes were seemingly in accordance with the current CHO recommendations (Mujika et al., 2014), it is important to note that these intakes were assessed in just six 'weight stable', internationally competitive swimmers; and thus, may not be reflective of

most adolescent swimming populations. Indeed, contrasting evidence was reported by Kabasakalis et al. (2007), who showed that highly trained male and female swimmers in Greece consumed CHO intakes of 3–5 g·kg BM^{-1}·day^{-1} at both high-volume and low-volume training phases. Moreover, it appeared that males reduced their CHO intakes in favour of dietary fat during the high-volume training stage, possibly due to: (a) dietary norms in this population (e.g., Mediterranean diet; Philippou et al., 2017); (b) misreporting in such a small participant sample (four males, five females); or (c) having poor knowledge of sport nutrition principles. A final study found very high CHO intakes in a cohort of German female swimmers regardless of being in intensive training, competition, or rest periods (~10 g·kg BM^{-1}·day^{-1}) (Zietz et al., 2009). Interestingly, these intakes were observed in swimmers of varying ages (10–20 years) and training levels, though it was unclear why these intakes were so high compared to previous investigations. Current longitudinal studies therefore display inconsistent results across small and varied cohorts, giving little indication of the current CHO intakes of highly trained adolescent swimmers, particularly in males.

Most research regarding the CHO intakes of adolescent swimmers was conducted 10–20 years ago, which might now provide an outdated perspective. Therefore, more recent research involving highly trained young adults (aged 19–25 years) shall briefly be discussed, as these intakes may have continued from adolescence (Table 1.2). An investigation from Brazil followed 18 international- and national-level swimmers over an eight-month period, observing low CHO intakes (<6 g·kg BM^{-1}·day^{-1}) in 76% of all dietary assessments (Montenegro et al., 2017). However, these intakes were initially monitored with just a two-day food diary in the first week, with 24-hour recalls used for the seven time points thereafter; both assessment methods associated with unreliable results and underreporting (Magkos & Yannakoulia, 2003). Nonetheless, this evidence was supported by Trindade et al. (2017), who also showed that Brazilian swimmers consumed low CHO intakes before, during, and after exercise; contributing to inadequate daily intakes (males: 5.4 g·kg BM^{-1}·day^{-1}, female: 4.7 g·kg BM^{-1}·day^{-1}) to support a high-volume training phase. In contrast, both Matsuda et al. (2019) and Mizugaki et al. (2021) recently reported CHO intakes within the recommended ranges in national- and

international-level swimmers from the USA and Japan, respectively. Both groups of swimmers reported consuming between 6–10 g·kg BM^{-1}·day^{-1} during periods of high-volume training and appeared to alter their intakes each day depending on training load. Although, as with other research using singular time points, these studies only provided a three-day window of CHO intake that could have either been underreported, or purposely increased in response to the added dietary scrutiny (Burke, 2015). Given this scant research, further longitudinal research is needed to understand the current CHO practices of highly trained adolescent swimmers.

Overall, the current literature is equivocal regarding the CHO intakes of highly trained adult and adolescent swimmers. A large proportion of studies have reported inadequate CHO intakes during high-volume training phases, which could impair training quality, recovery, and immunity at key points of the competitive season (Burke & Mujika, 2014; Pyne et al., 2014). This is a concern for adolescent swimmers since being able to train at a high standard on a daily basis is essential for maximising training adaptations and consequently, making continuous progressions in racing performance (Mujika et al., 2014). On the other hand, research has reported that some swimmers consume high CHO intakes that are not periodised over the course of the season, potentially leading to body mass increases during low-volume training phases that could offset performance (Alméras et al., 1997; Kjendlie et al., 2004). Besides these mixed outcomes, however, much of the research involving highly trained adolescent swimmers may now be outdated, obscuring the current understanding of CHO intakes behaviour. The importance of this understanding was recently made clear during COVID-19 pandemic, where large decreases and increases in swimming volume were caused by national lockdowns and self-isolation periods (Haddad et al., 2021). Therefore, given the lack of research, and the possibility of future pandemics occurring, further longitudinal observations of the dietary CHO intakes of highly trained swimmers during high-volume and low-volume training periods (i.e., COVID-19) are required.

Table 1.2. An overview of studies that have reported the dietary carbohydrate intakes of highly trained adolescent and young adult swimmers.

Authors	Participants			Methods		Results	
	Sample size	Training status (nation)	Age (years)	Collection method	Time of season or volume	Absolute CHO intake ($g \cdot d^{-1}$)	Relative CHO intake ($g \cdot kg\ BM^{-1} \cdot d^{-1}$)
Adolescents (aged 11–18 years)							
Alméras et al. (1997)	6 (all female)	International (Canada)	F = 17 ± 1	Written food diary (3-day)	Start of season 4 months 8 months 12 months 2-month rest	F = 392 ± 67 F = 391 ± 69 F = 401 ± 72 F = 334 ± 52 F = 328 ± 78	F = 6.6 F = 6.6 F = 6.6 **F = 5.4** F = 5.1
Arachchi et al. (2015)	38 (M = 16, F = 22)	National & international (Sri Lanka)	M = 17 ± 1 F = 17 ± 2	24-hour recall (3 day)	6 days·week^{-1} 2 hours·day^{-1}	M = 743 ± 63 F = 651 ± 93	N/A
Berning et al. (1991)	43 (M = 22, F = 21)	National (USA)	M = 16 ± 2 F = 15 ± 2	Written food diary (5-day)	Training camp 10 km·day^{-1}	M = 596 ± 21 F = 428 ± 24	M = 7.7 F = 7.4
Collins et al. (2012)	91 (M = 30, F = 61)	Mixed (USA)	14 ± 3	FFQ (12-month recall)	N/A	N/A	M = 6.4 ± 2.6 F = 5.5 ± 2.3
da Costa et al. (2013)	77 (all female)	National (Brazil)	N/A (range: 11–19 years)	Written food diary (3-day)	N/A	$F_{<15}$ = 275 $F_{<15(ED)}$ = 263 $F_{\geq 15}$ = 372 $F_{\geq 15(ED)}$ = 259	**$F_{<15}$ = 5.9** **$F_{<15(ED)}$ = 4.9** $F_{\geq 15}$ = 6.5 **$F_{\geq 15(ED)}$ = 4.5**
Hassapidou et al. (2002)	35 (M = 20, F = 15)	National & international (Greece)	M = 16 ± 1 F = 16 ± 1	Weighed food diary (7-day)	In-season	M = 314 ± 50 F = 288 ± 20	**M = 4.6 ± 1.0** **F = 4.8 ± 1.6**
Hawley & Williams (1991)	20 (M = 9, F = 11)	N/A (New Zealand)	M = 13 ± 1 F = 13 ± 2	Weighed food diary (4-day)	6 km·day^{-1} 6 days·week^{-1}	M = 404 ± 88 F = 292 ± 87	M = 7.3 ± 1.7 **F = 5.5 ± 2.5**
Kabasakalis et al. (2007)	9 (M = 4, F = 5)	International (Greece)	M = 18 ± 1 F = 17 ± 2	Written food diary (3-day)	Week 0: Pre-season Week 10: 57 km·week^{-1}	M = 340 F = 254 M = 276 F = 298	M = 4.5 F = 4.1 **M = 3.7** **F = 4.7**

Table 1.2 continued

Authors	Participants			Methods		Results	
	Sample size	Training status (nation)	Age (years)	Collection method	Time of season or volume	Absolute CHO intake ($g \cdot d^{-1}$)	Relative CHO intake ($g \cdot kg\ BM^{-1} \cdot d^{-1}$)
Adolescents (aged 11–18 years)							
Kabasakalis et al. (2007) *continued*	9 (M = 4, F = 5)	International (Greece)	M = 18 ± 1 F = 17 ± 2	Written food diary (3-day)	Week 19: Minor taper Week 32: Major taper	M = 283 F = 272 M = 285 F = 256	**M = 3.8** **F = 4.3** **M = 3.7** **F = 4.0**
Martínez et al. (2011)	36 (M = 22, F = 14)	Regional & national (Spain)	M = 16 ± 1 F = 15 ± 1	24-hour recall (3-days)	30-36 $km \cdot week^{-1}$ 6 $days \cdot week^{-1}$	M = 345 ± 13 F = 203 ± 12	**M = 5.6** **F = 3.6**
Simič & Mohorko (2018)	19 (M = 6, F = 13)	International (Slovenia)	M = 16 ± 1 F = 14 ± 1	Weighed food diary (3-days)	21 ± 3 $hours \cdot week^{-1}$	M = 594 F = 395	M = 8.1 ± 1.3 F = 6.9 ± 2.1
Zietz et al. (2009)	23 (all female)	Regional & national (Germany)	F = 14 ± 3	Written food diary (3-day)	Off-season General prep. Specific prep. Competition	F = 630 ± 117 F = 723 ± 152 F = 622 ± 122 F = 669 ± 154	N/A N/A N/A N/A
Young adults (aged 19-25 years)							
Abood et al. (2004)	15 (all female)	Collegiate (USA)	F = 19 ± 2	Written food diary (3-day)	In-season 8 weeks later	F = 375 ± 39 F = 277 ± 44	**F = 5.6** **F = 4.1**
Barr & Costill (1992)	24 (M_S = 12, M_L = 12)	Collegiate (USA)	M = 19 ± 1	Written food diary (2-day)	Early season: 10 $km \cdot week^{-1}$ Mid-season: $_S$ = 22 $km \cdot week^{-1}$, $_L$ = 44 $km \cdot week^{-1}$ Late-season: 22 $km \cdot week^{-1}$	M_S = 500 ± 44 M_L = 501 ± 36 M_S = 474 ± 40 M_L = 600 ± 38 M_S = 438 ± 32 M_L = 545 ± 34	M_S = 6.3 M_L = 7.0 M_S = 6.0 M_L = 8.3 M_S = 5.5 M_L = 7.6
de Carvalho et al. (2012)	8 (all male)	National (Brazil)	N/A (range: 18–25 years)	Written food diary (3-day)	Pre-season General prep. Taper	M = 538 M = 590 M = 508	M = 7.0 M = 7.6 M = 6.4
Farajian et al. (2004)	31 (M = 20, F =11)	National & international (Greece)	M = 21 ± 4 F = 21 ± 4	24-hour recall (4-day)	7-17 $km \cdot d^{-1}$ 6 $d \cdot wk^{-1}$	M = 361 ± 114 F = 248 ± 76	**M = 5.0 ± 1.5** **F = 3.8 ± 1.2**

Table 1.2 continued

Authors	Participants			Methods		Results	
	Sample size	Training status (nation)	Age (years)	Collection method	Time of season or volume	Absolute CHO intake ($g \cdot d^{-1}$)	Relative CHO intake ($g \cdot kg\ BM^{-1} \cdot d^{-1}$)
Young Adults (aged 19–25 years)							
Lukaski et al. (1989)	12 (all female)	National (USA)	N/A	Written food diary (7-day)	Pre-season Post-season	F = 271 ± 20 F = 334 ± 17	F = 4.4 F = 5.3
Lukaski et al. (1990)	29 (M = 13, F = 16)	National (USA)	N/A	Written food diary (7-day)	Pre-season Post-season	M = 429 ± 24 F = 285 ± 20 M = 480 ± 25 F = 320 ± 18	M = 5.5 F = 4.6 M = 6.3 F = 5.0
Lukaski et al. (1996)	10 (M = 5, F = 5)	National (USA)	N/A	Written food diary (3-day)	Specific prep./Taper	M = 440 ± 33 F = 260 ± 22	**M = 5.7** **F = 4.1**
Matsuda et al. (2018)	13 (all male)	National (USA)	M = 20 ± 1	Written food diary (3-day)	General prep. Day 2 Day 3 Day 4	 M = 589 ± 123 M = 449 ± 84 M = 553 ± 111	 M = 8.7 ± 1.8 M = 6.7 ± 1.3 M = 8.2 ± 1.7
Mizugaki et al. (2021)	8 (M = 2, F = 6)	International (Japan)	M = 24 ± 1 F = 21 ± 2	Weighed food diary (3-day)	Training camp	Day 1 = 530 ± 208 Day 2 = 531 ± 166 Day 3 = 614 ± 136	Day 1 = 8.3 ± 3.1 Day 2 = 8.2 ± 2.3 Day 3 = 9.6 ± 1.6
Montenegro et al. (2017)	18 (M = 10, F = 8)	National & international (Brazil)	M = 20 ± 3 F = 20 ± 3	Week 1: written food diary (2-day); Week 6-32: 24-hour recall (1-day)	Week 1: General prep. Week 6: Mixed prep. Week 9: Specific prep. Week 14: Competition Week 18: General prep. Week 24: Mixed prep. Week 28: Specific prep. Week 32: Competition	M = 410 F = 272 M = 428 F = 275 M = 400 F = 255 M = 471 F = 248 M = 347 F = 203 M = 360 F = 213 M = 367 F = 220 M = 386 F = 174	**M = 5.7 ± 1.5** **F = 4.0 ± 2.3** M = 6.0 ± 2.3 **F = 4.1 ± 1.9** **M = 5.6 ± 1.7** **F = 3.8 ± 1.1** M = 6.6 ± 1.8 F = 3.7 ± 1.4 **M = 4.8 ± 1.3** **F = 3.0 ± 1.0** **M = 5.0 ± 1.2** **F = 3.2 ± 1.2** **M = 5.1 ± 1.4** **F = 3.3 ± 1.0** M = 5.3 ± 2.8 **F = 2.7 ± 1.3**

Table 1.2 continued

Authors	Participants			Methods		Results	
	Sample size	Training status (nation)	Age (years)	Collection method	Time of season or volume	Absolute CHO intake ($g \cdot d^{-1}$)	Relative CHO intake ($g \cdot kg\ BM^{-1} \cdot d^{-1}$)
Young Adults (aged 19–25 years)							
Ousley-Pahnke et al. (2001)	16 (all female)	National (USA)	F = 20 ± 1	Written food diary (4-day)	Taper: 4.3 $km \cdot day^{-1}$	F = 362 ± 109	F = 5.5
Petersen et al. (2006)	24 (all female)	National (USA)	F = 20 (median)	Photograph food diary (3-day)	Pre-season	F = 365 ± 108	F = 5.7
					Mid-season: 6.4-10 $km \cdot day^{-1}$	F = 381 ± 116	F = 6.0
Sato et al. (2011)	19 (M = 6, F = 13)	National (Japan)	M = 20 ± 1 F = 19 ± 1	Photograph food diary (3-day)	General prep. 3.5 $km \cdot day^{-1}$	M = 443 ± 135 F = 347 ± 64	M = 6.8 ± 2.5 **F = 5.9 ± 1.2**
					Specific prep. 6-7 $km \cdot day^{-1}$	M = 474 ± 77 F = 373 ± 62	M = 7.2 ± 1.6 F = 6.3 ± 1.2
Trindade et al. (2017)	19 (M = 11, F = 8)	National & international (Brazil)	M = 21 ± 3 F = 20 ± 3	Written food diary (3-day)	General prep. 9 $km \cdot day^{-1}$	M = 402 ± 98 F = 298 ± 109	**M = 5.4 ± 1.3** **F = 4.7 ± 2.0**
Vallières et al. (1989)	6 (all female)	International (Canada)	F = 22 ± 1	Written food diary (3-day)	3.3 $km \cdot day^{-1}$	F = 336 ± 53	**F = 5.4**
					30 days later	F = 341 ± 59	**F = 5.4**
Van Handel et al. (1984)	27 (M = 13, F = 14)	National & international (USA)	M = 22 ± 3 F = 17 ± 2	Written food diary (3-day)	In-season	M = 532 ± 108 F = 305 ± 35	M = 6.7 **F = 4.9**

All data are presented as mean ± standard deviation. CHO = carbohydrate. M = male swimmers; M_S/M_L = male sub-groups completing either 'short' (22 $km \cdot week^{-1}$) or 'long' (44 $km \cdot week^{-1}$) weekly distances. F = female swimmers; $F_{<15}/F_{\geq 15}$ = female sub-groups either aged '<15 years' or '≥15 years'; $_{(ED)}$ = swimmers with a diagnosed eating disorder. FFQ = food frequency questionnaire. N/A = insufficient data reported. **Bold text** indicates a CHO intake <3 $g \cdot kg\ BM^{-1} \cdot day^{-1}$ during taper and competitions, and <6 $g \cdot kg\ BM^{-1} \cdot day^{-1}$ during training phases (Desbrow et al., 2014; Mujika et al., 2014).

1.2.3 Protein

Protein is an essential macronutrient that provides the 'building blocks' (amino acids) to support a variety of physiological functions, including repairing and remodelling damaged tissues; synthesising new muscle and mitochondrial proteins; and creating new proteins involved with immune functioning (i.e., immunoglobulins, cytokines) (Moore et al., 2014; Walsh, 2019); all of which are important to support adaptations to swimming training. Furthermore, protein has further roles within bone and hormone production (Bonjour et al., 2001; Rose, 2019), making daily intakes an important consideration for growth and development (Aerenhouts et al., 2013; Forbes, 1964). However, while adolescent swimmers will have increased protein needs compared to the general population (Baxter-Jones et al., 2008), there is little evidence to suggest that their protein needs are greater than highly trained adults (Mazzulla et al., 2018). Provided adequate energy is consumed, it appears that protein recommendations to maximise net protein balance are mainly influenced by total body mass, rather than age or development (Desbrow et al., 2014). Because of this, a protein recommendation of 1.5–2 g·kg BM^{-1}·day^{-1} is thought to replace any exercise-induced amino acid oxidative losses, enhance whole body net protein balance, and support the normal growth and development of adolescent athletes (Desbrow, 2021; Hannon et al., 2020b). Although this has not been specifically observed in adolescent swimmers, this protein recommendation is in accordance with evidence in adult swimmers; such that a protein intake of 1.4–1.9 g·kg BM^{-1}·day^{-1} has been mooted to support protein balance during high-volume swimming training phases (Matsuda et al., 2018); whereas 2.3–3.0 g·kg BM^{-1}·day^{-1} may be required under very high training loads (≥6 hours·day^{-1}, 10–12 km·day^{-1}).

Only two studies have monitored the protein intakes of adolescent swimmers multiple times during a competitive season, both of which identified that males (1.5–2.4 g·kg BM^{-1}·day^{-1}) and females (1.5–1.8 g·kg BM^{-1}·day^{-1}) achieved the recommendations at all assessment points (Alméras et al., 1997; Kabasakalis et al., 2007). However, these observations were identified in small cohorts (n <10) of internationally competitive adolescents, and therefore it is unclear whether these outcomes can be

generalised to highly trained adolescents who are on a development pathway. All remaining studies have only assessed protein intakes at singular time points, which provide less accurate depictions of the daily intakes within this cohort (Burke, 2015). Nonetheless, most studies appear to support that both adolescent male (1.5–2.7 g·kg BM^{-1}·day^{-1}) and female swimmers (1.5–2.1 g·kg BM^{-1}·day^{-1}) have little difficulty consuming adequate daily protein (Table 1.3). While two studies did show contrasting evidence in females (1.3–1.4 g·kg BM^{-1}·day^{-1}; Collins et al., 2012; Martínez et al., 2011), these both utilised retrospective (24-hour recall, FFQ) rather than prospective assessment methods (food diaries), and included swimmers of mixed training levels (vs. specifically highly trained swimmers); factors that could have affected the reliability of dietary reporting (Burke, 2015; Magkos & Yannakoulia, 2003). Given this paucity of evidence, further research investigating the current protein intakes of highly trained adolescent swimmers at various training phases is required.

It should be noted that lower protein intakes (<1.5 g·kg BM^{-1}·day^{-1}) have been observed in young adult swimmers (Table 1.3); however, this likely due to the age of these studies rather than declines in protein intake as swimmers reach adulthood. Indeed, early protein guidelines for athletes were set at 12–15% of DEI in the 1980s and early 1990s (American Dietetic Association, 1987), before increasing to 1–1.7 g·kg BM^{-1}·day^{-1} in the late 1990s and 2000s (Lemon, 1998; Tarnopolsky, 2004). Therefore, while historical studies might suggest that low protein intakes were being consumed, these might have been optimal at the time (e.g., Barr & Costill, 1991; Farajian et al., 2004; Lukaski et al., 1989). Since 2010, studies have showed that young adult swimmers have little difficulty achieving the current protein guidelines (de Carvalho et al., 2012; Sato et al., 2011; Trindade et al., 2017), though these do not give an indication of how protein intakes might change at different phases of the competitive season (or during lockdown phases of a global pandemic). Montenegro et al. (2017) sought to address this by monitoring protein intakes over an eight-month period, showing protein to be in the recommended range for swimmers on all but one occasion: females in the first week of the season (1.4 g·kg BM^{-1}·day^{-1}). Though intakes were reportedly increased thereafter, this should be interpreted cautiously since dietary assessment methods in week one (two-day food diary) were

different to all follow-up time points (24-hour recall for one day), potentially misrepresented actual protein intakes (Magkos & Yannakoulia, 2003). Overall, the current evidence regarding the protein intake of swimmers is either dated, based on single time points, or has used unreliable assessment methods; thus, requiring further research over a longitudinal timeframe.

Table 1.3. An overview of studies that have reported the dietary protein intakes of highly trained adolescent and young adult swimmers.

Authors	Participants			Methods		Results	
	Sample size	Training status (nation)	Age (years)	Collection method	Time of season or volume	Absolute protein intake ($g \cdot d^{-1}$)	Relative protein intake ($g \cdot kg\ BM^{-1} \cdot d^{-1}$)
Adolescents (aged 11–18 years)							
Alméras et al. (1997)	6 (all female)	International (Canada)	F = 17 ± 1	Written food diary (3-day)	Start of season 4 months 8 months 12 months 2-month rest	F = 96 ± 20 F = 93 ± 22 F = 105 ± 23 F = 96 ± 21 F = 95 ± 29	F = 1.6 F = 1.6 F = 1.7 F = 1.6 F = 1.5
Arachchi et al. (2015)	38 (M = 16, F = 22)	National & international (Sri Lanka)	M = 17 ± 1 F = 17 ± 2	24-h recall (3 days)	6 days·week^{-1} 2 hours·day^{-1}	M = 86 ± 17 F = 78 ± 14	N/A
Berning et al. (1991)	43 (M = 22, F = 21)	National (USA)	M = 16 ± 2 F = 15 ± 2	Written food diary (5-day)	Training camp 10 km·day^{-1}	M = 166 ± 5 F = 107 ± 4	M = 2.1 F = 1.8
Collins et al. (2012)	91 (M = 30, F = 61)	Mixed (USA)	14 ± 3	FFQ (12-month recall)	N/A	N/A	M = 1.7 ± 0.8 **F = 1.3 ± 0.7**
da Costa et al. (2013)	77 (all female)	National (Brazil)	N/A (range: 11–19 years)	Written food diary (3-day)	N/A	$F_{<15}$ = 98 $F_{<15(ED)}$ = 91 $F_{\geq 15}$ = 114 $F_{\geq 15(ED)}$ = 98	$F_{<15}$ = 2.1 $F_{<15(ED)}$ = 1.7 $F_{\geq 15}$ = 2.0 $F_{\geq 15(ED)}$ = 1.7
Hassapidou et al. (2002)	35 (M = 20, F = 15)	National & international (Greece)	M = 16 ± 1 F = 16 ± 1	Weighed food diary (7-day)	In-season	M = 112 ± 15 F = 90 ± 13	M = 1.6 ± 0.5 F = 1.5 ± 0.3
Hawley & Williams (1991)	20 (M = 9, F = 11)	N/A (New Zealand)	M = 13 ± 1 F = 13 ± 2	Weighed food diary (4-day)	6 km·day^{-1} 6 days·week^{-1}	M = 108 ± 38 F = 79 ± 24	M = 1.9 ± 0.6 F = 1.5 ± 0.6
Kabasakalis et al. (2007)	9 (M = 4, F = 5)	International (Greece)	M = 18 ± 1 F = 17 ± 2	Written food diary (3-day)	Week 0: Pre-season Week 10: 57 km·week^{-1}	M = 174 F = 112 M = 176 F = 110	M = 2.3 F = 1.8 M = 2.4 F = 1.7

Table 1.3 continued

Authors	Participants			Methods		Results	
	Sample size	Training status (nation)	Age (years)	Collection method	Time of season or volume	Absolute protein intake ($g \cdot d^{-1}$)	Relative protein intake ($g \cdot kg\ BM^{-1} \cdot d^{-1}$)
Adolescents (aged 11–18 years)							
Kabasakalis et al. (2007) *continued*	9 (M = 4, F = 5)	International (Greece)	M = 18 ± 1 F = 17 ± 2	Written food diary (3-day)	Week 19: Minor taper Week 32: Major taper	M = 137 F = 113 M = 115 F = 112	M = 1.8 F = 1.8 M = 1.5 F = 1.8
Martínez et al. (2011)	36 (M = 22, F = 14)	Mixed (Spain)	M = 16 ± 1 F = 15 ± 1	24-hour recall (3-day)	30-36 km·week^{-1} 6 days·week^{-1}	M = 125 ± 9 F = 77 ± 7	M = 1.9 ± 0.2 **F = 1.4 ± 0.1**
Simič & Mohorko (2018)	19 (M = 6, F = 13)	International (Slovenia)	M = 16 ± 1 F = 14 ± 1	Weighed food diary (3-day)	21 ± 3 hours·week^{-1}	M = 198 F = 97	M = 2.7 ± 0.9 F = 1.7 ± 0.4
Zietz et al. (2009)	23 (all female)	Regional & national (Germany)	F = 14 ± 3	Written food diary (3-day)	Off-season General prep. Specific prep. Competition	F = 164 ± 47 F = 164 ± 31 F = 163 ± 51 F = 179 ± 68	N/A N/A N/A N/A
Young adults (aged 19-25 years)							
Abood et al. (2004)	15 (all female)	Collegiate (USA)	F = 19 ± 2	Written food diary (3-day)	In-season 8 weeks later	F = 78 ± 11 F = 78 ± 29	**F = 1.2** **F = 1.2**
Barr & Costill (1992)	24 (M_S = 12, M_L = 12)	Collegiate (USA)	M = 19 ± 1	Written food diary (2-day)	Early season: 10 km·week^{-1} Mid-season: $_S$ = 22 km·week^{-1}, $_L$ = 44 km·week^{-1} Late season: 22 km·week^{-1}	M_S = 120 ± 9 M_L = 123 ± 7 M_S = 112 ± 8 M_L = 136 ± 9 M_S = 123 ± 11 M_L = 126 ± 5	M_S = 1.5 M_L = 1.7 **M_S = 1.4** M_L = 1.9 M_S = 1.6 M_L = 1.8
de Carvalho et al. (2012)	8 (all male)	National (Brazil)	N/A (range: 18–25 years)	Written food diary (3-day)	Pre-season General prep. Taper	M = 128 M = 164 M = 137	M = 1.7 M = 2.1 M = 1.7

Table 1.3 continued

Authors	Participants			Methods		Results	
	Sample size	Training status (nation)	Age (years)	Collection method	Time of season or volume	Absolute protein intake ($g \cdot d^{-1}$)	Relative protein intake ($g \cdot kg\ BM^{-1} \cdot d^{-1}$)
Young Adults (aged 19–25 years)							
Farajian et al. (2004)	31 (M = 20, F =11)	National & international (Greece)	M = 21 ± 4 F = 21 ± 4	24-hour recall (4-day)	7-17 $km \cdot day^{-1}$ 6 $days \cdot week^{-1}$	M = 146 ± 44 F = 88 ± 27	M = 1.8 ± 0.6 **F = 1.4 ± 0.5**
Lukaski et al. (1989)	12 (all female)	National (USA)	N/A	Written food diary (7-day)	Pre-season Post-season	F = 61 ± 6 F = 60 ± 4	**F = 1.0** **F = 1.0**
Lukaski et al. (1990)	29 (M = 13, F = 16)	National (USA)	N/A	Written food diary (7-day)	Pre-season Post-season	M = 110 ± 4 F = 74 ± 3 M = 132 ± 4 F = 86 ± 4	**M = 1.4** **F = 1.2** M = 1.7 **F = 1.4**
Lukaski et al. (1996)	10 (M = 5, F = 5)	National (USA)	N/A	Written food diary (3-day)	Specific prep./Taper	M = 120 ± 7 F = 76 ± 5	M = 1.5 **F = 1.2**
Matsuda et al. (2018)	13 (all male)	National (USA)	M = 20 ± 1	Written food diary (3-day)	General prep. Day 2 Day 3 Day 4	M = 142 ± 28 M = 106 ± 38 M = 142 ± 39	M = 2.1 ± 0.4 M = 1.6 ± 0.6 M = 2.1 ± 0.6
Mizugaki et al. (2021)	8 (M = 2, F = 6)	International (Japan)	M = 24 ± 1 F = 21 ± 2	Weighed food diary (3-day)	Training camp	Day 1 = 166 ± 57 Day 2 = 173 ± 49 Day 3 = 190 ± 56	Day 1 = 2.6 ± 0.8 Day 2 = 2.7 ± 0.7 Day 3 = 3.0 ± 0.7
Montenegro et al. (2017)	18 (M = 10, F = 8)	National & international (Brazil)	M = 20 ± 3 F = 20 ± 3	Week 1: written food diary (2-day); Weeks 6-32: 24-hour recall	Week 1: General prep. Week 6: Mixed prep. Week 9: Specific prep. Week 14: Competition Week 18: General prep. Week 24: Mixed prep.	M = 166 F = 95 M = 186 F = 127 M = 171 F = 114 M = 164 F = 127 M = 188 F = 115 M = 202 F = 133	M = 2.3 ± 0.2 **F = 1.4 ± 0.4** M = 2.6 ± 0.5 F = 1.9 ± 0.5 M = 2.4 ± 0.7 F = 1.7 ± 0.4 M = 2.3 ± 0.7 F = 1.9 ± 0.6 M = 2.6 ± 0.8 F = 1.7 ± 0.6 M = 2.8 ± 0.8 F = 2.0 ± 0.6

Table 1.3 continued

Authors	Participants			Methods		Results	
	Sample size	Training status (nation)	Age (years)	Collection method	Time of season or volume	Absolute protein intake ($g \cdot d^{-1}$)	Relative protein intake ($g \cdot kg\ BM^{-1} \cdot d^{-1}$)
Young Adults (aged 19–25 years)							
Montenegro et al. (2017) *continued*	18 (M = 10, F = 8)	National & international (Brazil)	M = 20 ± 3 F = 20 ± 3	Week 1: written food diary (2-day); Weeks 6-32: 24-hour recall	Week 28: Specific prep. Week 32: Competition	M = 209 F = 133 M = 175 F = 109	M = 2.9 ± 0.9 F = 2.0 ± 0.5 M = 2.4 ± 0.8 F = 1.7 ± 0.4
Ousley-Pahnke et al. (2001)	16 (all female)	National (USA)	F = 20 ± 1	Written food diary (4-day)	Taper: 4.3 $km \cdot day^{-1}$	F = 80 ± 25	**F = 1.2**
Paschoal & Amancio (2004)	8 (all male)	International (Brazil)	M = 19 ± 1	Written food diary (4-day)	3 $hours \cdot day^{-1}$ 6 $days \cdot week^{-1}$	M = 164	M = 2.3 ± 0.5
Petersen et al. (2006)	24 (all female)	National (USA)	F = 20 (median)	Photograph food diary (3-day)	Pre-season Mid-season: 6.4-10 $km \cdot day^{-1}$	F = 79 ± 29 F = 83 ± 28	**F = 1.2** **F = 1.3**
Sato et al. (2011)	19 (M = 6, F = 13)	National (Japan)	M = 20 ± 1 F = 19 ± 1	Photograph food diary (3-day)	General prep. 3.5 $km \cdot day^{-1}$ Specific prep. 6-7 $km \cdot day^{-1}$	M = 103 ± 23 F = 86 ± 10 M = 116 ± 22 F = 93 ± 10	M = 1.6 ± 0.5 F = 1.5 ± 0.2 M = 1.8 ± 0.5 F = 1.6 ± 0.2
Trindade et al. (2017)	19 (M = 11, F = 8)	National & international (Brazil)	M = 21 ± 3 F = 20 ± 3	Written food diary (3-day)	General prep. 9 $km \cdot day^{-1}$	M = 164 ± 40 F = 98 ± 25	M = 2.2 ± 0.4 F = 1.5 ± 0.5
Vallières et al. (1989)	6 (all female)	International (Canada)	F = 22 ± 1	Written food diary (3-day)	3.3 $km \cdot day^{-1}$ 30 days later	F = 92 ± 20 F = 92 ± 23	F = 1.5 F = 1.5
Van Handel et al. (1984)	27 (M = 13, F = 14)	National & international (USA)	M = 22 ± 3 F = 17 ± 2	Written food diary (3-day)	In-season	M = 184 ± 22 F = 92 ± 17	M = 2.3 F = 1.5

All data are presented as mean ± standard deviation. M = male swimmers; M_S/M_L = male sub-groups completing either 'short' (22 $km \cdot week^{-1}$) or 'long' (44 $km \cdot week^{-1}$) weekly distances. F = female swimmers; $F_{<15}/F_{\geq 15}$ = female sub-groups either aged '<15 years' or '≥15 years'; $_{(ED)}$ = swimmers diagnosed with an eating disorder. FFQ = food frequency questionnaire. N/A = not available as the appropriate data was not reported. **Bold text** indicates that protein intake was below the minimally recommended 1.5 $g \cdot kg\ BM^{-1} \cdot day^{-1}$ as recommended by Desbrow (2021) and Shaw et al. (2014).

1.2.4 Fat

An adequate fat intake is important for swimmers to meet essential fatty acid requirements (i.e., omega-3, omega-6), support the absorption of fat-soluble vitamins, and provide sufficient energy for growth and development (Petrie et al., 2004). Fats also provide a vital energy substrate for moderate-intensity exercise (~50–75% $\dot{V}O_{2max}$), with an athlete's ability to oxidise fatty acids at higher exercise intensities associated with glycogen sparing and in increase in exercise capacity (Stellingwerff et al., 2007). It should be noted, however, that worthwhile improvements in fat oxidation during exercise are more effectively produced because of training adaptations as opposed to dietary manipulation (Harvey et al., 2019; Shaw et al., 2010). Indeed, while high fat intakes (≥50% DEI) are consistently found to enhance acute fat metabolism during low- and moderate-intensity exercise, there is currently little evidence to suggest that this holds a performance advantage over high CHO diets (Burke, 2021; Vogt et al., 2003). Moreover, replacing CHO with dietary fat intake for as little as 5–6 days could produce adaptations that reduces the capacity to utilise muscle glycogen, which is likely to impair performance when high-intensity work (i.e., racing) is required (Burke et al., 2021; Havemann et al., 2006); although these effects are yet to be determined in swimming. Nonetheless, until research suggests otherwise, dietary monitoring should ensure that swimmers are first prioritising CHO and protein intakes, while only consuming fat to support daily health and energy requirements.

There are currently no clear fat intake recommendations thought to enhance the health and performance of highly trained athletes, therefore adult and adolescent swimmers are advised to consume fat in accordance with public health guidelines (Desbrow, 2021; Hannon et al., 2020b). These typically suggest that 20–35% of DEI is consumed as fat, primarily through unprocessed food options to support the intake of essential fatty acids (British Nutrition Foundation, 2021; Desbrow et al., 2021). This use of public health guidelines was supported in a review by Domínguez et al. (2017), who suggested that swimmers would benefit from consuming the upper fat intake range (30–35% of DEI) when training sessions are of high energetic demand, and the lower fat intake range (20–25% of

DEI) when high-intensity swimming/high CHO is prioritised. However, given that many swimmers possibly under-consume energy, it is unclear whether advising fat intakes as a percentage of DEI is appropriate for meeting minimal requirements. Stellingwerff et al. (2011) addressed this by recommending the following fat intakes relative to body mass: 1.5–2 g·kg BM^{-1}·day^{-1} when training with high-volumes and low intensities; 1–1.5 g·kg BM^{-1}·day^{-1} when training quality and intensity is prioritised; and 0.8–1.2 g·kg BM^{-1}·day^{-1} during tapers and competitions. Adhering to these alternative guidelines could potentially support the provision of adequate energy for each training phase, yet swimmers should be cautious not to exceed these thresholds since this could compromise muscle glycogen replenishment and tissue repair if CHO and protein are displaced (Shaw et al., 2014).

Research in adolescent swimmers has often suggested that high fat intakes are consumed, though this questionable when intakes are considered relative to body mass (Table 1.4). Early work by Berning et al. (1991) first identified fat intakes that exceeded the guidelines set for public health (41–43% of DEI) and athletic populations (2.8–3.2 g·kg BM^{-1}·day^{-1}). However, swimmers were based on a training camp during this investigation and no information was given on dietary controls. Food might therefore have been provided by catering services or swimmers may have sourced meals themselves from restaurants, both of which would differ to normal daily practices. In the research to have followed, only Kabasakalis et al. (2007) have observed swimmers to consume fat intakes exceeding the athlete guidelines (2.1 g·kg BM^{-1}·day^{-1}, 41% of DEI). Though, it should be noted that this intake was only reported in four Greek males during the off-season, which could have been achieved when consuming a traditional Mediterranean diet alongside processed foods when performance was not prioritised (Hassapidou et al., 2002). Other studies have suggested that swimmers consumed high fat diets based on a ≥35% contribution of DEI (Collins et al., 2012; Martínez et al., 2011); however, this assumption is likely to be misplaced considering that fat intakes fell within the 1–2 g·kg BM^{-1}·day^{-1} range. As such, high fat intakes are currently not thought to be a major concern for swimmers at present; hence, they should instead place focus on achieving higher CHO intakes from quality sources to reduce the contribution of fat to DEI.

Table 1.4. An overview of studies that have reported the dietary fat intakes of highly trained adolescent and young adult swimmers.

Authors	Participants			Methods		Results	
	Sample size	Training status (nation)	Age (years)	Collection method	Time of season or volume	Proportion of DEI (%)	Relative fat intake (g·kg BM^{-1}·day^{-1})
Adolescents (aged 11–18 years)							
Alméras et al. (1997)	6 (all female)	International (Canada)	F = 17 ± 1	Written food diary (3days)	Start of season 4 months 8 months 12 months 2-month rest	F = 28 ± 10 F = 24 ± 10 F = 25 ± 8 F = 24 ± 8 F = 27 ± 10	F = 1.4 F = 1.2 F = 1.2 **F = 0.9** F = 1.0
Arachchi et al. (2015)	38 (M = 16, F = 22)	National & international (Sri Lanka)	M = 17 ± 1 F = 17 ± 2	24-hour recall (3 days)	6 days·$week^{-1}$ 2 hours·day^{-1}	**M = 14 ± 6** **F = 13 ± 2**	N/A
Berning et al. (1991)	43 (M = 22, F = 21)	National (USA)	M = 16 ± 2 F = 15 ± 2	Written food diary (5 days)	Training camp 10 km·day^{-1}	**M = 43** **F = 41**	**M = 3.2** **F = 2.8**
Collins et al. (2012)	91 (M = 30, F = 61)	Mixed (USA)	14 ± 3	FFQ (12-month recall)	N/A	**M = 36 ± 4** **F = 36 ± 7**	M = 2.0 ± 0.8 F = 1.8 ± 1.0
da Costa et al. (2013)	77 (all female)	National (Brazil)	N/A (range: 11–19 years)	Written food diary (3 days)	N/A	$F_{<15}$ = 29 $F_{<15(ED)}$ = 31 $F_{\geq15}$ = 27 $F_{\geq15(ED)}$ = 27	$F_{<15}$ = 1.4 $F_{<15(ED)}$ = 1.2 $F_{\geq15}$ = 1.3 $F_{\geq15(ED)}$ = 1.1
Hassapidou et al. (2002)	35 (M = 20, F = 15)	National & international (Greece)	M = 16 ± 1 F = 16 ± 1	Weighed food diary (7 days)	In-season	**M = 43 ± 6** **F = 41 ± 3**	M = 2.0 ± 0.7 F = 1.8 ± 0.4
Hawley & Williams (1991)	20 (M = 9, F = 11)	N/A (New Zealand)	M = 13 ± 1 F = 13 ± 2	Weighed food diary (4 days)	6 km·day^{-1} 6 days·$week^{-1}$	M = 30 F = 27	M = 1.8 F = 1.1
Kabasakalis et al. (2007)	9 (M = 4, F = 5)	International (Greece)	M = 18 ± 1 F = 17 ± 2	Written food diary (3 days)	Week 0: Pre-season Week 10: 57 km·$week^{-1}$	**M = 41** F = 32 **M = 43** **F = 37**	**M = 2.1** F = 1.3 M = 2.0 F = 1.7

Table 1.4 continued

Authors	Participants			Methods		Results	
	Sample size	Training status (nation)	Age (years)	Collection method	Time of season or volume	Proportion of DEI (%)	Relative fat intake (g·kg BM^{-1}·day^{-1})
Adolescents (aged 11–18 years)							
Kabasakalis et al. (2007) *continued*	9 (M = 4, F = 5)	International (Greece)	M = 18 ± 1 F = 17 ± 2	Written food diary (3 days)	Week 19: Minor taper Week 32: Major taper	**M = 40** **F = 36** **M = 45** **F = 41**	M = 1.7 F = 1.5 M = 1.8 F = 1.7
Martínez et al. (2011)	36 (M = 22, F = 14)	Mixed (Spain)	M = 16 ± 1 F = 15 ± 1	24-hour recall (3 days)	30-36 km·$week^{-1}$ 6 days·$week^{-1}$	M = 34 ± 2 **F = 38 ± 3**	M = 1.7 F = 1.3
Simič & Mohorko (2018)	19 (M = 6, F = 13)	International (Slovenia)	M = 16 ± 1 F = 14 ± 1	Weighed food diary (3 days)	In-season 21 ± 3 hours·$week^{-1}$	M = 23 ± 5 F = 26 ± 7	M = 1.0 **F = 0.8**
Zietz et al. (2009)	23 (all female)	Regional & national (Germany)	F = 14 ± 3	Written food diary (3 days)	Off-season General prep. Specific prep. Competition	**F =37 ± 7** F = 32 ± 11 F = 29 ± 9 F = 28 ± 12	N/A N/A N/A N/A
Young adults (aged 19–25 years)							
Abood et al. (2004)	15 (all female)	Collegiate (USA)	F = 19 ± 2	Written food diary (3 days)	In-season 8 weeks later	F = 24 ± 7 F = 23 ± 6	**F = 0.9** **F = 0.7**
Barr & Costill (1992)	24 (M_S = 12, M_L = 12)	Collegiate (USA)	M = 19 ± 1	Written food diary (2 days)	Early season: 10 km·$week^{-1}$ Mid-season: $_S$ = 22 km·$week^{-1}$ $_L$ = 44 km·$week^{-1}$ Late season: 22 km·$week^{-1}$	M_S = 32 M_L = 34 M_S = 29 M_L = 32 M_S = 30 M_L = 31	M_S = 1.6 M_L = 1.9 M_S = 1.3 **M_L = 2.1** M_S = 1.3 M_L = 1.8
de Carvalho et al. (2012)	8 (all male)	National (Brazil)	N/A (range: 18–25 years)	Written food diary (3 days)	Pre-season General prep. Taper	M = 27 M = 29 M = 30	M = 1.4 M = 1.7 M = 1.6

Table 1.4 continued

Authors	Participants			Methods		Results	
	Sample size	Training status (nation)	Age (years)	Collection method	Time of season or volume	Proportion of DEI (%)	Relative fat intake (g·kg BM^{-1}·day^{-1})
Young Adults (aged 19–25 years)							
Farajian et al. (2004)	31 (M = 20, F =11)	National & international (Greece)	M = 21 ± 4 F = 21 ± 4	24-hour recall (4 days)	7-17 km·$days^{-1}$ 6 days·$week^{-1}$	**M = 40 ± 6** F = 34 ± 9	M = 1.7 F = 1.2
Lukaski et al. (1989)	12 (all female)	National (USA)	N/A	Written food diary (7 days)	Pre-season Post-season	F = 34 F = 30	F = 1.2 F = 1.2
Lukaski et al. (1990)	29 (M = 13, F = 16)	National (USA)	N/A	Written food diary (7 days)	Pre-season Post-season	M = 35 ± 1 F = 35 ± 1 M = 34 ± 1 F = 30 ± 2	M = 1.7 F = 1.4 M = 1.8 F = 1.2
Lukaski et al. (1996)	10 (M = 5, F = 5)	National (USA)	N/A	Written food diary (3 days)	Specific prep./Taper	M = 32 **F = 38**	M = 1.8 F = 1.4
Matsuda et al. (2018)	13 (all male)	National (USA)	M = 20 ± 1	Written food diary (3 days)	General prep. Day 2 Day 3 Day 4	 M = 33 ± 4 M = 31 ± 6 M = 35 ± 6	 **M = 2.3 ± 0.6** M = 1.7 ± 0.8 **M = 2.4 ± 0.8**
Mizugaki et al. (2021)	8 (M = 2, F = 6)	International (Japan)	M = 24 ± 1 F = 21 ± 2	Weighed food diary (3 days)	Training camp Day 1 Day 2 Day3	 28 ± 4 26 ± 3 28 ± 3	 1.8 ± 0.4 1.7 ± 0.5 **2.1 ± 0.5**
Montenegro et al. (2017)	18 (M = 10, F = 8)	National & international (Brazil)	M = 20 ± 3 F = 20 ± 3	Week 1: written food diary (2 days); Week 6-32: 24-hour recall	Week 1: General prep. Week 6: Mixed prep. Week 9: Specific prep. Week 14: Competition Week 18: General prep. Week 24: Mixed prep.	M = 27 F = 29 M = 25 F = 27 M = 23 F = 27 M = 24 F = 26 M = 26 F = 25 M = 25 F = 24	M = 1.4 ± 0.6 **F = 0.9 ± 0.2** M = 1.3 ± 0.3 **F = 0.9 ± 0.2** M = 1.2 ± 0.4 **F = 0.8 ± 0.2** M = 1.3 ± 0.5 F = 0.8 ± 0.3 M = 1.2 ± 0.5 **F = 0.7 ± 0.3** M = 1.2 ± 0.4 **F = 0.7 ± 0.3**

Table 1.4 continued

Authors	Participants			Methods		Results	
	Sample size	Training status (nation)	Age (years)	Collection method	Time of season or volume	Proportion of DEI (%)	Relative fat intake (g·kg BM^{-1}·day^{-1})
Young Adults (aged 19–25 years)							
Montenegro et al. (2017) *continued*	18 (M = 10, F = 8)	National & international (Brazil)	M = 20 ± 3 F = 20 ± 3	Week 1: written food diary (2 days); Week 6-32: 24-hour recall	Week 28: Specific prep. Week 32: Competition	M = 26 F = 21 M = 24 F = 27	M = 1.2 ± 0.4 **F = 0.6 ± 0.3** M = 1.2 ± 0.5 **F = 0.7 ± 0.2**
Ousley-Pahnke et al. (2001)	16 (all female)	National (USA)	F = 20 ± 1	Written food diary (4 days)	Taper: 4.3 km·day^{-1}	F = 23 ± 5	F = 0.9 ± 0.4
Petersen et al. (2006)	24 (all female)	National (USA)	F = 20	Photograph food diary (3 days)	Pre-season Mid-season: 6.4-10 km·day^{-1}	F = 24 ± 6 F = 22 ± 6	F = 0.8 **F = 0.8**
Sato et al. (2011)	19 (M = 6, F = 13)	National (Japan)	M = 20 ± 1 F = 19 ± 1	Photograph food diary (3 days)	General prep. 3.5 km·day^{-1} Specific prep. 6-7 km·day^{-1}	M = 29 ± 5 F = 35 ± 4 M = 27 ± 6 F = 34 ± 4	M = 1.5 F = 1.8 M = 1.5 F = 1.8
Trindade et al. (2017)	19 (M = 11, F = 8)	National & international (Brazil)	M = 21 ± 3 F = 20 ± 3	Written food diary (3 days)	General prep. 9 km·day^{-1}	M = 29 ± 7 F = 29 ± 5	M = 1.4 ± 0.4 F = 1.1 ± 0.1
Vallières et al. (1989)	6 (all female)	International (Canada)	F = 22 ± 1	Written food diary (3 days)	3.3 km·day^{-1} 30 days later	F = 35 ± 7 F = 33 ± 7	F = 1.6 F = 1.4
Van Handel et al. (1984)	27 (M = 13, F = 14)	National & international (USA)	M = 22 ± 3 F = 17 ± 2	Written food diary (3 days)	In-season	M = 34 ± 8 F = 30 ± 7	**M = 2.1** F = 1.2

All data are presented as mean ± standard deviation. DEI = daily energy intake. M = male swimmers; M_S/M_L = male sub-groups completing either 'short' (22 km·$week^{-1}$) or 'long' (44 km·$week^{-1}$) weekly distances. F = female swimmers; $F_{<15}$/$F_{\geq 15}$ = female sub-groups either aged '<15 years' or '≥15 years'; $_{(ED)}$ = swimmers diagnosed with an eating disorder. FFQ = food frequency questionnaire. N/A = insufficient data reported. **Bold text** indicates fat intakes outside the 1–2 g·kg BM^{-1}·day^{-1}, or 20–35% ranges when in season (Domínguez et al., 2017; Stellingwerff et al., 2011).

1.3 Micronutrients

Whereas macronutrients are required in large amounts (i.e., ≥100 g·day^{-1}) to provide energy, it is the small amounts of dietary micronutrients (i.e., mg·day^{-1} and µg·day^{-1}) that enable this energy to be released and/or transformed for use in physiological processes (Huskisson et al., 2007). Indeed, all micronutrients have their own individual roles, including O_2 transport, tissue repair, immunity, bone health, and growth (Beck et al., 2021); all of which could support swimming performance if adequate intakes are consumed across the season (Lukaski et al., 1996). It should be acknowledged, however, that micronutrients themselves do not possess ergogenic mechanisms, and any improvements in performance are likely due to: (a) swimmers maintaining health across the year, resulting in greater training adaptations; and/or (b) swimmers overturning the deleterious effects of micronutrient deficiency (for a review see Huskisson et al., 2007; Lukaski, 2004).

Though swimmers place far greater physical demands on their bodies compared to the general population, it is currently unclear whether this increases their micronutrient requirements (Beck et al., 2021; Jordan et al., 2020). For example, it has been suggested that increased vitamin intakes (i.e., B vitamins, vitamin C) might be required to support energy metabolism and offset the oxidative stress associated with exercise, whereas increased mineral intakes (i.e., calcium, iron) may be necessary to replace losses that occur through sweat and urine (Huskisson et al., 2007). Furthermore, swimmers who restrict their DEI or avoid certain food groups (e.g., meat, dairy) could be placed at risk of micronutrient deficiencies (da Costa et al., 2013; Lukaski et al., 2004), even if vitamin and mineral supplements are consumed (Farajian et al., 2004). As there are no optimal micronutrient guidelines available for swimmers at present, it is advised that swimmers achieve their country's reference nutrient intakes (RNI) through a varied, energy balanced diet as a minimum (Thomas et a., 2016), with supplemental intakes considered if these cannot be achieved through diet alone (Close et al., 2022).

1.3.1 Calcium

While most micronutrients are achieved as part of a varied diet, the intakes of calcium, iron, and vitamin D can be more challenging (Desbrow et al., 2014; Thomas et al., 2016). A suboptimal calcium status is likely to occur in athletes who either fail to consume an adequate DEI or who regularly avoid high calcium foods (e.g., milk, cheese, yogurt) (Thomas et al., 2016); possibly resulting in poor bone health and/or suboptimal bone growth (Desbrow et al., 2014). The current UK RNIs for adolescents (aged 11–18 years) are ≥1000 mg·day^{-1} for males, and ≥800 mg·day^{-1} for females (British Nutrition Foundation, 2021). However, these intakes have been suspected to be suboptimal for supporting bone turnover in highly active adolescents (Petrie et al., 2004), therefore higher intakes for male (≥1300 mg·day^{-1}) and female (≥1100 mg·day^{-1}) athletes have been proposed (Vatanparast et al., 2010). Current evidence (Table 1.5) suggests that male swimmers either consume or are close to consuming calcium intakes at the higher intake threshold (1197–1716 mg·day^{-1}). Females, on the other hand, often fail to consume such high amounts (684–1411 mg·day^{-1}); though, this may be related to female swimmers being more likely to underreport or omit part of their total food intake (da Costa et al., 2013; Martínez et al., 2011). Nonetheless, since most research shows that both sexes consume the UK RNI for calcium, and this lower threshold has been found to be sufficient for supporting bone growth in female adolescent swimmers (Czeczelewski et al., 2013), it is not currently thought that calcium intakes are a major cause for concern. Despite this, calcium intakes should be continued to be monitored on an individual basis alongside DEI to ensure that health, performance, and growth are being supported.

1.3.2 Iron

In athletic populations, it is estimated that ~3–11% of males and ~15–35% of females could have a deficient iron status, which is a concern for health and performance given the roles of iron in blood cell production and O_2 delivery (Sim et al., 2019). Like calcium, both males and females can be subject to a suboptimal iron status when consuming inadequate energy, or if foods high in iron

bioavailability are being avoided (e.g., meats) (Thomas et al., 2016); although the risks are higher in females due to additional iron losses during the menstrual cycle (Pedlar et al., 2018). The current UK RNIs for adolescents (aged 11–18 years) appear to account for sex and growth, with there currently being little evidence to support swimmers exceeding the following amounts (Desbrow, 2021): ≥14.8 mg·day^{-1} for females; and ≥11.3 mg·day^{-1} for males (British Nutrition Foundation, 2021). Research in swimmers showed that male swimmers consistently report iron intakes exceeding the UK RNI (Table 1.5). Females have also achieved the UK RNI in most studies to date, with intakes below this threshold only occurring when: (a) underreporting has been suspected (Hawley & Williams, 1991; Martínez et al., 2011); (b) lower RNIs were used (Lukaski et al., 1989, 1990); (c) supplement intakes were not considered (Kabasakalis et al., 2007); or (d) when LEA was identified (da Costa et al., 2013). Other studies reporting intakes slightly below the UK RNI (~13–14 mg·day^{-1}) have found no negative effects on swimmers' health (Vallières et al., 1989) or performance (Lukaski et al., 1996). This research therefore suggests that swimmers may be a low-risk group for consuming suboptimal iron; however, future research should consider these intakes on an individual basis alongside DEI, as this could identify a preceding risk factor for iron deficiency.

1.3.3 Vitamin D

Even when swimmers consume a varied diet meeting their energy and macronutrient requirements, they are still unlikely to consume adequate vitamin D (Thomas et al., 2016). The paucity of vitamin D in foods and beverages means that only ~10% of daily requirements can be attained through diet alone, whereas the remaining ~90% is produced naturally following direct exposure to ultraviolet B (UVB) radiation (e.g., sunlight, tanning beds) (Holick et al., 1977). To meet the dietary vitamin D requirements, the UK RNI is set at 400 IU·day^{-1} for all adults and adolescents (British Nutrition Foundation, 2021). However, the current dietary vitamin D intakes consumed by swimmers has either not been reported in dietary assessments, or intakes have been consistently below the UK RNI at 40–368 IU·day^{-1} (Table 1.5). This is a concern among swimmers, as sustaining a sufficient vitamin D

status has been associated with benefits to skeletal muscle function, training adaptations, bone health, and immunity (Owens et al., 2018); all of which can support long-term health and performance. Therefore, considering that swimmers do not achieve the minimally recommended vitamin D through dietary intake, additional focus should be placed on this population gaining vitamin D exposure through direct sunlight and/or supplementation.

The measurement of circulating 25-hydroxyvitamin D (25(OH)D) is currently thought to be the best indicator of recent vitamin D exposure (past 21–30 days), whether obtained from UVB or dietary sources (Owens et al., 2018). However, the interpretation of 25(OH)D concentrations are currently contested, dependant on whether authors choose to utilise thresholds recommended by the National Academy of Medicine (i.e., ≤25 nmol·L^{-1} = 'deficient', ≥50 nmol·L^{-1} = 'sufficient'; Ross et al., 2011) or the Endocrine Society (i.e., ≤50 nmol·L^{-1} = 'deficient', ≥75 nmol·L^{-1} = 'sufficient'; Holick et al., 2011). While the more conservative of these guidelines may be appropriate to offset deficiency and support bone health, it is suggested that a 25(OH)D within the range of 75–125 nmol·L^{-1} is essential to support the many alternative functions of vitamin D (e.g., skeletal muscle function, recovery, immunity) (Owens et al., 2018; Pludowksi et al., 2018; Zhang et al., 2018). Based on this notion, this thesis will therefore refer to vitamin D status with the following language, akin to the Endocrine Society guidelines: 0–24 nmol·L^{-1} = 'severely deficient'; 25–49 nmol·L^{-1} = 'deficient'; 50–74 nmol·L^{-1} = 'insufficient'; 75–125 = 'sufficient'; 125–250 nmol·L^{-1} = 'high, but reportedly safe'; and >375 nmol·L^{-1} = 'potentially toxic'; which are considered to be appropriate for both adolescent (Desbrow et al., 2014) and adult swimmers (Thomas et al., 2016). A caveat to this interpretation of vitamin D status is that it is most appropriate for Caucasian swimmers, with swimmers of darker skin tones (i.e., Black and Hispanic) often presenting lower serum 25(OH)D without physiological consequences (Cauley et al., 2005; Hannan et al., 2008).

Exposing ~20% of the body to direct sunlight (i.e., without clothing or sunscreen) for 5–15 min·day^{-1} is considered a safe and convenient strategy to acquire adequate UVB radiation (Holick, 2004).

However, applying this strategy to swimming populations has its challenges. Firstly, this strategy may not be effective year-round since insufficient UVB protons reach the earth's surface during the winter (Holick, 2004), meaning that natural vitamin D production is likely to be inhibited. Moreover, in countries located at latitudes ≥40° N (e.g., UK = 50–53° N), even the autumn and spring months are associated with a reduction in daylight hours, a lower angle of the sun, and cloudy weather conditions; each of which contribute to an 80–100% decline in UVB availability (Farrokhyar et al., 2015; Webb et al., 1988). Secondly, when small periods of the day do permit adequate sunlight exposure, it may that swimmers do not maximise these opportunities due to spending large amounts of time indoors, either through training, competing, resting; or in the case of adolescents, in full-time education (Farrokhyar et al., 2015; Todd et al., 2015). Considering these barriers to vitamin D production, a recommendation for athletes is to attain a 25(OH)D ≥122.5 nmol·L^{-1} in the summer months, as this could help maintain a sufficient vitamin D status until the end of the winter period (Galan et al., 2012; Lewis et al., 2013b). Although, as this is not always possible, then vitamin D supplements should be considered.

Vitamin D supplements are consistently found to offset seasonal declines in circulating 25(OH)D that are occur in swimming populations. Indeed, both Lewis et al. (2013b) and Rockwell et al. (2020a) showed that supplementing with 4000–5000 IU·day^{-1} vitamin D_3 maintained 25(OH)D concentrations across the autumn and winter months, compared to large declines when a placebo (PLA) was consumed (August to November: -30 nmol·L^{-1}; December to March: -20 nmol·L^{-1}). Yet, while supplementation appeared to be favourable, the location of these studies (USA: 37–38° N) enabled swimmers to attain a 25(OH)D ≥120 nmol·L^{-1} during the summer, thus most swimmers maintained a sufficient vitamin D status regardless of the declines (i.e., 132 ± 42 vs. 110 ± 36 nmol·L^{-1}, Lewis et al., 2013b; 131 ± 29 vs. 81 ± 16 nmol·L^{-1}, Rockwell et al., 2020a). This outcome is not universal, however, since adolescent swimmers in Israel (31–32° N) displayed insufficient 25(OH)D during an autumn training period (October: 62 ± 12 nmol·L^{-1}), which consequently continued to decline near to levels of deficiency during the winter when supplements were not used (January: 51 ± 11 nmol·L^{-1})

(Dubnov-Raz et al., 2015a). Though, when supplemental vitamin D_3 (2000 IU·day^{-1}) was consumed, an increased 25(OH)D occurred over this same timeframe (January: 74 ± 16 nmol·L^{-1}). Interestingly, only 48% of swimmers developed a sufficient vitamin D status with this supplement strategy, indicating that larger doses and/or a longer supplement duration was required. Finally, despite not reporting changes in 25(OH)D, Geiker et al. (2017) showed that 97% of adolescent swimmers in Denmark (55° N) developed an insufficient vitamin D status during the winter (April: 53 ± 18 nmol·L^{-1}). Combined, this current research suggests that that vitamin D insufficiency may be a global problem in swimming populations, possibly warranting all swimmers to ingest between 2000–5000 IU·day^{-1} vitamin D_3 from October to March.

In recent years, the importance of vitamin D and risks of deficiency have become well known and incorporated into educational material for swimmers (Foo et al., 2021). Indeed, a large proportion (72–97%) of athletes now recognise the health and performance benefits of sustaining a sufficient vitamin D status (Hollabaugh et al., 2022; Leitch et al., 2021; Walker et al., 2014), yet this knowledge does not guarantee adherence to supplement recommendations. This is because some athletes either: (a) do not believe themselves to be at risk of deficiency (Leitch et al., 2021); (b) lack confidence in their supplement knowledge (Walker et al., 2014); (c) have poor adherence to supplement protocols (Hollabaugh et al., 2022); and/or (d) do not value the cost of vitamin D_3 supplements as a worthwhile investment (Rockwell et al., 2020b). Evidence of this has been demonstrated in swimmers, such that only 56% of Danish adolescent swimmers reported using vitamin D_3 supplementation during the winter months, despite being at a very high risk of deficiency (i.e., ~30 hours·week^{-1} of indoor training, latitude: 55° N) (Geiker et al., 2017). Moreover, those that did use supplements reported highly variable vitamin D_3 doses (mean: 2600 ± 1960 IU·day^{-1}), resulting in both supplement users (57 ± 21 nmol·L^{-1}) and non-users (39 ± 13 nmol·L^{-1}) having insufficient 25(OH)D following the winter. Given that suboptimal vitamin D supplement behaviours exist in swimmers, further monitoring of seasonal 25(OH)D changes in swimmers at high risks of deficiency is required (e.g., UK-based, Farrokhyar et al., 2015). Ideally, this should be conducted alongside education to key

stakeholders (i.e., swimmers, coaches, parents/guardians) to ensure that adequate practices can be followed.

Table 1.5. An overview of studies that have reported the dietary calcium, iron, and vitamin D intakes of highly trained adolescent and young adult swimmers.

Authors	Participants			Methods		Results		
	Sample size	Training status (nation)	Age (years)	Collection method	Time of season or volume	Calcium intake ($mg \cdot day^{-1}$)	Iron intake ($mg \cdot day^{-1}$)	Vitamin D intake ($IU \cdot day^{-1}$)
Adolescents (aged 11–18 years)								
Berning et al. (1991)	43 (M = 22, F = 21)	National (USA)	M = 16 ± 2 F = 15 ± 2	Written food diary (5 days)	Training camp 10 $km \cdot day^{-1}$	M = 1634 ± 76 F = 1235 ± 96	M = 26 ± 1 F = 18 ± 1	N/A
Collins et al. (2012)	91 (M = 30, F = 61)	Mixed (USA)	14 ± 3	FFQ (12-month recall)	N/A	M = 1197 ± 469 F = 1117 ± 521	M = 20 ± 7 F = 15 ± 7	M = 280 ± 160 F = 200 ± 160
da Costa et al. (2013)	77 (all female)	National (Brazil)	N/A (range: 11-19 years)	Written food diary (3 days)	N/A	$F_{<15}$ = 843 $F_{<15(ED)}$ = 819 $F_{\geq 15}$ = 909 $F_{\geq 15(ED)}$ = 706	$F_{<15}$ = 13 $F_{<15(ED)}$ = 13 $F_{\geq 15}$ = 16 $F_{\geq 15(ED)}$ = 13	N/A
Hassapidou et al. (2002)	35 (M = 20, F = 15)	National & international (Greece)	M = 16 ± 1 F = 16 ± 1	Weighed food diary (7 days)	In-season	M = 1421 ± 64 F = 1411 ± 120	M = 14 ± 5 F = 19 ± 4	N/A
Hawley & Williams (1991)	20 (M = 9, F = 11)	N/A (New Zealand)	M = 13 ± 1 F = 13 ± 2	Weighed food diary (4 days)	6 $km \cdot day^{-1}$ 6 $days \cdot week^{-1}$	M = 1418 ± 499 F = 1013 ± 562	M = 20 ± 7 F = 14 ± 4	N/A
Kabasakalis et al. (2007)	9 (M = 4, F = 5)	International (Greece)	M = 18 ± 1 F = 17 ± 2	Written food diary (3 days)	Mean over 32 weeks	M = 1619 ± 597 F = 1189 ± 481	M = 17 ± 3 F = 14 ± 3	M = 132 ± 136 F = 84 ± 76
Martínez et al. (2011)	36 (M = 22, F = 14)	Mixed (Spain)	M = 16 ± 1 F = 15 ± 1	24-hour recall (3 days)	30-36 $km \cdot week^{-1}$ 6 $days \cdot week^{-1}$	M = 1234 ± 51 F = 684 ± 80	M = 16 ± 1 F = 11 ± 0	M = 72 ± 4 F = 40 ± 12
Simič & Mohorko (2018)	19 (M = 6, F = 13)	International (Slovenia)	M = 16 ± 1 F = 14 ± 1	Weighed food diary (3 days)	In-season 21 ± 3 hours·$week^{-1}$	M = 1716 ± 353 F = 899 ± 347	M = 26 ± 7 F = 17 ± 5	M = 368 ± 252 F = 113 ± 75

Table 1.5 continued

Authors	Participants			Methods		Results		
	Sample size	Training status (nation)	Age (years)	Collection method	Time of season or volume	Calcium intake ($mg \cdot day^{-1}$)	Iron intake ($mg \cdot day^{-1}$)	Vitamin D intake ($IU \cdot day^{-1}$)
Young adults (aged 19–25 years)								
Abood et al. (2004)	15 (all female)	Collegiate (USA)	F = 19 ± 2	Written food diary (3 days)	In-season 8 weeks later	F = 918 ± 305 F = 695 ± 329	F = 15 ± 4 F = 13 ± 5	N/A N/A
Barr & Costill (1992)	24 (all male)	Collegiate (USA)	M = 19 ± 1	Written food diary (2 days)	Early season: 10 $km \cdot week^{-1}$	M = 1509 ± 121	M = 24 ± 2	N/A
Farajian et al. (2004)	31 (M = 20, F =11)	National & international (Greece)	M = 21 ± 4 F = 21 ± 4	24-hour recall (4 days)	7-17 $km \cdot day^{-1}$ 6 $days \cdot week^{-1}$	M = 1491 ± 717 F = 1010 ± 452	M = 23 ± 9 F = 15 ± 5	M = 240 ± 148 F = 160 ± 96
Lukaski et al. (1989)	12 (all female)	National (USA)	N/A	Written food diary (7 days)	Pre-season Post-Season	N/A N/A	F = 13 ± 1 F = 12 ± 1	N/A N/A
Lukaski et al. (1990)	29 (M = 13, F = 16)	National (USA)	N/A	Written food diary (7 days)	Pre-season Post-season	N/A N/A	M = 20 ± 1 F = 14 ± 1 M = 22 ± 1 F = 14 ± 1	N/A N/A
Lukaski et al. (1996)	10 (M = 5, F = 5)	National (USA)	N/A	Written food diary (3 days)	Specific prep./Taper	N/A	M = 19 ± 2 F = 13 ± 1	N/A
Ousley-Pahnke et al. (2001)	16 (all female)	National (USA)	F = 20 ± 1	Written food diary (4 days)	Taper: 4.3 $km \cdot day^{-1}$	F = 1247 ± 387	F = 19 ± 9	N/A
Paschoal et al. (2004)	8 (all male)	International (Brazil)	M = 19 ± 1	Written food diary (4 days)	3 $hours \cdot day^{-1}$ 6 $days \cdot week^{-1}$	M = 1112 ± 462	M = 22 ± 4	N/A
Petersen et al. (2006)	24 (all female)	National (USA)	F = 20	Photograph food diary (3 days)	Pre-season Mid-season: 6.4-10 $km \cdot day^{-1}$	F = 1131 ± 611 F = 1231 ± 699	F = 16 ± 5 F = 20 ± 8	N/A N/A
Vallières et al. (1989)	6 (all female)	International (Canada)	F = 22 ± 1	Written food diary (3 days)	3.3 $km \cdot day^{-1}$	F = 970 ± 369	F = 13 ± 4	N/A

All data are presented as mean ± standard deviation. M = male swimmers. F = female swimmers; $F_{<15}/F_{\geq 15}$ = female sub-groups either aged '<15 years' or '≥15 years'; $_{(ED)}$ = swimmers diagnosed with an eating disorder. FFQ = food frequency questionnaire. N/A = insufficient data reported.

1.4 Nutritional Supplements

Nutritional supplements are justified in adolescent swimmers if they support the achievement of daily nutrient recommendations, correct nutrient deficiencies, or enhance performance (Close et al., 2022). At present, a wide variety of nutritional supplements are commercially available, therefore this thesis will refer to supplements in the following sub-categories based on the descriptions of Garthe and Maughan (2018): 'sports supplements' that provide a convenient source of energy and nutrients (e.g., high CHO or high protein drinks, bars, gels, or powders); 'health supplements' that are either used to treat or avoid micronutrient deficiencies (e.g., multivitamins, iron, vitamin D); and 'ergogenic aids' that are natural food components but have potential to enhance performance when consumed at heightened doses (e.g., caffeine [CAF], sodium bicarbonate [$NaHCO_3$], and inorganic nitrates). Other subcategories include 'herbal', 'botanical', and 'functional' supplements, each of which are claimed to promote optimal health; however, the production methods and bioactive ingredients of these supplements are often unclear, giving rise to potential safety and doping concerns (Winterstein & Storrs, 2001).

Prior to using any nutritional supplement, a risk-benefit analysis should be conducted (Figure 1.1). Indeed, while many different sports, health, and ergogenic supplements are known to be safe and effective when the appropriate ingestion strategies are followed (Maughan et al., 2018), there remains a concern that swimmers could overlook safe practices in favour of adopting 'just in case' or 'more is better' philosophies (Derave & Tipton, 2014). For example, swimmers who consume high doses of health supplements (e.g., iron) could place themselves at risks of toxicity if adequate dietary intakes are already being consumed (Marcinowska-Suchowierska et al., 2018; Mettler & Zimmermann, 2010). Similarly, high doses of ergogenic aids can induce adverse side-effects immediately before exercise (e.g., gastrointestinal upset, anxiety, tachycardia), which could potentially induce ergolytic effects on swimming performance (Maughan et al., 2018). A second consideration is that supplement manufacturing conforms to less rigorous standards than the production of food and medicines,

culminating in 10–38% of all supplements in Europe and the USA being cross-contaminated with undeclared prohibited substances (Duiven et al., 2021; Outram & Stewart, 2015). Given that swimmers are often considered to engage in widespread supplement use (Corrigan & Kazlauskas, 2003; Dascombe et al., 2010; Huang et al., 2006), this could increase the likelihood of adolescent swimmers inadvertently ingesting banned substances and facing doping violations. However, knowledge of swimmers' current supplement behaviours is now either dated (Baylis et al., 2001), or restricted to adult swimmers of elite status (Moreno et al., 2022; Shaw et al., 2016a). An updated perspective on the current supplement practices of highly trained young swimmers is therefore required to advise safe practices for the future.

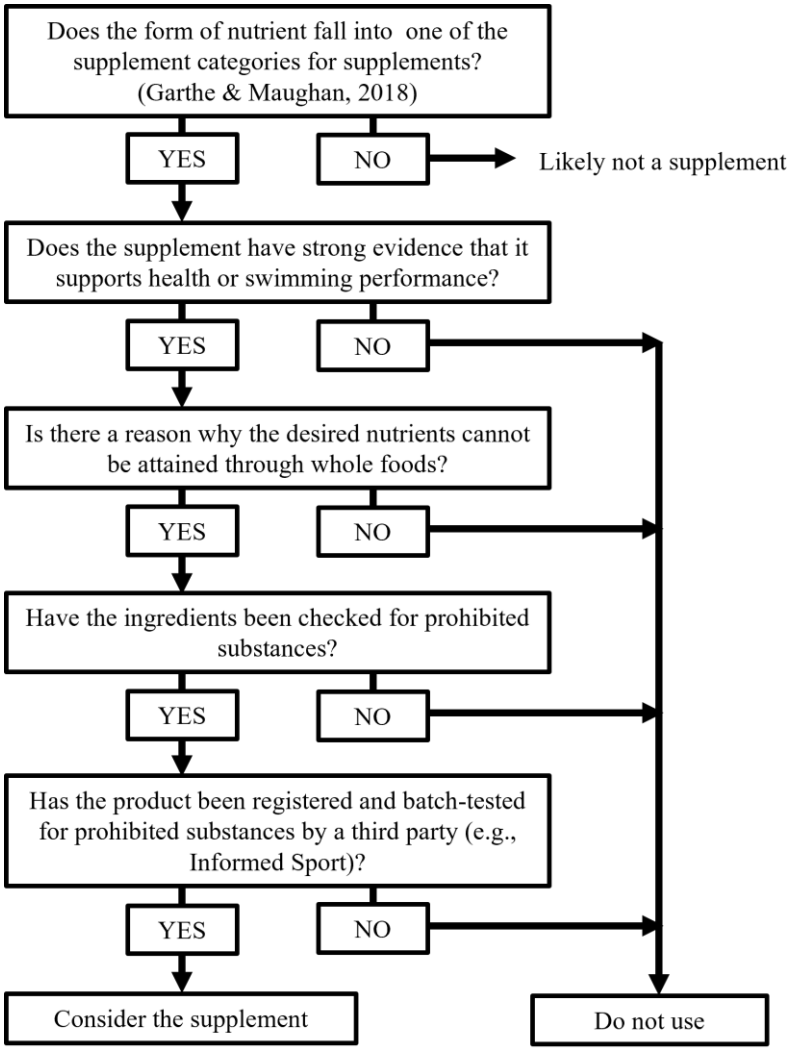

Figure 1.1. Decision flow chart when considering new supplements. Adapted from Close et al. (2022).

1.4.1 Current Supplement Practices

Early studies in Olympic athletes placed swimmers among the highest supplement users, with 56% of swimmers using supplements at the 1996 Games, which increased to ~70% of swimmers at the 2000 Games (Corrigan & Kazlauskas, 2003; Huang et al., 2006). Although, 'supplements' in historical studies were mostly defined as vitamins, minerals, and amino acids; therefore, intakes are now higher given the emergence of sports supplements and ergogenic aids (Maughan et al., 2018). Indeed, later reports showed that 97–99% of Australian swimmers used nutritional supplements prior to the 1998 and 2009 World Aquatic Championships (Baylis et al., 2001; Shaw et al., 2016a), albeit with an increase in the total number (mean increase: +3.3 supplements) and types of supplements (sports: +1.8 supplements, ergogenic: +1.2 supplements) being consumed across the 11-year window (Shaw et al., 2016b). Along with more supplements now being available to swimmers, there is also an increased dissemination of supplement information (or misinformation) occurring via the internet, which appears to inform most supplement practices made by swimmers and their coaches, rather than seeking advice from qualified nutritionists (Jovanov et al., 2019; Moreno et al., 2022). Consequently, large supplement intakes may not be restricted to elite competitors, with national and international swimmers in Spain both reporting an equally prevalent consumption rate (~87%); including little differences in the total number and types of supplements being reported (Moreno et al., 2022). Given that adolescents make up a large proportion of competitors at the national level, this suggests that supplement use is as similarly widespread in adolescents as it is with adults; though with younger cohorts receiving less guidance on safe practices (Dascombe et al., 2010).

The supplement use of adolescent swimmers is currently difficult to determine as this population's intakes have either been investigated alongside other sports (Dascombe et al., 2010), or have been overlooked in dietary investigations (Berning et al., 1991; Collins et al., 2012; da Costa et al., 2013; Martínez et al., 2011). Nonetheless, an early study by Hawley and Williams (1991) found that 20% of adolescent swimmers reported using micronutrient supplements; though their use was questionable as

the UK RNIs were already being achieved through food alone. Kabasakalis et al. (2007) also suggested that adolescent swimmers engaged in widespread supplement use, mainly through the consumption of iron and multivitamins (prevalence not reported). Similarly, these supplements appeared to be misplaced as they contributed towards excessive iron, calcium, and vitamin E intakes, all of which could have become toxic (Mettler & Zimmermann, 2010). More recently, Simič and Mohorko (2018) showed that all adolescents from the Slovenian national team used sports supplements (CHO and electrolytes: 100%, protein: 78%), whereas 79% also utilised supplements from the health and ergogenic categories (omega-3 fatty acids: 42%, multivitamin: 32%, creatine: 5%). These intakes suggested that current adolescent swimmers might have decreased the intake of micronutrient supplements, while increasing the use of convenient energy and macronutrient sources; showing a more justified use of nutritional supplements (Close et al., 2022). Sajber et al. (2019) followed this up by showing that a high proportion of adolescent swimmers (boys: 65%, girls: 56%) were using nutritional supplements even at the regional level, but as no further details were provided on the supplements being used, or where they sourced their supplement information, it is currently unclear if their practices differed from adults.

In summary, further research is warranted in adolescent swimmers at different ages and stages of swimming development, to determine: (a) the age where prevalent supplement use begins; (b) who informs supplement use; (c) what types of supplements are being consumed; and (d) where supplements are being sourced from. Education to modify these factors can support practitioners to target the appropriate stakeholders (e.g., swimmers, coaches, parents/guardians) to ensure they approach qualified nutritionists for advice on supplement use.

1.5 Nutritional Ergogenic Aids

Nutritional ergogenic aids can promote physiological changes in the body that can provide a ~0.2–3% improvement in exercise performance (Maughan et al., 2018). Though these overall improvements are

small, they should be considered in the context of the fine margins involved in competitive swimming. For example, at the 2022 Commonwealth Games, the difference between winning a gold medal and finishing in fourth position in the men's 200 m backstroke final was 0.51 s (0.4%). Furthermore, where two swimmers performed very similarly in the women's 400 m freestyle heats (4:14.92 vs. 4:15.37, 0.2% difference), only the quicker of these times made it through to the competition final. Therefore, for elite swimmers to optimise competition performances and maximise their opportunities for sporting success, the use of nutritional ergogenic aids is not only justified, but perhaps required for all events.

Whether adolescent swimmers should consume ergogenic aids is a more contested topic, given this life phase brings growth, development, and competition experiences that are going to produce much larger improvements in swimming performance than expected with supplements (Desbrow et al., 2014). Therefore, upon a risk-benefit analysis, the marginal performance improvements associated with ergogenic aids may be outweighed when comparing the risks of adverse side-effects and/or inadvertent doping (Derave & Tipton, 2014). Many ergogenic aids are also yet to have their long-term safety assessed during growth and development, making it currently unclear whether they may be related to future health problems (Desbrow, 2021). However, many adolescent athletes view ergogenic supplements as important for performance and consume them in light of the possible health risks (Jovanov et al., 2019). It is therefore intuitive to provide this age-group with appropriate education and advice so that swimmers and key stakeholders (coaches, parents/guardians, sport medicine staff) can make informed choices on supplement use, rather than relying on uncredible sources. Indeed, ergogenic aids can be used safely in this cohort when appropriate dosing strategies and supplement sources are used. While this viewpoint is contrary to previous discouragement (Desbrow et al., 2014; Maughan et al., 2007), it should be noted that the negative stigma surrounding supplements may be related to steroids and other banned substances often being categorised as 'ergogenic aids' (Tokish et al., 2004). Moreover, the consistent discouragement of ergogenic aids has meant that some athletes avoid the guidance of qualified nutritionists, rather than seeking it out

(Kasper et al., 2020). Together, further research is therefore required to identify optimal ergogenic supplement practices in highly trained adolescent swimmers, supporting this cohort to engage in safe and effective practices rather than pushing them towards non-evidence-based advice.

At present, only five legal nutritional ergogenic aids are considered to be safe and have strong evidence of a performance enhancing effect: creatine, beta-alanine, CAF, $NaHCO_3$, and nitric oxide (NO)-stimulating supplements (Maughan et al., 2018). Of these, creatine (~1–6 weeks) and beta-alanine (~4–24 weeks) require chronic supplementation to make changes within the skeletal muscle; increasing phosphocreatine availability and carnosine concentrations, respectively (Saunders et al., 2017; Wax et al., 2021). Identifying a performance effect with these supplements is therefore liable to logistical difficulties in highly trained swimmers, since the training and competitive schedules cannot be controlled for such long periods. Indeed, each individual will complete differing training intensities and volumes, as well as specialise in different swimming strokes; which combined has produced equivocal performance outcomes when creatine (8–27 weeks, Peyrebrune et al., 2005; Theodorou et al., 1999) and beta-alanine (4–12 weeks, Chung et al., 2012; de Salles Painelli et al., 2007; Mero et al., 2013; Norberto et al., 2020) have been utilised in a swimming setting. Therefore, while the practical applications of creatine and beta-alanine as potential training aids for swimmers have been discussed elsewhere (Derave & Tipton, 2014; Domínguez et al., 2017; Hopwood et al., 2006), this thesis will give further attention to CAF, $NaHCO_3$, and NO supplements, which could all have acute performance benefits on race day.

1.5.1 Caffeine

Caffeine is the world's most widely used psychoactive stimulant that is regularly consumed by ~90% of adults and ~75% of adolescents due to its presence in tea, coffee, chocolate, and soft drinks (Guest et al., 2021; Temple et al., 2017). In terms of supplementation, CAF has been found to be the most popular nutritional ergogenic aid used by swimmers (49–54 %; Moreno et al., 2022; Shaw et al.,

2016a), which is is perhaps no surprise considering that CAF is associated with ≥3% improvements in short-duration power output and anaerobic time-trial performances (e.g., racing), as well as 1–8% improvements in total work output in repeated sprint exercises (e.g., training) (Maughan et al., 2018). Moreover, additional CAF benefits appear to support fatigue tolerance, aerobic endurance, and cognitive function, suggesting that CAF can be effective in a range of exercise tasks lasting between 1–60 min (Burke, 2008; Grgic et al., 2020; Guest et al., 2021); though it should be noted that much of this work has not been conducted in swimming. Nonetheless, based on the prospective ergogenic benefits, it has been suggested that CAF could be an effective supplement for swimmers who compete in short- (50–100 m), middle- (200–400 m), and long-distance (800–1500 m) swimming events (Grgic, 2022).

Multiple physiological mechanisms can explain the ergogenic benefits of CAF, including effects at both the central and peripheral level. This is because, once absorbed from the gastrointestinal tract, CAF enters the bloodstream and easily crosses the blood-brain barrier, as well as all other cellular membranes in the body (Goldstein et al., 2010). At present, however, it is generally accepted that, even at small doses, CAF primarily acts at the central nervous system (CNS) by challenging adenosine for adenosine receptor binding sites; subsequently blocking adenosine actions such as inducing sleepiness, increasing pain perception, and decreasing arousal (Davis & Green, 2009; Guest et al., 2021). At larger doses, CAF may also stimulate the CNS to increase adrenaline and dopamine release, both of which can act centrally to improve mood and motivation, and possibly decrease perceived exertion and pain during exercise (Duncan et al., 2013; Smirmaul et al., 2017). It is with this enhanced adrenaline release that peripheral mechanisms were first proposed, since adrenaline is associated with increased fatty acid mobilisation and glycogen sparing during endurance exercise (Graham, 2001). However, CAF has demonstrated inconsistent effects on fat oxidation rate, while providing ergogenic effects in exercise that is not reliant on glycogen availability; therefore, this has since been dismissed as a primary mechanism (Guest et al., 2021). Alternatively, CAF can induce peripheral changes by enhancing calcium ion (Ca^{2+}) mobilisation and potassium (K^{+}) uptake in the

skeletal muscle (via increased sodium (Na^+)/K^+ ATPase activity) (Davis et al., 2003; Tarnopolsky, 1994); changes that could enhance excitation-contraction coupling and help sustain contractile force while swimming (Cairns & Lindinger, 2008). Hence, when these potential synergistic benefits occur at the central and peripheral levels, CAF is considered as one of the most reliable ergogenic aids available to athletes.

Most research suggests that the optimal CAF dose lies within the range of 3–6 mg·kg BM^{-1}, though this may differ on an individual basis (Guest et al., 2021; Maughan et al., 2018). Higher CAF doses (≥6 mg·kg BM^{-1}) generally do not provide added performance benefits but may increase the likelihood of experiencing side-effects (Graham & Spriet, 1995; Pasman et al., 1995), such as gastrointestinal upset, anxiety, jitters, and insomnia (Sökmen et al., 2008); all of which could negatively impact competition swimming performances. Alternatively, lower CAF doses (≤3 mg·kg BM^{-1}) have the potential to be ergogenic, although this is most likely to occur in swimmers who habitually consume low CAF intakes or rarely use CAF supplements (Pickering & Kiely, 2019b). As an example, a 60 kg swimmer with a daily CAF intake of 50 mg·day^{-1} (<1 mg·kg BM^{-1}) might benefit from a bolus 120 mg dose (2 mg·kg BM^{-1}) prior to racing. This is thought to occur since habitually low CAF users (≤2 mg·kg BM^{-1}·day^{-1}) are less accustomed to CNS stimulation and can receive an ergogenic benefit through central factors alone (Spriet, 2014). On the other hand, more habitual CAF users (≥3 mg·kg BM^{-1}·day^{-1}) can be less sensitive to CNS stimulation and might therefore require a dose within the 3–6 mg·kg BM^{-1} range to activate both central and peripheral mechanisms (Astorino et al., 2010; Talanian & Spriet, 2016). Resultantly, swimmers of all ages should trial small CAF doses in training first to identify a ‘minimal effective dose’.

The optimal CAF timing is currently dubious given that various sources are now available. These include anhydrous powder, energy drinks, gels, gums, and mouth rinses; which all possess ergogenic potential if appropriate doses are used (Wickham & Spriet, 2018). Currently, the most efficacious approach is to ingest CAF anhydrous in capsule or solution form, as this is the most frequently used in

research and shown to be effective when consumed 60 min before exercise (Harty et al., 2020; Skinner et al., 2013). This ingestion window seems to allow sufficient time for CAF to leave the gut and enter the bloodstream (~20–45 min), before being transported to the relevant sites at the CNS (Kamimori et al., 2002). This differs from gums and mouth rinses that do not enter the stomach, with these sources being rapidly absorbed through the oral cavity (5–15 min; Kamimori et al., 2002). As such, these CAF sources could potentially be ingested closer to exercise when there is limited time between races at competitions. In contrast, multiple ingredient sources (e.g., energy drinks and bars) could delay CAF absorption from the stomach and require consumption further away from exercise (Abuhelwa et al., 2017). Though, it is important to note that CAF timings are typically based on the shortest timeframe to become ergogenic, and each source might instead have a long-lasting ergogenic window owing to a CAF half-life remaining in the system for ~3–6 hours (Bell & McLellan, 2002; Sökmen et al., 2008). However, until further research fully supports the use of alternative CAF sources and timings, it is currently recommended that 3–6 mg·kg BM^{-1} of CAF anhydrous is ingested 60 min pre-exercise to give the greatest chance of an ergogenic effect (Maughan et al., 2018).

The consumption of low-to-moderate CAF doses (≤3 mg·kg BM^{-1}·day^{-1}) are currently considered to be safe for adolescents (European Food Safety Authority [ESFA], 2015), with little evidence to suggest these intakes are negative to long-term health or behaviour (Wikoff et al., 2017). However, habitual CAF intakes should be considered prior to using supplements, especially in swimmers who are smaller in size and can easily consume the 3 mg·kg BM^{-1}·day^{-1} threshold through dietary sources. For example, a 50 kg swimmer could ingest 2 mg·kg BM^{-1} CAF by consuming a bar of dark chocolate (10–50 mg) and a can of cola (50 mg), which if then followed by supplemental CAF could result in a very large daily intake (Guest et al., 2021). Another issue is that individuals may respond very differently to CAF ingestion, such that some swimmers might have positive experiences before racing (e.g., alertness, concentration, well-being), whereas others might have negative side-effects that could negate performance (e.g., anxiety, irritability, violent tendencies) (Temple, 2017). Finally, CAF can become toxic (3–10 g), and even fatal (≥10 g), if large doses are consumed (Wikoff et al., 2017).

Though these large amounts of CAF are difficult to consume naturally though diet, it is a very possible circumstance when using anhydrous powder (~4 g·teaspoon) and/or misinterpreting dose calculations (g·kg BM^{-1} rather than mg·kg BM^{-1}). For these reasons, it is important that an appropriately qualified performance nutritionist manages the CAF supplementation of adolescent athletes.

Despite CAF showing strong evidence as an ergogenic aid for over 30 years (Grgic et al., 2020), only two studies have investigated the effects in adolescent swimmers. In an early study, the ingestion of 250 mg CAF (~4 mg·kg BM^{-1}) an hour before a 100 m freestyle time-trial was found to enhance the swimming speed of regional-level adolescents (age: 17 ± 2 years) when compared to a PLA (+0.04 $m \cdot s^{-1}$, g = 0.82; Collomp et al., 1992). Moreover, CAF maintained swimming speed in a follow-up 100 m time-trial after 20 min passive recovery, offsetting the performance decrements that normally occur in repeated efforts (vs. PLA: +0.06 $m \cdot s^{-1}$, g = 1.23). However, as these benefits were only observed in seven low-level swimmers with a CAF dose exceeding the ESFA (2015) safety recommendations, it is unclear whether these effects translate to highly trained adolescents using a minimal effective dose. Alternatively, the second study observed no performance benefits when trained adolescent females (age: 14 ± 1 years) ingested 3 mg·kg BM^{-1} CAF 30 min before a 400 m freestyle time-trial (-3.6 s, g = 0.08) (Azizimasouleh et al., 2014). While the ~4 s (1%) improvement might appear to show a practical significance, this was difficult to determine given that comparable changes are expected with daily variation (Stewart & Hopkins, 2000); thus, a longer CAF ingestion window (i.e., 60 min) was perhaps required for more noticeable performance enhancements to occur. Thus, based on this limited and equivocal research, further investigation is required in highly trained adolescent swimmers to elucidate optimal CAF strategies in competition.

Three studies in competitive adults suggest that CAF could be an effective ergogenic aid for short-distance swimming events, although these should be interpreted with caution. For example, both Vanata et al. (2014) and Lara et al. (2015) both found 3 mg·kg BM^{-1} CAF to provide a ~1%

improvement in 50-yard (-0.2 s, g = 0.06) and 50 m (-0.3 s, g = 0.08) performances, respectively. However, despite these results being statistically significant, it is difficult to conclude that such small changes occurred solely through CAF ingestion, since performance times in time-trial swimming vary by ~1.1% on a daily basis (Stewart & Hopkins, 2000). This was compounded by 'trivial' effect sizes (g <0.20; Cohen, 1988) in both studies, although this was potentially caused by large standard deviations (SD) in the data due to these studies using: (a) lesser trained swimmers (Vanata et al., 2014); or (b) various swimming strokes (Lara et al., 2015). Goods et al. (2017) followed this up by showing a similar 0.9% performance increase (-0.4 s, g = 0.34) in an initial 75 m freestyle swim following 3 mg·kg BM^{-1} CAF ingestion. Interestingly, this result did not reach statistical significance, but did exceed a smallest worthwhile change (SWC = 0.2 s) and produced a 'small' effect size (g = 0.2–0.5); suggesting some practical significance for highly trained swimmers. Moreover, when 75 m efforts were repeated for six bouts, an average 1.3% performance enhancement was found in the CAF group (mean improvement: -0.5 s, g = 0.47), including five of six sprints exceeding the SWC. Therefore, combined with the results of Collomp et al. (1992), these data suggest that CAF might be more consistently ergogenic for single and repeated freestyle swimming in 75–100 m distances.

Currently, there is currently little research on the effects of CAF for middle- and long-distance swimming. In a small cohort (n = 6) of international swimmers, the ingestion of 6 mg·kg BM^{-1} CAF 45 min before exercise enhanced a 200 m freestyle time-trial by 1.1% (-1.4 s, g = 0.39) compared to PLA (Pruscino et al., 2008). However, after 30 min recovery, a repeated 200 m time-trial performance declined in the CAF condition (+1.5 s, g = -0.42), suggesting that 6 mg·kg BM^{-1} CAF could be detrimental to performance when used early in a competition. In the final CAF study, the ingestion of 6 mg·kg BM^{-1} 150 min before a 1500 m swimming time-trial enhanced performance by 1.8% (-23 s, g = 0.59), albeit in recreational adults (MacIntosh & Wright, 1995). Despite the prolonged CAF ingestion window, a reduction in plasma K^+ was observed immediately prior to swimming, potentially indicating a greater skeletal muscle uptake that could have delayed fatigue (Cairns & Lindinger, 2008; Lühker et al., 2017). Although, it is unclear if similar peripheral mechanisms would occur in highly

trained adolescents. Additionally, both these performance increases were observed with CAF doses twice the ESFA safety recommendation, therefore further research is required with low-to-moderate doses before CAF can be considered as an effective ergogenic aid for middle- and long-distance swimming for adolescents.

While there does appear to be some evidence that CAF enhances 100–1500 m competitive swimming performances, research has not yet considered the challenges when ingesting CAF in competition. Firstly, research studies do not replicate the same level of pre-race anxiety that would occur at major swimming competitions; therefore, some swimmers may experience exacerbated symptoms of tachycardia, nervousness, and gastrointestinal upset after CAF ingestion, which could all have negative implications for performance (Meeusen & Decroix, 2018). Secondly, CAF is known to disrupt sleep time and quality if consumed up to six hours before bed (Drake et al., 2013). This could be problematic at major swimming competitions that typically take place across 3–7 days, which require maximal swimming performances to be completed in heats and finals. This often presents a strategic trade-off for swimmers who must decide on either prioritising evening CAF ingestion for immediate performance enhancement or avoid CAF to support sleep and recovery for the next morning's heats. However, there is currently no research investigating how CAF might affect the sleep of highly trained swimmers, or to what extent evening CAF ingestion might impact next day swimming performances, which is an area for future research.

1.5.2 Sodium Bicarbonate

Though only small amounts of $NaHCO_3$ would typically be found in the diet, the supplementation of a large bolus dose (~15–30 g depending on body mass) is known to produce alkalotic changes in the blood that are purported to augment buffering capacity (Maughan et al., 2018). Specifically, $NaHCO_3$ is associated with a ~2% performance enhancement in high-intensity exercise tasks that are reliant on anaerobic glycolysis (~30 s to 5 min) (Grgic et al., 2021), with a reduced efficacy when exercise

durations begin to exceed 10 min (Carr et al., 2011a). Based on this possible performance impact, approximately 21–44% of national- and international-level swimmers are currently thought utilise $NaHCO_3$ as an ergogenic aid (Moreno et al., 2022; Shaw et al., 2016a). Given the exercise intensity and duration that $NaHCO_3$ exerts its ergogenic potential, it is expected that supplementation would be most efficacious in middle-distance races (i.e., 200–800 m), as well as high-intensity interval swimming that produces large perturbations in blood acid-base balance (Grgic & Mikulic, 2022).

Though it is well established that $NaHCO_3$ has alkalotic properties that can benefit exercise performance, the precise mechanism of action is still debated (Fitts, 2016; Westerblad, 2016). The most researched and accepted $NaHCO_3$ mechanism is its role as a hydrogen ion (H^+) buffer during exercise (Maughan et al., 2018). This occurs since there is an almost immediate rise in blood bicarbonate (HCO_3^-) concentration following $NaHCO_3$ ingestion, subsequently increasing the pH gradient between the intracellular and extracellular environments (Lancha Junior et al., 2015). To establish acid-base balance, this biochemical change increases the clearance rate of lactate (La^-) and H^+ from the exercising muscles (Bishop et al., 2004), which is purported to delay fatigue since the intramuscular accumulation of H^+ accumulation is associated with impairments to glycolytic enzyme function (Hollidge-Horvat et al., 1999); Ca^{2+} sensitivity and handling (Allen et al., 1992); and actin-myosin cross-bridge cycling (Fitts, 2008). Alternatively, $NaHCO_3$ ingestion also affects the intracellular and extracellular balance of strong ions, including chloride (Cl^-), K^+, Ca^{2+}, and Na^+ (Siegler et al., 2016); which all contribute to skeletal muscle function (Cairns & Lindinger, 2008). Specifically, $NaHCO_3$ might upregulate various skeletal muscle pumps and co-transporters, such as the Na^+/K^+, Na^+–K^+–Cl^-, or K^+/H^+ exchangers; thus, helping sustain strong ion balance to delay losses in muscle excitability while swimming (Siegler & Gleadall-Siddall, 2010). However, while $NaHCO_3$ influences ionic movements before and during exercise, this mechanism is currently under-researched and questions whether optimal $NaHCO_3$ ingestion should be timed to maximise beneficial strong ion shifts or peak blood HCO_3^- concentrations.

Given that $NaHCO_3$ is largely accepted for its blood buffering capabilities, the current best practice with supplementation is to coincide a peak blood HCO_3^- concentration to the start of exercise (McNaughton et al., 2016). Based on group mean averages, this would typically result in swimmers having to ingest $NaHCO_3$ 60–90 min pre-exercise when using a solution form (Price & Singh, 2008), or 120–150 min pre-exercise when using capsules (Carr et al., 2011b). However, this time varies considerably between individuals (solution: 40–125 min, Gough et al., 2017; capsules: 60–240 min; de Oliveira et al., 2020); therefore, it is encouraged that swimmers undergo time to peak testing to identify their individual $NaHCO_3$ absorption characteristics (McNaughton et al., 2016). Conversely, this has view as been challenged since it has been suggested that the ergogenic effects of $NaHCO_3$ occur once baseline blood HCO_3^- concentrations are increased by ≥5 $mmol \cdot L^{-1}$ (Heibel et al., 2018). As such, this removes the focus on specific $NaHCO_3$ timings since a long-lasting 'ergogenic window' is likely to be produced with capsule ingestion (~1–4 hours, de Oliveira et al., 2020; Jones et al., 2016). To date, only one study has compared performance when $NaHCO_3$ has been ingested at an individualised (40–160 min pre-exercise) versus standardised time points (60 min pre-exercise), finding a 0.5% faster (-2 s, g = 0.19) 2000 m rowing time in world-class athletes with the individualised approach (Boegman et al., 2020). Interestingly, this improvement occurred despite both ingestion strategies producing similar blood HCO_3^- changes (+5.5 vs. +6.0 $mmol \cdot L^{-1}$), potentially inferring that other ergogenic mechanisms take place when $NaHCO_3$ is individualised, although this requires further research.

The optimal $NaHCO_3$ dosing strategy should also be considered based on individual tolerance, given that common gastrointestinal side-effects might have ergolytic effects on exercise performance (Cameron et al., 2010; Kahle et al., 2013). Gastrointestinal disturbances are caused by the dissociation of $NaHCO_3$ in the stomach, which produces carbon dioxide and water that can subject swimmers to stomach cramps, nausea, and diarrhoea during critical race preparations (e.g., <30 min pre-exercise) (Grgic et al., 2021). Typically, an acute dose of 0.3 $g \cdot kg\ BM^{-1}$ induces large increases in blood HCO_3^- while balancing the side-effects (McNaughton et al., 1992a). A singular dose at competitions is

therefore thought to be safe for adolescents, though multi-day ingestion is questionable due to the high Na^+ load (Gough et al., 2023; Robey et al., 2015). However, this dosing method has been shown to be safe in adult athletes across five consecutive days, with blood markers of acid-base balance (e.g., blood Na^+, HCO_3^-, pH) and blood pressure remaining within the safety ranges (Kahle et al., 2013; Mueller et al., 2013). Nonetheless, the 0.3 g·kg BM^{-1} dose caused severe side-effects in some individuals, and in this scenario alternative ingestion strategies should be considered. A practical solution is to ingest $NaHCO_3$ in capsules with a high-CHO meal, since this can negate the side-effects by delaying absorption from the stomach (Carr et al., 2011b). A smaller (0.2 g·kg BM^{-1}) dose could also be ergogenic while also reducing the total amount of $NaHCO_3$ that enters the stomach, ultimately providing a more tolerable dosing option (Gough et al., 2018b; 2022; Gurton et al., 2020). A variety of $NaHCO_3$ ingestion strategies should therefore be trialled in training in the first instance, to identify an individualised dosing approach for competition.

To date, only one study has investigated the effects of $NaHCO_3$ on adolescent swimming performance. In this study, Zajac et al. (2009) administered 0.3 g·kg BM^{-1} $NaHCO_3$ (solution, 90 min pre-exercise) to nationally competitive swimmers (age: 15 ± 1 years) before 4 x 50 m repeated freestyle sprints (60 s passive recovery). The outcome was a 2.1% increase in performance in the first swimming sprint (-0.5 s, g = 0.50), which was unexpected as the short exercise timeframe and supramaximal intensity is thought to produce a rapid rate of H^+ accumulation that overrun the HCO_3^- buffering system, even following $NaHCO_3$ ingestion (de Araujo Dias, 2015; Higgins et al., 2013; McNaughton et al., 1992b). Moreover, the swimmers only displayed pre-exercise increases in blood HCO_3^- of +3.4 mmol·L^{-1}, a smaller increase than typically observed in adults (Gough et al., 2017), and lower than the proposed +5–6 mmol·L^{-1} ergogenic threshold (Heibel et al., 2018). Though, as this blood measure was taken 30 min before exercise, it is plausible that blood HCO_3^- continued to increase by the time exercise began. Two alternate explanations are therefore speculated to explain this result in adolescents: (a) a greater intramuscular uptake of strong ions that enhanced excitation-contraction coupling (Siegler et al., 2016); or (b) minor $NaHCO_3$ side-effects increased the

expectancy of an ergogenic effect in the first bout (McClung & Collins, 2007). Since strong ions or blinding success were not measured in this study, further research is required to elucidate how adolescent swimmers can best utilise $NaHCO_3$ supplementation in practice.

The effects of $NaHCO_3$ on adult swimming performance is also unclear, especially over short distances (~60 s duration). Pierce et al. (1992) first found that collegiate swimmers performed no differently in a 100-yard time-trial regardless of whether $NaHCO_3$ (53.6 ± 0.8 s), PLA (54.1 ± 0.9 s), or no supplement was consumed (52.9 ± 0.9 s). Although, this study did administer a lower 0.2 g·kg BM^{-1} $NaHCO_3$ dose (60 min pre-exercise), which potentially did not increase blood HCO_3 concentrations ≥5 mmol·L^{-1} in all swimmers when ingested at a standardised pre-exercise time point (Gough et al., 2017). Campos et al. (2012) and Mero et al. (2013) followed this study by also showing no $NaHCO_3$ benefits on single-effort 100 m freestyle performances. Interestingly, the international swimmers in these studies performed slightly worse with $NaHCO_3$ versus PLA (+0.5 s, g = -0.20 and +0.6 s, g = -0.24, respectively), suggesting $NaHCO_3$ does not support 100 m events in competition. Similarly, both studies compromised their results by administering $NaHCO_3$ capsules 60 min before exercise, whereas a window of ~120–150 min may have been required for most swimmers to reach a peak blood HCO_3^- concentration (Carr et al., 2011b). Alternatively, de Salles Painelli et al. (2013) found a 3.2% improvement (-2.4 s, g = 0.40) in a 100 m freestyle performance when 0.3 g·kg BM^{-1} $NaHCO_3$ (solution) was ingested 90 min before exercise, although this result was found in just seven swimmers of low training status. Nonetheless, this positive result appeared to occur when $NaHCO_3$ was timed appropriately based on its ingestion method. Based on these results, it is currently inconclusive whether $NaHCO_3$ improves single effort swimming of short distances (≤100 m), warranting further research with individualised dosing strategies.

Middle-distance swimming (200–400 m, ~2–4 min) has the strongest potential to be enhanced by $NaHCO_3$ supplementation (Grgic & Mikulic, 2022), though equivocal results have similarly been observed. For example, four studies have administered a comparable $NaHCO_3$ dosing protocol (0.3

g·kg BM^{-1}, capsules, 90 min pre-exercise) to national- and international-level swimmers, with only Lindh et al. (2008) showing a performance enhancement for a 200 m freestyle time-trial (-1.8 s, *g* = 0.41). In contrast, Joyce et al. (2012) found no $NaHCO_3$ benefit on 200 m swimming versus PLA (-0.8 s, *g* = 0.13), though the swimmers used variable swimming strokes that may have required differing pacing strategies, and thus aerobic contributions versus freestyle alone (Pyne & Sharp, 2014). Nonetheless, Pruscino et al. (2008) also observed no significant $NaHCO_3$ effects on an initial 200 m freestyle performance, but a 'small' effect size might have indicated a practical significance (-0.6 s, *g* = 0.20). However, this study split the $NaHCO_3$ dose across the 90 min ingestion window (seven equally spaced doses), which failed to produce a significant increase in blood HCO_3^- prior to exercise. Finally, Kumstát et al. (2014) observed no $NaHCO_3$ effects on a 400 m freestyle time-trial, possibly because this event requires a lower glycolytic component and is also subject to pacing strategies (Rodríguez & Mader, 2011). It should be noted that because <10 swimmers were involved in each study, and each study used a standardised ingestion timeframe, it is also plausible that many swimmers in these studies did not achieve blood HCO_3^- increases above the proposed ergogenic threshold (≥5 mmol·L^{-1}) (Heibel et al., 2018; Jones et al., 2016).

Research also suggests that $NaHCO_3$ enhances acid-base recovery between exercise bouts (Gough et al., 2018a, 2019a), potentially supporting recovery between races at swimming competitions. Mero et al. (2013) observed this effect between 2 x 100 m freestyle efforts, where 0.3 g·kg BM^{-1} $NaHCO_3$ (capsules, 60 min pre-exercise) had no effect on the first bout, but offset fatigue in the second bout compared to a PLA (-1.0 s, *g* = 0.34). Similarly, Pruscino et al. (2008) shown that 0.3 g·kg BM^{-1} $NaHCO_3$ (capsules, split across 90 min) had little benefit in an initial 200 m time-trial, yet after 30 min recovery, swimmers were able to reproduce their performance compared to the depreciating times in the PLA group (-1.6 s, *g* = 0.37). These improvements likely occurred since $NaHCO_3$ capsules were ingested close to the initial effort, allowing continued increases in blood HCO_3^- and intramuscular strong ion uptake to occur during the recovery periods (Siegler et al., 2016). In contrast, Pierce et al. (1992) did not find 0.2 g·kg BM^{-1} $NaHCO_3$ (solution, 90 min pre-exercise) to have any

benefit towards an initial 100-yard freestyle time-trial, a follow-up 200-yard time-trial (-0.6 s, g = 0.13), or a third 200-yard time-trial using mixed strokes (+3.5 s, g = -0.23). However, as blood HCO_3^- changes were not reported, it is possible that the dosing strategy did not enhance pre-exercise concentrations for all swimmers; whereas a 20 min recovery may have been too short for acid-base balance to fully recover between time-trials (Gough et al., 2019a). Together, this evidence suggests that 0.3 g·kg BM^{-1} $NaHCO_3$ supports secondary swimming performances in competition, but perhaps at the expense of performance in the first race. Further research is therefore required to investigate whether individualised $NaHCO_3$ strategies could overcome this issue.

The benefits of $NaHCO_3$ might extend beyond competition swimming and support training performance, particularly in sets of high-intensity, repeated efforts with short rest intervals (Grgic et al., 2021). Indeed, Gao et al. (1988) observed 0.2 g·kg BM^{-1} $NaHCO_3$ (solution, 60 min pre-exercise) to maintain swimming speed (~1.64 m·s^{-1}) across 5 x 100-yard bouts, compared to a decreased speed in the final two bouts when consuming a PLA (~1.61 m·s^{-1}). Gough et al. (2023) recently supported this outcome, showing 0.3 g·kg BM^{-1} $NaHCO_3$ (solution, 60 min pre-exercise) maintained swimming performance across 8 x 50 m efforts, resulting in faster swimming speeds compared to PLA in the final four bouts (~0.5–1.3 s, g = 0.26–0.79). Furthermore, Siegler and Gleadall-Siddall (2010) also found 0.3 g·kg BM^{-1} $NaHCO_3$ (solution, 150 min pre-exercise) to reduce the cumulative time to complete 8 x 25 m freestyle efforts by 2.3% (vs. PLA: -3.8 s, g = 0.14). However, it should be noted that all three of these studies observed ergogenic benefits in adult swimmers of collegiate or regional training status, and not in highly trained adolescents. In contrast, Campos et al. (2012) failed to show any benefits of 0.3 g·kg BM^{-1} $NaHCO_3$ in international-level adults during a 6 x 100 m freestyle swimming protocol (vs. PLA: +0.1 s, g = -0.07). Though, as this study administered $NaHCO_3$ capsules 60 min before exercise, it was unlikely that these swimmers achieved a heighted blood buffering capacity prior to exercise (Carr et al., 2011a; Jones et al., 2016). The evidence is therefore promising regarding the use of $NaHCO_3$ as a training aid, although further research is still needed to

firstly translate these findings to highly trained adolescent swimmers, and secondly to ensure the safety of $NaHCO_3$ following long-term repeated ingestion.

In summary, $NaHCO_3$ has promise as an ergogenic aid to support single and follow-up swimming performances in competition (de Salles Painelli et al., 2013; Lindh et al., 2008; Mero et al., 2013; Pruscino et al., 2008), as well as high-intensity interval swimming during key training sets (Gao et al., 1988; Gough et al., 2023; Siegler & Gleadall-Siddall, 2010; Zajac et al., 2009). However, these effects are often inconsistent with an abundance of research also suggesting that $NaHCO_3$ has no effect, particularly in highly trained swimmers (Campos et al., 2012; Joyce et al., 2012; Kumstát et al., 2014; Pierce et al., 1992). The underlying reason for these differences appears to lie in timing of $NaHCO_3$ ingestion, whereby studies have not accounted for the delay in $NaHCO_3$ absorption in the stomach with capsules (Carr et al., 2011b), and have not considered that each swimmer has individual $NaHCO_3$ absorption characteristics (Gough et al., 2017; Jones et al., 2016). Moreover, no study has currently considered whether strong ion changes could be the primary acting mechanism, and whether timing $NaHCO_3$ at an individualised peak in strong ion difference (SID) could be a more beneficial ingestion strategy. Therefore, to ensure that adolescent swimmers can benefit from $NaHCO_3$ ingestion, research must first identify whether they display individual time course changes in blood HCO_3^- and SID like adults. Following this research, ingestion strategies based on peak blood HCO_3^- (and potentially peak SID) should be compared versus standardised $NaHCO_3$ ingestion, to identify whether contemporary $NaHCO_3$ strategies can provide more consistent benefits to swimming exercise in this cohort.

1.5.3 Nitric Oxide Supplements

Nitric oxide is a free-radical gas with an involvement in various physiological functions, such as blood flow regulation, mitochondrial respiration, neurotransmission, and skeletal muscle contractile function (Jones et al., 2021). It is therefore purported that enhancing NO production during exercise

can reduce the O_2 cost of ATP resynthesis, lower the ATP cost of cross-bridge formation, enhance the function of type II muscle fibres, and promote O_2 delivery to the working muscles; all of which could subsequently enhance O_2 uptake kinetics and exercise efficiency (Affourtit et al., 2015; Bailey et al., 2009; Jones et al., 2016). At present, the human body has two known complementary pathways in which NO can be produced: the NO synthase (NOS) dependent pathway and the nitrate (NO_3^-)–nitrite (NO_2^-)–NO reduction pathway (Figure 1.2); thus, supplement strategies that can enhance either of these is thought to promote ergogenic benefits for prolonged submaximal exercise and/or repeated sprint tasks over ≥12–40 min durations (Maughan et al., 2018).

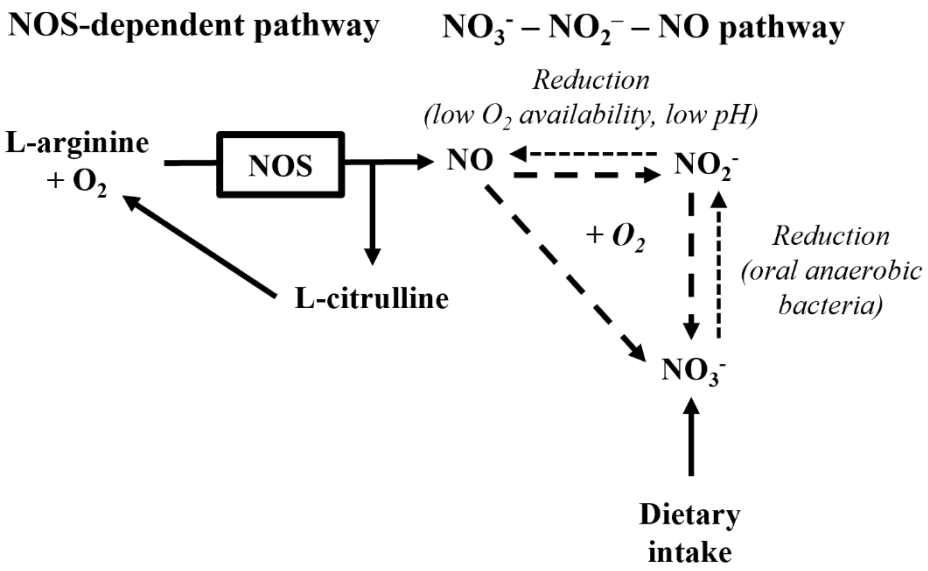

Figure 1.2. The pathways of NO production. NOS = nitric oxide synthase, NO_3^- = nitrate, NO_2^- = nitrite, O_2 = oxygen. Adapted from Jones et al. (2018).

The endogenous production of NO by NOS enzymes is well defined and has been extensively reviewed (see Bredt, 1999; Moncada & Higgs, 2003). In short, the NOS enzymes (typically referred to endothelial, neuronal, and inducible NOS) catalyse a complex reaction through the oxidation of L-arginine, which culminates in the production of NO and L-citrulline, with the latter then recycled back into L-arginine in a continuous production cycle (Figure 1.2). However, this NOS-dependent pathway

can be compromised during high-intensity exercise when O_2 availability is limited, and hence L-arginine cannot continue to be oxidised at a similar rate (Jones et al., 2018). Alternatively, the reduction of NO_2^- to NO is enhanced in hypoxic and acidic conditions, making it the dominant NO production pathway during exercise (Castello et al., 2006; Modin et al., 2001). Body stores of NO_3^- and NO_2^- can be increased though the dietary intake of leafy green and root vegetables, such as lettuce, spinach, rocket, celery, and beetroot (Hord et al., 2009); although the absolute quantity of whole foods required to elicit this effect can be impractical prior to exercise. Resultantly, supplemental intakes of NO-related amino acids (e.g., L-arginine and L-citrulline) and concentrated fruit and vegetable juices (e.g., beetroot juice [BRJ]) could enhance NO availability prior to exercise, and as such, could be considered as potential ergogenic aids for swimming performance (Bescós et al., 2012; d'Unienville et al., 2021; Jones et al., 2021).

Beetroot juice is currently the most researched and recommended NO supplement option for athletes (Jones et al., 2021; Rojas-Valverde et al., 2021; Zamani et al., 2021). For an ergogenic effect, it is recommended that swimmers consume a BRJ dose consisting of 300–600 mg NO_3^- in the 2–3 hours prior to exercise (Maughan et al., 2018), with potentially higher doses of 600–1200 mg NO_3^- required for swimmers who are highly trained and/or habitually consume high NO_3^- diets (Jones et al., 2021). Severe side-effects are not typically associated with BRJ ingestion, though susceptible swimmers might experience nausea, gastrointestinal discomfort, and 'beeturia': the passing of red betacyanin pigments that is not harmful but could be distressing (Watts et al., 1993; Wickham et al., 2018). Furthermore, it should be noted that the recommended BRJ doses exceed the current ESFA safety guidelines for NO_3^- ingestion ($\leq$3.7 mg·kg BM^{-1}·day^{-1}, ~240 mg for a 65 kg swimmer) (Babateen et al., 2018). Indeed, NO_3^- doses above this threshold are associated with the production of carcinogenic *N*-nitroso compounds, raising safety concerns with regular BRJ ingestion (Zamani et al., 2021). However, these risks are thought to be negated when NO_3^- is ingested alongside antioxidants and polyphenols, meaning the naturally occurring vitamin C, betanin, and betalain in BRJ are likely to mitigate any future health issues (Bedale et al., 2016; Swartz et al., 2019). Together, the ingestion of

BRJ is currently considered to be safe for consumption (Jones et al., 2018), though without long-term evidence in adolescents, concerned swimmers and their parents/guardians might wish to consider alternative NO supplement options.

Common L-arginine dosing strategies include ingesting 0.15 g·kg BM^{-1} (~10–11 g) 60–90 min pre-exercise, or the chronic ingestion of 2–12 g·day^{-1} for 4–8 weeks (Viribay et al., 2020); both of which are not currently thought to produce adverse health effects in adults (McNeal et al., 2018; Wu et al., 2009), but could cause gastrointestinal side-effects when ingested in bolus doses (≥9 g) (Grimble, 2007). L-citrulline and/or citrulline malate (CM) could therefore be more appropriate supplement options for swimmers, since typical dosing strategies (8–15 g, 60 min pre-exercise) are not currently known to have any side-effects, but still enhance both plasma L-arginine and L-citrulline concentrations (Moinard et al., 2008; Gough et al., 2021). Moreover, L-citrulline supplements are currently thought to be safe for adolescents and are regularly used in long-term replacement therapy for children with urea dysfunction (Papadia et al., 2018). These findings are, however, difficult to apply to adolescent athletes who already have healthy cardiovascular and urea functioning, and as such, further research regarding the long-term safety of L-citrulline and CM supplements in young, healthy athletes is required. Despite this, L-citrulline clears from the system relatively quickly (~90 min) following ingestion (Moinard et al., 2008), potentially suggesting that acute doses on an infrequent basis, such as key training sets and/or competitions, are likely to be safe in this cohort.

Research investigating the effects of BRJ on swimming performance is currently scarce, though a recent study was conducted in nationally competitive adolescents (age: 16 ± 2 years) (Moreno et al., 2023). This study showed that BRJ (~400 mg NO_3^-) ingested three hours before exercise did not improve performance across 6 x 100 m repeated freestyle time-trials, though a potential practical significance was observed in the final bout (-1.0 s, g = 0.34). Indeed, BRJ potentially reduced cumulative fatigue throughout the earlier bouts via an enhanced exercise economy (Jones et al., 2018), though this could not be confirmed since no blood La^- or subjective differences were observed

compared to the PLA supplement. Similarly, regional/collegiate swimmers received no benefit from a larger BRJ dose (~800 mg NO_3^-) three hours before a 168 m backstroke time-trial (-1.2 s, g = 0.13) (Lowings et al., 2017); nor were any ergogenic effects observed in 100 m or 200 m time-trials (both +0.1 s, g = -0.01) following a chronic BRJ dosing protocol (~500 mg·day^{-1} NO_3^- over three days) (Esen et al., 2019). Interestingly, these lack of performance benefits occurred despite considerable pre-exercise increases in plasma NO_2^-, suggesting that the NO mechanisms were active but do not benefit maximal swimming performances lasting 1–3 min. This is perhaps expected given that enhancing NO availability is purported to benefit exercise efficiency and O_2 uptake kinetics; hence, having greater potential for improving submaximal swimming performances in key aerobic training sets (i.e., Pinna et al., 2014) and/or competitive race distances ≥400 m.

There is also limited research regarding the use of L-citrulline and L-arginine supplements in swimming populations, with unclear performance outcomes to date. Hsueh et al. (2018) was the first to investigate these supplements in competitive adolescent swimmers (age: 16 ± 1 years), finding the combined ingestion of 0.05 g·kg BM^{-1} L-arginine, 0.05 g·kg BM^{-1} L-citrulline, and 0.09 g·kg BM^{-1} branched-chain amino acids an hour before an initial 50 m time-trial (mixed strokes) improved performance by 2.8% (-0.9 s, g = 1.67). Moreover, further sprints in the second (-0.8 s, g = 0.32) and seventh bouts (-0.9 s, g = 0.19) of the 8 x 50 m swimming protocol were also improved. However, it is unclear by which acting mechanism this supplement improved performance, given that NO production and urea clearance were unchanged with such low L-arginine and L-citrulline doses (~2.7 g of each supplement). This was supported by a recent study also suggesting that NO production was not enhanced via the ingestion of either 8 g·day^{-1} L-arginine, 8 g·day^{-1} L-citrulline, or a PLA supplement for eight consecutive days; ultimately resulting in no differences in 100 m or 200 m swimming time-trials between groups (Esen et al., 2022). Though, as this study only included five low-level swimmers per group without a crossover in supplement ingestion, it is difficult to distinguish supplement effects versus inter-individual variances in swimming performance. Subsequently, the ingestion of L-arginine or L-citrulline cannot be recommended as nutritional

ergogenic aids for swimmers at present, with further research using larger doses and/or increased sample sizes being required.

A relatively new form of NO supplement is citrulline malate (CM), which is currently gaining attention for its ergogenic properties (Gonzalez & Trexler 2020; Vårvik et al. 2021). The mechanistic actions of CM are not well understood given its recent emergence, though three key mechanisms are suggested. The first involves L-citrulline as a pre-cursor to NO production via the NOS pathway, and as such, CM may increase muscle blood flow, mitochondrial efficiency, glucose uptake, and type II muscle contractility during exercise (Affourtit et al., 2015; Bailey et al., 2009; Jones et al., 2021). The second mechanism is related to L-citrulline being a component in the urea cycle, which could enhance ammonia clearance during exercise (Breuillard et al. 2015). This may be important since exercise-induced increases in ammonia are associated with muscular fatigue by facilitating La^- production, and in turn, preventing the ATP production via the aerobic utilisation of pyruvate (Gough et al. 2021). The final mechanism concerns the addition of malate and its role as an intermediate in the tricarboxylic acid (TCA) cycle, potentially enhancing the generation of ATP during aerobic fuel metabolism (Bendahan et al. 2002). Thus, based on these purported mechanisms, it is intuitive to suggest that CM would provide an ergogenic benefit to whole-body exercise with a larger aerobic component (Gough et al., 2021), such as swimming training or middle-and-long distance swimming events (Rodríguez & Mader, 2011).

There are currently no studies investigating the effects of CM on swimming performance, whereas only two studies were identified that could be considered to involve aerobic exercise: time to volitional tolerance (T_{LIM}) cycling at 90–100% peak O_2 uptake ($\dot{V}O_{2peak}$) (Cunniffe et al., 2016; Gills et al., 2021). The first of these administered 12 g CM to well-trained cyclists an hour before exercise, yet participants were to complete 10 x 15 s maximal cycle ergometer sprints prior to the T_{LIM} test (Cunniffe et al., 2016). Resultantly, the carryover of fatigue may have negated aerobic performance since there no clear differences in time to fatigue (+7 s, g = 0.12), mean power output, work

completed, or perceived exertion between the CM and PLA conditions. In a follow-up study, recreational cyclists ingested 8 g CM 60 min before a T_{LIM} test at 90% $\dot{V}O_{2peak}$, with a five min Wingate test completed immediately afterwards (Gills et al., 2021). However, despite the aerobic exercise being performed first, no ergogenic benefits were attained from CM ingestion (-1 s, g = 0.01). Importantly, this study only used an 8 g CM dose, whereas doses of up to 15 g may be necessary to elicit peak plasma L-citrulline concentrations (Moinard et al., 2008). Furthermore, the translation of performances in T_{LIM} tests to competitive sports performance is questionable, given no competitive sport events base their outcomes on the time and distance achieved before exhaustion (Currell & Jeukendrup, 2011; Laursen et al., 2002). Therefore, further research that investigates the proposed aerobic mechanisms of CM is warranted.

1.6 Aims of the Thesis

- The first aim of this thesis (Chapter 3) was to observe and analyse the changes in dietary energy, macronutrient, and micronutrient intakes of highly trained adolescent swimmers under three distinct conditions: (a) normal training in preparation for competitions (i.e., before COVID-19); (b) while in reduced training with no competition schedule (i.e., during the COVID-19 lockdown); and (c) upon a return to training after a prolonged period away from sport (i.e., after the COVID-19 lockdown). Based on previous research (Alméras et al., 1997; Kabasakalis et al., 2007; Montenegro et al., 2017), it is hypothesised that little dietary adaptations would be made by adolescent swimmers in response to their changing training demands.

- The second aim of this thesis (Chapter 4) was to investigate the current dietary supplement intakes and practices of highly trained adolescent swimmers at three distinct phases in the swimming talent pathway: (a) developmental (aged 11–14 years); (b) age-group (aged 13–17 years); and (c) experienced national competitors (aged ≥16 years). It is hypothesised that

supplement use is widespread across all swimming talent stages, albeit with a change in reasoning, advisors, individual supplements used, and frequency of ingestion once swimmers reach higher levels of competition (Garthe & Maughan, 2018).

- The third aim of this thesis (Chapter 5) was to monitor changes in vitamin D status in highly trained adolescent swimmers from an autumn (October) training period, until a mid-season winter (January) training time point. This would also involve a secondary observation of vitamin D supplement uptake by swimmers and parents/guardians who have been educated on safe and effective supplement protocols. As per Geiker et al. (2017), it is hypothesised that adolescent swimmers in the UK do not adhere to supplement recommendations, and thus suffer large decreases in circulating vitamin D from the autumn to winter training periods.

- The fourth aim of this thesis (Chapter 6) was to explore the effects of a minimal effective CAF dose on the evening 100 m simulated competition performances of highly trained adolescent swimmers, before monitoring the effects this has on perceived sleep parameters and next day performance in a simulated 100 m morning heat. It is hypothesised that CAF would enhance swimming performance in the evening (Collomp et al., 1992), but could consequently hinder sleep and recovery for a repeated effort the next morning.

- The fifth aim of this thesis was two-fold. Firstly, to identify the time course response in blood HCO_3^- and strong ions following the ingestion of 0.3 g·kg BM^{-1} $NaHCO_3$ in highly trained adolescent swimmers (Chapter 7a); in which it is hypothesised that highly variable blood acid-base responses would occur akin to adults (Gough et al., 2017; Jones et al., 2016). Secondly, to compare whether $NaHCO_3$ ingestion strategies timed based on: (a) individualised time to peak blood HCO_3^-; or (b) group mean peak blood HCO_3^-; are more effective than PLA supplements for enhancing high-intensity swimming performances (repeated sprints) and recovery for a subsequent 200 m time-trial bout (Chapter 7b). Similar

to Boegman et al. (2020), it is hypothesised that the individualised $NaHCO_3$ strategy would enhance the possibility of achieving a pre-exercise peak in blood HCO_3^-, subsequently increasing performance versus standardised $NaHCO_3$ and PLA supplements.

- The final aim of this thesis (Chapter 8) was to observe whether the novel supplementation of CM can benefit the aerobic swimming capacity of highly trained adolescents, which is hypothesised to enhanced performance based on the proposed mechanisms appearing to align with whole body exercise with a large aerobic component (e.g., swimming). Collectively, these final three aims of this thesis will provide evidence for ergogenic supplement practices to enhance support racing, training, and recovery attributes.

Chapter 2 – General Methods

2.1 General Project Methods

2.1.1 Ethical Considerations

All experimental studies were approved by the Health, Education, and Life Sciences Faculty Academic Ethics Committee (Sport and Exercise) at Birmingham City University (BCU). Prospective research participants were all aged between 11–23 years and recruited from a high-performance swimming club, therefore safeguarding procedures were closely followed for all investigations in line with government guidelines (Department for Digital, Culture, Media, and Sport [DCMS], 2017). Permission of access was granted prior to each study by the head coach and gatekeeper of the swimming club, at which point swimmers, their parents/guardians, and coaches were provided with a full description of the study via a participant information sheet. All swimmers and parents/guardians who verbally agreed to participate in studies were then given a minimum of 24 hours to ask any questions about the research before signing an informed consent form. Additionally, all swimmers completed BCU general health screening questionnaires and medical screening forms prior to any exercise or supplement ingestion. Throughout the entirety of this project, the Data Protection Act 2018 (DCMS, 2018) and BCU codes of practice were closely followed regarding the collection, storage, and destroying of data for adults and children.

2.1.2 Participants

The investigated high-performance swimming club had three tiers of swimming participation. At the highest level, swimmers were all aged ≥16 years; nationally competitive in open age categories; and regularly attended selection trials for international competitions (e.g., British Swimming Championships). These swimmers completed between 7–9 pool (volume: 50–60 km·week^{-1}) and 3–6 land-based training sessions·week^{-1} in line with ‘elite’ swimmers in the UK (Pollock et al., 2019). The middle tier consisted of swimmers who were all nationally competitive in their respective age groups (aged 13-17 years), but not yet at the performance level to challenge in open age categories. All

swimmers at this level completed between 5–8 pool (volume: 40–50 km·week^{-1}) and 2–3 land-based training sessions·week^{-1}. The final tier consisted of developmental swimmers who were nationally competitive in their age groups (aged 11–14 years) but were not yet at the age and/or performance level to qualify for national competitions. These swimmers would complete 4–6 pool (volume: 20–30 km·week^{-1}) and 1–2 land-based training sessions·week^{-1}. For the remainder of this thesis, swimmers from these three performance tiers will be referred to as 'national', 'age-group', and 'development' swimmers, respectively. Examples training schedules of the national swimmers involved in this thesis can be found in Tables 2.1 and 2.2.

Table 2.1. Typical general preparatory training schedule of highly trained adolescent swimmers between September and December.

Day	Morning Training	Evening Training
Monday	**04:45–07:00:** A1 aerobic (~7000 km) **07:15–08:00:** Gym (≥18 years only)	**16:15–18:30:** A3 aerobic (~7000 km) **18:40–19:00:** Land circuit training
Tuesday	**04:45–07:00:** A2 aerobic (~10,000 km) Selected long-distance swimmers only	**16:15–18:30:** Threshold (~7000 km) **18:40–19:00:** Land core training
Wednesday	**04:45–07:00:** Speed (~5,000 km) **07:15–08:00:** Gym (≥18 years only)	Rest
Thursday	Rest	**17:30–17:50:** Land circuit **18:00–20:30:** $\dot{V}O_{2max}$ (~9,000 km)
Friday	**04:45–07:00:** A1 aerobic (~6500 km)	**16:15–18:30:** Speed (~6000 m)
Saturday	**05:45–08:00:** Tolerance & Speed (~5500 km) **08:15–09:00:** Gym (all)	Rest
Sunday	Rest	Rest

A1 = skills focus, ~70% maximal heart rate, <1 mmol·L^{-1} lactate; A2 = low intensity, ~75–80% of maximal heart rate, ~1 mmol·L^{-1} lactate; A3 = >2000 m pace, 85–90% maximal heart rate, ~3 mmol·L^{-1} lactate; Threshold = 2000m pace, ~95% maximal heart rate, ~4 mmol·L^{-1} lactate; $\dot{V}O_{2max}$ = 400 m pace (medium to low rest), maximal heart rate, ~6–8 mmol·L^{-1} lactate; Tolerance = >200 m pace (medium rest), maximal heart rate, >8 mmol·L^{-1} lactate; Speed = >50 m pace (maximal intensity, long rest). Training definitions adapted from Shaw et al. (2014).

Table 2.2. Typical specific preparatory training schedule of highly trained adolescent swimmers between January and August.

Day	Morning Training	Evening Training
Monday	**04:45–07:00:** A1 aerobic (~7000 km) **07:15–08:00:** Gym (≥18 years only)	**16:15–18:30:** Threshold (~7000 km) **18:40–19:00:** Land circuit training
Tuesday	**04:45–07:00:** A2 aerobic (~10,000 km) Selected long-distance swimmers only	**16:15–18:30:** Tolerance (~7000 km) **18:40–19:00:** Land core training
Wednesday	**04:45–07:00:** Speed (~5,000 km) **07:15–08:00:** Gym (≥18 years only)	Rest
Thursday	Rest	**17:30–17:50:** Land circuit **18:00–20:30:** $\dot{V}O_{2max}$ (~9,000 km)
Friday	**04:45–07:00:** A1 aerobic (~6500 km)	**16:15–18:30:** Speed (~6000 m)
Saturday	**05:45–08:00:** Tolerance & Speed (~5500 km) **08:15–09:00:** Gym (all)	Rest
Sunday	Rest	Rest

A1 = skills focus, ~70% maximal heart rate, <1 mmol·L^{-1} lactate; A2 = low intensity, ~75–80% of maximal heart rate, ~1 mmol·L^{-1} lactate; A3 = >2000 m pace, 85–90% maximal heart rate, ~3 mmol·L^{-1} lactate; Threshold = 2000m pace, ~95% maximal heart rate, ~4 mmol·L^{-1} lactate; $\dot{V}O_{2max}$ = 400 m pace (medium to low rest), maximal heart rate, ~6–8 mmol·L^{-1} lactate; Tolerance = >200 m pace (medium rest), maximal heart rate, >8 mmol·L^{-1} lactate; Speed = >50 m pace (maximal intensity, long rest). Training definitions adapted from Shaw et al. (2014).

Chapters 3–5 were focussed on the nutrition intakes and behaviours of highly trained adolescent swimmers; therefore, national and age-group swimmers were considered for participation based on their age (≥13 years) and 'highly trained' status (i.e., nationally competitive, McKay et al., 2021). Development swimmers only participated in Chapter 4 as a comparison group regarding their supplement intakes. The latter chapters of this thesis (Chapters 6–8) focussed on ergogenic aids, hence only national and selected age-group swimmers (aged ≥16 years, nationally competitive) were recruited for these studies. More detailed descriptions of research participants and inclusion/exclusion criteria can be found within each specific chapter.

2.1.3 Experimental Design

A descriptive and cross-sectional design was used to investigate the nutrition intakes (Chapter 3), supplement practices (Chapter 4), and changes in vitamin D status (Chapter 5) of highly trained adolescent swimmers. All data were obtained by the same researcher, who was a qualified (MSc) and registered (SENr) performance nutritionist. Chapters 6–8 were all experimental trials that were conducted at the same swimming facilities in the West Midlands, UK (25 m pool). Each study was PLA-controlled with a repeated measures design, with the order of trials counterbalanced and randomised using a block randomisation method. Supplements were also double blinded from the researcher and swimmers for Chapters 6 and 8. A single-blind method used in Chapters 7a and 7b due to the researcher conducting time to peak blood HCO_3^- testing with each swimmer, and thus knowing the $NaHCO_3$ ingestion timings. All experimental trials were structured into the swimmers' training routines, to be completed on the same day of the week, at the same time of day, and seven days apart. This approach was chosen to reduce the effects of confounding variables, such as differences in sleep, training stress, nutrient timings, and circadian rhythms that may occur across the training week (Drust et al., 2005).

2.1.4 Pre-Experiment Screening and Procedures

For Chapters 6–8, swimmers were requested to follow their habitual pre-training or pre-competition nutrition intakes prior to exercise, albeit with the avoidance of acute ergogenic supplements during the experimental period. These instructions were given for two reasons: (a) to increase external validity (Shaw et al., 2014); and (b) to potentially reduce the severity of gastrointestinal side-effects (Carr et al., 2011b). Swimmers were requested to send a photograph of all food, fluid, and supplement items consumed to the researcher 24 hours prior to familiarisation trials in each chapter (for full instructions see section 2.2.2). This information was used to calculate energy, macronutrient, and fluid intakes by the lead researcher, with the original photographs then re-sent to swimmers to facilitate dietary replication for experimental trials. Swimmers who were co-ingesting creatine and/or beta-alanine

were permitted to participate in studies if supplementation had been consistent for more than 24 weeks. This was firstly to account for these supplements being present in the diets of highly trained swimmers in practice (Moreno et al., 2022; Shaw et al., 2016a), and secondly because the largest physiological adaptations with these supplements would have already taken place (Chung et al., 2012; Peyrebrune et al., 2005). Though it is plausible that these supplements may have reduced the possible window to observe ergogenic effects, this was replicable to applied practice, and thus any acute performance changes observed within Chapters 6–8 were likely to have occurred due to the ingestion of the experimental supplements. A minimum of seven days separated experimental trials in each chapter, which was used as an adequate washout period for $NaHCO_3$ (Siegler et al., 2010) and CM (Gough et al., 2021) supplements, whereas swimmers abstained from CAF for at least 12 hours prior to any experimental trials (Graham, 2001). None of the swimmers reported habitually using acute ergogenic aids for training purposes, including reporting negligible habitual CAF uses (see Chapter 3, section 3.3.7 and Chapter 6, section 6.2.2).

Most swimmers and their parents/guardians were receiving sport nutrition support from the lead researcher throughout each investigation, which was embedded into their daily routines by their high-performance swimming club. National swimmers received individual support via nutrition consultations, body composition analysis, competition planning, and advice regarding ergogenic supplementation. Both national and age-group swimmers received classroom-based group education workshops (i.e., Foo et al., 2021), were given regular nutritional prompts via mobile group communication (WhatsApp, Menlo Park, USA), and had access to electronic PDF and presentation resources (Google Drive, Mountain View, USA). The researcher did not directly engage with development swimmers, but the parents/guardians of all three training groups received access to the online resources and could communicate with the researcher via mobile group communication. The level and frequency of individual support provided to swimmers and parents/guardians was determined by their engagement with the provisions.

2.2 General Experimental Procedures

2.2.1 Participant Anthropometric and Training Characteristics

Body mass and height were determined in each study using electronic scales (Seca 813, Hamburg, Germany) and a stadiometer (Seca 213, Hamburg, Germany), respectively. These measures were taken at the same time of day while swimmers were wearing their training costumes. The training records of each swimmer were kept by their respective swimming coaches, which were used to give a description of training time (i.e., hours·week^{-1}) and volume (i.e., km·week^{-1}) within each experimental chapter. This was cross-referenced with the swimmers individually, where they were also asked to self-report any additional training outside of the swimming environment (e.g., land-based or other sports). The swimmers' training status was also indicated in each chapter by displaying their mean World Aquatics (WA) points. These were presented for the swimmers' best swimming event in Chapters 3, 4, 5, and 7a, while the WA points for the swimming event that best represented the experimental exercise was displayed in Chapters 6, 7b, and 8. The use of WA points enables a comparison of swimming performance across different events, such that points closer to 1000 (the world-record) indicate a world-class performance (WA, 2023). The points are calculated using the following equation (Equation 1).

$$(1)\ \text{WA points} = 1000 \times (\text{world-record time (s)} / \text{swim time (s)})^3$$

2.2.2 Dietary Assessments

Dietary intakes were assessed using a mobile-based photographed food diary in line with previously validated methods in highly trained adolescent athletes from the UK (Costello et al., 2017). Each swimmer was requested to take two photographs of every food, fluid, and supplement item consumed over a 24-hour period; where the first image displayed the meal before it was started, and the second

showed the remaining food and fluids that had not been consumed. If the meal was consumed in its entirety, then a photograph was still requested as confirmation. To standardise food and fluid portions, swimmers were provided with a paper 1 x 1 cm grid placemat to include with each food photograph, whereas measurement shakers were used for poured fluids (Nyström et al., 2016). Photographs were sent immediately to the lead researcher in real-time using a picture messaging smartphone application (WhatsApp, Mountain View, CA, USA). Further details were also requested regarding the brand of product, cooking methods, and a clear description of the items in each meal using either text or voice recordings. For unsatisfactory contributions, swimmers were immediately contacted asking for further clarification. In Chapter 3, this process was completed across three days, including two training days and one rest day, as this process provides accurate estimations of habitual energy and macronutrient consumption (Burke, 2015). While longer duration food diaries are thought to increase the reliability of the collected data, this generally comes at the cost of greater participant burden and reduced compliance, and/or deliberate alterations in eating behaviour to simplify the recording process (Magkos & Yannakoulia, 2003). Chapters 6–8 only required this process to be completed during the familiarisation trial, to standardise energy and macronutrient consumption for all subsequent experimental trials.

All images and information collected as part of dietary assessments were inputted into dietary analysis software (Nutritics 3.06, Dublin, Ireland) for each swimmer by the lead researcher. Food items that were not available in the Nutritics database were manually inputted using information from the packaging label. This process gave a detailed description of the energy and macronutrient content of the food, fluid, and supplement items consumed, as well as further information regarding micronutrient intakes (e.g., calcium, iron, vitamin D), CHO and lipid components (e.g., fibre, saturated fats), and habitual CAF consumption. In Chapter 3, the mean intakes across the three-day collection window were used to estimate the swimmers' typical daily nutrition intakes as per previous recommendations (Costello et al., 2017). All nutrients were reported in absolute values, with energy, macronutrients, and CAF further presented relative to body mass to standardise intakes between

swimmers. A small pilot study showed that the lead researcher had an ‘excellent’ intra-rater reliability and validity for the analysis of energy and macronutrient intakes (see Chapter 3, section 3.2.3).

2.2.3 Supplement Questionnaire

In Chapter 4, the lead researcher conducted a short interview (~10–15 min) with swimmers based on the questions of a validated supplement intake questionnaire (Sanchez-Oliver, 2012), which has recently been used to assess the supplement intakes of swimmers from both pool (Moreno et al., 2022) and open water disciplines (Jiménez-Alfageme et al., 2022). The interview method was adapted from an online questionnaire due to its logistical ease in adolescent swimmers, as it enabled the researcher to instantly clarify questions and ask for more information if answers were unclear. The researcher also provided a comprehensive list of supplements and was able to explain each one in further detail to facilitate the recall of supplement intakes. Furthermore, some adolescents did not have access to their own mobile devices, therefore this method enabled swimmers to give honest answers without being influenced by parents/guardians or coaches. The questions asked were as follows: (a) what supplements have you consumed; (b) for what purpose did you consume that supplement; (c) who or where did you receive information about that supplement; (d) how frequently would that supplement be consumed; and (e) from where was that supplement purchased? Swimmers were asked to detail the supplements they consumed in the last 12 months as per previous research (Moreno et al., 2022; Shaw et al., 2016a).

2.2.4 Vitamin D Measurements

Blood spot cards were used to determine serum 25(OH)D concentrations in Chapter 5 due to their close agreement (r = 0.74–0.97), yet less invasive procedures compared to venepuncture methods (Binks et al., 2021; Heath et al., 2014; Man et al., 2019; Zakaria et al., 2020). The collection process required four fingertip capillary blood drops (~50–75 µL), which were spotted onto a filter paper at

four equally spaced targets to allow for radial dispersion. All blood collection occurred as the swimmers arrived at their normal swimming training, therefore cards were sealed and allowed to dry at room temperature for between 2–3 hours until the end of the training session. Samples were then posted to an independent laboratory (Sandwell & West Birmingham Hospitals NHS Trust, Birmingham, UK) where they were analysed by liquid chromatography-tandem mass spectrometry (LC-MS/MS) within 7–14 days. This process was completed twice per participant to identify any seasonal changes in vitamin D status. These were completed at mid-season training phases in the autumn (October) and winter (January).

2.2.5 Blood Metabolites

Capillary blood samples were conducted to provide physiological measures of exercise intensity (i.e., blood La^-, Chapters 6–8) and acid-base balance (Chapters 7a and 7b). Blood for these samples were drawn from the fingertip using a disposable lancing device (AccuCheck Safe-T-Pro, Indianapolis, USA). For the determination of blood La^- concentration, a 5 µL sample was collected into a Lactate Pro 2 device (Arkray, Kyoto, Japan) and analysed within 15 s. These devices have been shown to be valid and reliable for identifying blood La^- concentrations at rest, at La^- threshold, and during maximal intensity exercise when devices are used interchangeably (Bonaventura et al., 2015; Crotty et al., 2021). The determination of blood acid-base variables required the collection of 70 µL of blood into a sodium heparinized clinitube (Radiometer Medical, Denmark), which was then inserted into a blood gas analyser (ABL9, Radiometer Medical, Denmark) for the analysis of blood HCO_3^-, pH, and electrolyte (Na^+, K^+, Ca^{2+}, Cl^-) concentrations. The blood gas analyser used in this thesis has been found to be reliable for the above parameters and valid against other commercially available devices (Gough et al., 2017; Radiometer Medical, 2019; Stadlbauer et al., 2011). Together, this combined collection of blood La^- and electrolytes was used to calculate the apparent SID using a freely available spreadsheet (i.e., $K^+ + Na^+ + Ca^{2+} - Cl^- - La^-$; Lloyd, 2004). This method has displayed an ‘excellent’ correlation ($r = 0.98$) for predicted SID versus the observed SID in past research (Figge et al., 1991).

Furthermore, this method of calculating the apparent SID has been used in similar research that has investigated strong ion changes following $NaHCO_3$ ingestion (Gough et al., 2019a, 2019b).

2.2.6 Blood Pressure

An automated sphygmomanometer (Boso-Medicus Uno, Bosch & Sohn, Gerlingen, Germany) was used to collect three samples of systolic (SBP) and diastolic blood pressure (DBP) from the brachial artery in Chapter 8, based on the premise that CM could enhance blood flow and reduce blood pressure during exercise (Barkhidarian et al., 2019; Gough et al., 2021). The mean of three blood pressure readings was used as the physiological measures of SPB and DBP, with all three measurements taken immediately after one another due to the time sensitivity of results. This method was consistent with past research investigating blood pressure changes with NO (Vanhatalo et al., 2010) and L-citrulline supplements (Bailey et al., 2015).

2.3 Perceptual Measures

2.3.1 Ratings of Perceived Exertion

Ratings of perceived exertion (RPE) for the whole body were recorded as a subjective measure of effort using a CR10 Borg scale during all exercise trials (Chapters 6, 7b, 8), where 1 represented ‘no exertion’, and 10 represented ‘maximal exertion’ (Borg, 1998). This CR10 RPE scale was selected since this was routinely used to set exercise intensities in the swimmers’ normal swimming training.

2.3.2 Supplement Side-Effects

Since there was a possibility of adverse side-effects with the ingestion of CAF (Sökmen et al., 2008) and $NaHCO_3$ (Carr et al., 2011b), swimmers were asked to rate their subjective symptoms in Chapters

6, 7a, and 7b. These were measured using a visual analogue scale (VAS), with the scale anchored at each end of a 20 cm line with ‘no symptom’ on the left side and ‘severe symptom’ on the right side. This use of a VAS to quantify subjective side-effects, such as stomach discomfort and abdominal pain, has previously shown to be reliable (r = 0.98–0.99) in past research (Bahreini et al., 2015; Gallagher et al., 2002). In Chapters 7a and 7b, nine gastrointestinal symptoms were measured consistent with previous $NaHCO_3$ research (Cameron et al., 2010; Gough et al., 2017): nausea, flatulence, stomach cramping, belching, stomach ache, bowel urgency, diarrhoea, vomiting and stomach bloating. For Chapter 6, this scale was adapted to capture the subjective side-effects more commonly associated with CAF, including both physical (jitters, tachycardia, headache, stomach upset) and psychological symptoms (mood, alertness, tiredness, anxiety, arousal) (Sökmen et al., 2008). This approach was not used in Chapter 8 as there are currently no known side-effects following CM ingestion (Gough et al., 2021). Swimmers in this study were therefore asked document any physical or psychological symptoms throughout the investigation, in which none were reported.

Symptom severity was scored by swimmers by drawing a line between the two anchors on the VAS, which was then measured to the nearest millimetre and divided by 20 to give an arbitrary score out of 10 (e.g., 75 mm = 3.8 out of 10 rating). Scores closer to ‘0’ represented none or minor symptoms, whereas scores closer to ‘10’ suggested that symptoms were severe. Each experimental chapter describes the time intervals that each VAS was completed. In Chapter 6, CAF side-effects were calculated and reported at standardised time points for a direct comparison versus a PLA condition. In Chapters 7a and 7b, the most common and severe $NaHCO_3$ side-effects were reported due to the different ingestion timeframes between individuals. Furthermore, an aggregated score for gastrointestinal distress was also calculated and reported in Chapters 7a and 7b, such that the peak severity of all nine subjective side-effects were added together and reported. Swimmers were aware that they could voluntarily withdraw from studies at any time should they experience severe side-effects.

2.3.3 Subjective Sleep

Subjective sleep parameters were reported by swimmers in Chapter 6 to evaluate possible CAF effects. All swimmers were requested to follow their normal sleeping routines, environments, and timings throughout the investigation. Each morning upon waking, swimmers completed the Core Consensus Sleep Diary (CCSD), which is a validated tool for assessing self-reported sleep parameters (Carney et al., 2012; Maich et al., 2018). For logistical ease, the CCSD was adapted into a virtual questionnaire (Google Forms, Google, Mountain View, CA, USA) and distributed to swimmers through an instant messaging application (WhatsApp, Menlo Park, CA, USA). The questionnaire consisted of one 5-point Likert scale (1 = very poor, 5 = very good) for sleep quality, and six short-answer questions for sleep parameters: (a) what time did you physically get into bed; (b) what time did you intend to fall asleep; (c) what time did you think you actually fell asleep; (d) how long do you think you were awake in the night; (e) what time did you awake this morning; and (f) what time did you physically get out of bed? Moreover, this information was used to calculate the following variables: total sleep time; total time spent in bed; and sleep efficiency (i.e., total time in bed divided by total sleep time); in accordance with previous research in highly trained adolescent athletes (Ramírez et al., 2020). Answers to the questionnaires were followed up with swimmers while they prepared for experimental exercise to confirm the accuracy of the reported variables.

2.4 Exercise Protocols

2.4.1 Warm-Up

All swimmers completed a two-part warm-up prior to exercise, which were recorded and repeated for all subsequent trials in Chapters 6, 7b and 8. The first part of each warm-up took place poolside, where the swimmers self-prepared with land-based activity for 10–20 min. Though individual routines varied, warm-ups typically involved skipping (3–5 min), full body mobility (5–10 min), and bodyweight strength exercises (3–5 min). The swimmers then entered the swimming pool and

completed a 20–30 min warm-up that was prepared by the head swimming coach. Similarly, warm-ups varied between chapters, but typically involved ~1000 m of progressive intensity swimming.

2.4.2 Swimming Time-Trials

Swimming time-trials were used in this thesis to mimic a competition scenario, therefore measuring the effectiveness of acute CAF (Chapter 6) and $NaHCO_3$ (Chapter 7b) ingestion in practice. For Chapter 6, swimmers were to complete 100 m time-trials in their specialist strokes since this: (a) enabled a maximal effort to be given; and (b) did not logistically interfere with the swimmers' training for key competitions. The time-trial distance was selected based on previous research demonstrating that CAF enhanced the 100 m swimming performances of trained adolescents (Collomp et al., 1992). All time-trials were completed during an evening training session (7:00 PM) with a repeated bout completed the following morning (6:00 AM) in an attempt to mimic the time between evening finals and morning heats in competition. Chapter 7b involved the completion of a 200 m freestyle time-trial, which was selected as all participating swimmers in this chapter were proficient in the freestyle stroke. Moreover, maximal 200 m distance were within the exercise intensity and duration (~2 min) thought to benefit from $NaHCO_3$ ingestion (Grgic & Mikulic, 2022). Time-trials in this chapter were completed following an intermittent swimming protocol to measure the possible $NaHCO_3$ benefits on acid-base balance recovery. A 30 min active recovery window was selected consistent with Pruscino et al. (2008), who observed this recovery period to support a secondary 200 m freestyle performance following $NaHCO_3$ ingestion. To maximise competitiveness, all time-trials were performed in groups of 2–4 swimmers based upon their personal best times. All warm-ups, heats, and lanes were replicated for all time-trials. Swimming was timed by two experienced swimming coaches and the mean of both times was used as the performance measure. All time-trials were conducted between January and July as part 'speed' training within the specific preparatory period (Table 2.1).

2.4.3 Repeated Swimming Bouts

Repeated swimming bouts were used to induce the physiological states that were thought to benefit from $NaHCO_3$ (Chapter 7b) and CM (Chapter 8) ingestion. In Chapter 7b, all swimmers completed 6 x 75 m maximal swimming efforts in their specialist stroke, with each swimming bout occurring at 150 s intervals (~40–60 s exercise, ~90–110 s passive recovery). This was similar to previous swimming tests where $NaHCO_3$ has showed ergogenic potential (Gao et al., 1988; Gough et al., 2023). This swimming test was incorporated into the 'speed' training of the highly trained swimmers between April and July, as part of their specific preparatory training cycle (Table 2.2). For Chapter 8, all swimmers completed a 6 x 300 m freestyle swimming test where each exercise bout commenced at 4.5 min intervals (~3.5 min exercise, ~1 min passive recovery). This aerobic swimming test was utilised within the general preparatory training phase between September and December (Table 2.1). As both these swimming tests were commonly used in the investigated swimming club, previous data was analysed that showed that the current cohorts had an 'excellent' reproducibility of their performances (see sections 7a.2.5 and 8.2.4, respectively). Mean swimming times, the aggregated time to complete all swimming bouts, and the time to complete each individual swimming bout were analysed for performance effects. All swimming lanes were also kept consistent for each swimming test, and the mean of two swimming times recorded by experienced coaches were used as the performance measures.

2.4.4 Ingestion of Experimental and Placebo Supplements

Supplements in Chapter 6 were administered in a single hydroxypropyl methylcellulose capsule (size 00, Bulk Powders, Colchester, UK), consisting of either 3 mg·kg BM^{-1} CAF (anhydrous powder, Bulk Powders, Colchester, UK) or a visually matched PLA (cornflour, ASDA, Leeds, UK). Capsules were created and randomised by a sport and exercise technician to maintain the double-blind status. All capsules were administered to swimmers by the lead researcher 60 min prior to exercise in accordance with recommended dosing strategies (Maughan et al., 2018).

In Chapters 7a and 7b, the swimmers' personal blood HCO_3^- kinetics were monitored to provide a personalised ingestion strategy. All swimmers were requested to consume their normal 'pre-competition' meal 30–60 min prior to ingesting 0.3 g·kg BM^{-1} $NaHCO_3$ (bicarbonate of soda, Dr. Oetker, Bielefeld, Germany), which were administered in gelatine capsules in Chapter 7a (Size 0, Bulk Powders, Colchester, UK), and hydroxypropyl methylcellulose capsules in Chapter 7b (size 00, Bulk Powders, Colchester, UK), due to the capsule availability at those times. The dietary and capsule ingestion methods were chosen firstly, to replicate the gastrointestinal conditions that would be present when $NaHCO_3$ is ingested in practice (Remer & Manz, 1995); and secondly, to reduce the possibility of the swimmers experiencing severe gastrointestinal side-effects (Carr et al., 2011b). Chapter 7a describes the methods used to determine individualised time to peak HCO_3^-. In Chapter 7b, this process was used to inform individualised $NaHCO_3$ strategies based on the time each swimmer demonstrated a peak blood HCO_3^- concentration, whereas the standardised strategy involved ingesting $NaHCO_3$ 150 min before exercise based on group mean blood HCO_3^- peaks with capsule ingestion (Carr et al., 2011b; Jones et al., 2016). A PLA supplement that was matched for Na^+ content (0.21 g·kg BM^{-1} sodium chloride, ASDA, Leeds, UK) and capsule volume (added cornflour, ASDA, Leeds, UK) was ingested 90 min pre-exercise. Swimmers were not aware of their individual $NaHCO_3$ timings and were told the study was investigating the effects of three different $NaHCO_3$ timings to maintain their single-blind status.

For Chapter 8, an experimental solution of 15 g CM (100% CM, Myprotein, Manchester, UK) in 100 mL orange cordial (Sainsbury's, London, UK) and 300 mL water was ingested 60 min before exercise. The supplement ingestion timing was in accordance with previous research (Gough et al., 2021); however, a larger CM dose was used (vs. the typical 8–12 g) since this strategy elicits greater plasma L-citrulline responses without any adverse side-effects (Moinard et al., 2008). A PLA supplement consisting of 400 mL orange cordial (Sainsbury's, London, UK) was also ingested, which was consistent with previously used protocols (Cunniffe et al., 2016). None of the swimmers had any

prior experience of consuming CM supplements. All drinks were created and randomised by a sport and exercise technician and were administered to swimmers in opaque sports bottles to ensure blinding from the researcher and swimmers.

2.4.5 Supplement Belief

A supplement belief questionnaire was administered in Chapters 6, 7b, and 8 to confirm that the swimmers were successfully blinded of supplement condition. At the end of each experimental trial, swimmers were asked how confidently they could determine their supplement condition using a 1-5 Likert scale, with 1 representing 'not confident at all', and 5 representing 'extremely confident'. If participants scored above a three, they were then asked which supplement they perceived they had ingested.

2.5 General Statistical Procedures

2.5.1 Prior Statistical Tests

A priori power calculations were used to determine appropriate sample sizes in each chapter using a difference in means approach (G*Power, v.3.1.9.4, Universität Düsseldorf, Germany). The input parameters and recommended sample sizes are presented in each experimental chapter.

2.5.2 Differences Procedure

All data were analysed for normality and homogeneity of variance/sphericity using Shapiro-Wilk and Mauchly tests, respectively. If data was normally distributed then parametric tests were completed, either through conducting t-tests (two groups) or repeated measures analysis of variance (ANOVA) tests (three groups). If sphericity was violated, then degrees of freedom and *p* values were adjusted using the appropriate Huyn-Feldt (epsilon value >0.75) or Greenhouse-Geiser (epsilon value <0.75)

corrections. A violation was identified if a statistical value of $p < 0.05$ was identified in Mauchly tests. Where main effects or interactions were observed, partial eta squared ($P\eta^2$) effect sizes were reported and post hoc pairwise comparisons were determined via the Bonferroni correction. Effect sizes for $P\eta^2$ were interpreted as 'small' (0.01–0.05), 'moderate' (0.06–0.13), and 'large' (≥0.14) (Cohen, 1988). Effect sizes for pairwise comparisons were calculated using the Hedge's *g* bias correction, which accounted for the bias in Cohen's *d* with small ($n < 20$) participant samples (Lakens, 2013). These effect sizes (*g*) were considered to be 'trivial' (≤0.19), 'small' (0.20–0.49), 'moderate' (0.50–0.79), or 'large' (≥0.80), in accordance with Cohen's *d* interpretations (Cohen, 1988). If data normality was violated, appropriate non-parametric tests were used. In Chapter 4, this entailed the use of Kruskal-Wallis tests to analyse group level differences between three training groups, whereas Mann-Whitney U tests were used to analyse pairwise comparisons. All data are presented as mean ± SD, and statistical significance was set at $p < 0.05$ for all statistical tests (SPSS, v.25, IBM, Chicago, IL, USA).

For supplemental effects, a SWC in exercise tests was calculated by either multiplying the SD of the PLA group (Chapters 5 and 6) or a prior data set (Chapters 7b and 8) by 0.2, in accordance with Bernards et al. (2017). The SWC was used to give additional information regarding individual responses to supplementation (positive or negative), as such important, yet small, individual changes can often be masked by group mean changes (Bernards et al., 2017).

In Chapter 4, an interview technique was used to collect questionnaire data as outlined in section 2.2.4. These questions were asked to three groups of swimmers (national, age-group, and development), with the frequency distribution of answers compared between groups using Pearson's Chi-Square (χ^2) tests. These data are presented in the thesis as percentages, with Cramer's *V* effect sizes calculated between the differences in frequency distributions. Cramer's *V* effect sizes were interpreted as 'trivial' (≤0.04), 'weak' (0.05–0.09), 'moderate' (0.10–0.14), 'strong' (0.15–0.24), and 'very strong' (≥0.25) (Akoglu, 2018). These statistical tests were carried out in SPSS (v.25, IBM, Chicago, IL, USA).

2.5.3 Reliability Procedures

Throughout the thesis, intraclass correlation coefficient (ICC) analyses were used to determine the test-retest reliability of exercise protocols (Chapters 6–8) and intra-rater reliability of food diary analyses (Chapter 3). The protocols that were used were in accordance with previous guidelines (Hallgren, 2012; Koo & Li, 2016), such that a two-way mixed effects model for absolute agreement was employed to measure test-retest reliability, whereas a two-way mixed effects model for consistency was used to measure intra-rater reliability. Significance value (*p*) and *r* value are reported, with the latter interpreted as 'poor' (≤0.49), 'moderate' (0.50–0.74), 'good' (0.75–0.89), or 'excellent' (≥0.90) (Koo & Li, 2016). The ICC method for assessing reliability is considered to be stronger than Bland-Altman plots and Pearson's correlation coefficient since it reflects both correlation and agreement between measurements (Koo & Li, 2016). In addition to these statistics, coefficient of variation (CV) was also calculated and reported to show inter-individual differences in each chapter. This was performed by dividing the SD of the data by the mean and multiplying by 100 (Atkinson & Nevill, 1998).

2.5.4 Missing Data

On rare occasions, either through equipment or operator error, hot deck imputation was used to estimate the missing values of electrolyte data (Chapters 7a and 7b). This was considered a valid approach when only 1–5% of data is missing in experiments (Myers, 2011), and prevented the listwise deletion of complete participant data sets. Missing values were estimated using observations from similar swimmers, or where possible, from previous observations in the same swimmer in accordance with previously used protocols (Schafer & Graham, 2002).

Chapter 3 – Nutritional Intakes of Highly Trained Adolescent Swimmers Before, During, and After a Lockdown During the COVID-19 Pandemic

Chapter can be found at: Newbury, J.W., Foo, W.L., Cole, M., Kelly, A.L., Chessor, R.J., Sparks, S.A., Faghy, M.A., Gough, H.C. and Gough, L.A. (2022). Nutritional intakes of highly trained adolescent swimmers before, during, and after a national lockdown in the COVID-19 pandemic. *PLoS One*, 17(4), pp.e0266238. Available at: https://doi.org/10.1371/journal.pone.0266238.

3.1 Introduction

In late 2019, a novel strain of coronavirus (SARS-CoV-2) was identified that was responsible for the disease known as COVID-19, which has potential to cause severe respiratory distress in infected individuals (Zu et al., 2020). In January 2020, COVID-19 spread rapidly through infected aerosols and droplets produced when coughing, speaking, and breathing (Samet et al., 2021); leading to 763 million cases and 6.9 million deaths worldwide as of April 2023 (World Health Organisation, 2023). To reduce the spread, the UK Government imposed strict social distancing rules effective between March 2020 and May 2021, including three national lockdowns (March to July 2020, November to December 2020, January to April 2021) that each prohibited non-essential travel and activities (Institute for Government, 2022). Such measures forced all sporting competitions at the local (e.g., school sports), national (e.g., British Championships), and international levels (e.g., Olympic Games) to be either cancelled or postponed, whereas the closure of all schools and leisure centres meant most adolescent athletes did not have access to training facilities (Kelly et al., 2020). This particularly affected highly trained swimming populations whose large pool-based training volumes were unable to be replicated or substituted when at home in isolation (Haddad et al., 2021).

The large-scale disruptions to training caused by COVID-19 were likely to have affected the health and performances of highly trained swimmers, given that national- and international-level swimmers typically engage in 8–10 weekly pool training sessions, swimming approximately 40–60 km·week^{-1} (Pollock et al., 2019; Shaw et al., 2014; Trindade et al., 2017). Moreover, most swimmers will also engage in 3–5 weekly strength and conditioning sessions, often cumulating in a total training time exceeding 20 hours·week^{-1} (Pollock et al., 2019; Simič & Mohorko, 2018). During lockdowns, however, access to equipment and pool facilities were restricted, limiting the quality and quantity of training sessions. Indeed, athletes reported that their average lockdown training routines largely consisted of land-based cardiovascular and bodyweight strength exercises, which were only completed at moderate intensities for 30–60 min·day^{-1} (Pillay et al., 2020). While this reported

training information was not specific to swimmers as such, it is likely that swimmers followed these practices given their limited training options. It was therefore expected that swimmers would engage in largely reduced training loads compared to normal, and thus declines in muscle mass and technical conditioning were expected when lockdown conditions lasted for longer than 2–4 weeks (Jukic et al., 2020). In addition, a reduction in training hours would have certainly lowered DEE, possibly resulting in body fat accretion if DEI was not altered to match the new training demands (Alméras et al., 1997; Mujika et al., 2014). Considering that decreases in muscle mass and increases in body fat mass could negatively affect swimming performance (Dopsaj et al., 2020), it was critical that highly trained adolescent swimmers could quickly and appropriately adjust their nutritional intakes throughout the COVID-19 pandemic.

There is currently no evidence to suggest how swimmers adapt their nutrition in response to a lockdown situation, though examples from other sports have been reported. In elite paracyclists, no changes in the energy, macronutrient, or micronutrient intakes were observed during lockdown, despite the athletes reporting an increased sedentary behaviour (e.g., screen time) (Shaw et al., 2021). Nonetheless, these athletes were able to maintain their normal training volume and intensity despite home confinement, therefore large alterations in dietary intakes may not have been required. In rugby players, however, a reduced weekly number of training sessions was reported, which were completed with less intensity and motivation (Roberts et al., 2020). These athletes also reported consuming wither the same or greater energy intakes alongside inadequate amounts of daily protein (<1.5 g·kg BM·day^{-1}), though the implications of these actions were unclear since no measures of body mass and/or composition were reported. Furthermore, these observations took place within adult rugby players in New Zealand, where strict lockdowns were imposed for a much shorter duration (March to May 2020, August to September 2021) than in the UK (New Zealand Government, 2022). As such, the consequences of nutrition on body composition and performance in these populations cannot be compared to that of highly trained adolescent swimmers from the UK, who were unable to train normally for over four months.

Previous research suggests that swimmers do not alter their nutritional intakes in response to new training demands (Shaw et al., 2014); though, whether this is due to poor dietary habits or inaccurate dietary reporting is currently unclear (see Chapter 1, section 1.1.1). During lockdowns, however, young swimmers may have been faced with greater psychological stress than in previous observations, particularly around performance and body composition, that may have led to: (a) the development of restrictive/surplus dietary practices; (b) a tendency to consume poor quality foods; (c) unfavourable eating patterns (i.e., skipping breakfast, late meals); and/or (d) increased sedentary attitudes towards exercise (Chandler et al., 2021; di Cagno et al., 2020; Fitzgerald et al., 2021; Pillay et al., 2020). Therefore, where previous research suggests that swimmers would not adjust their DEI in response to the reduced training loads, this could not be confirmed under the pressures of COVID-19. Moreover, even if dietary changes were made during lockdown, it was not clear whether swimmers would retain the capacity to spontaneously increase DEI upon the return to sport (Roberts et al., 2020). Hence, to provide an updated perspective on whether highly trained adolescent swimmers can consume an adequate DEI to support their health and performance, the purpose of this study was to retrospectively analyse nutrition intakes on three occasions: (a) before the first COVID-19 lockdown (January 2020); (b) during the first national lockdown in the UK (April 2020); and (c) after the first UK lockdown regulations had eased (September 2020).

3.2 Methods

3.2.1 Participants

This research took place in a UK-based, high-performance swimming club, where 26 highly trained national and age-group swimmers (see Chapter 2, section 2.1.2) completed food diaries before and during the initial wave of the COVID-19 pandemic as part of their sport nutrition support (see Chapter 2, section 2.1.4). Based on the use of retrospective data, 10 swimmers were excluded from data analysis for providing unsatisfactory food diary contributions. A further three swimmers ended their

competitive swimming careers during the COVID-19 pandemic, and therefore did not complete a final food diary assessment. Resultantly, the food diaries of 13 highly trained adolescent swimmers were analysed for this study (Table 3.1). An a priori power calculation with input parameters of α = 0.05, ß = 0.80, and correspondence between measures = 0.3, determined this sample size appropriate for detecting medium effect sizes (0.50) in within factors repeated measures ANOVA tests (one group, three measures) with a power of 81% (G*Power, v.3.1.9.4, Universität Düsseldorf, Germany). At the time of the study, seven swimmers (54%) were ranked in the top 10 in the UK within their respective age groups for at least one event, while six (46%) were of the few invited to trial for Great Britain Olympic team for the delayed 2021 Games. Ethical approval was granted by BCU (Newbury/7594/R(B)/2020/Aug/HELS FAEC) and both swimmers and their parents/guardians provided written informed consent prior to their data being used for research purposes.

Table 3.1. Characteristics of the study participants.

	Combined (*n* = 13)	**Male (*n* = 5)**	**Female (*n* = 8)**
Age (years)	15 ± 1	15 ± 2	16 ± 1
Body mass (kg)	58.4 ± 8.5	55.6 ± 12.2	60.2 ± 5.5
Height (m)	1.66 ± 0.09	1.67 ± 0.02	1.66 ± 0.07
Time competitive (years)	5.6 ± 1.6	4.8 ± 1.8	6.3 ± 1.0

Mean ± SD.

3.2.2 Protocol and Measurements

All swimmers completed three-day, mobile-based photograph assessment food diaries in accordance with the previously described methods (Chapter 2, section 2.2.2). Briefly, this involved swimmers sending two photographs to the lead researcher using a picture messaging smartphone application (WhatsApp, Mountain View, CA, USA) every time a food, drink, or supplement was consumed; the first of which displayed a clear image of the meal/snack prior to consumption, and the second showing the remains of the meal once the meal/snack was finished. All swimmers completed a

‘before lockdown’ food diary while they were completing normal training in preparation for national competitions (January 2020). A second food diary was collected in April 2020 to assess the swimmers' nutritional intakes ‘during lockdown’. The final food diary was collected ‘after lockdown’ in September 2020, approximately one month following the return to sport. The 10 swimmers who were excluded from data analyses either did not provide a full three-day food diary or only provided written food diaries with poor details; thus, their nutritional profiles could not be adequately compared in this research.

To assess the adequacy of the swimmers’ nutritional intakes, their dietary information was compared to the general in-season nutrition recommendations for highly trained swimmers (i.e., Chapter 1, section 1.2). As such, the following energy and macronutrient guidelines were deemed appropriate for the purpose of this research; energy: 35–75 kcal·kg BM^{-1}·day^{-1}; CHO: 3–8 g·kg BM^{-1}·day^{-1}; protein: 1.5–2 g·kg BM^{-1}·day^{-1}; fat: 1–2 g·kg BM^{-1}·day^{-1}. All micronutrient intakes were compared against the current UK RNIs for adolescents (aged 15–18 years), which are later presented in Tables 3.4 and 3.5, respectively (British Nutrition Foundation, 2021).

3.2.3 Nutritional Information

The details of all food, fluid, and supplements consumed by each swimmer were inputted into an online dietary analysis software (Nutritics 3.06, Dublin, Ireland) by the lead researcher, as per the previously described methods (see Chapter 2, section 2.2.2). This provided information regarding the energy and macronutrient content of each food and drink item consumed, as well as further details on the CHO (e.g., sugar, fibre) and lipid components (e.g., omega-3 fatty acids, saturated fat), vitamins, minerals, trace elements, and CAF intakes. The mean intakes from across the three days were reported, as this approach provides accurate estimations of habitual energy and macronutrient consumption (Costello et al., 2017; Magkos & Yannakoulia, 2003). All nutrients were reported in

absolute values, with energy, macronutrients, and CAF intakes further presented relative to body mass.

A small pilot study was conducted to assess the sensitivity of the analysis, which involved the lead researcher analysing eight meals with a known energy and macronutrient content on two separate occasions. Additionally, one of the 600 kcal meals was repeatedly analysed on 20 separate occasions. These data were used to determine the intra-rater reliability and the validity of the assessment method for the lead researcher. Intra-rater reliability was assessed using CV and was determined to be 2.7%, 4.8%, 3.9% and 1.2% for energy (kcal), CHO (g), protein (g) and fat (g), respectively. The validity of the analysis method was assessed using an ICC and the CV of error, which were considered to be 'excellent' for energy (r = 0.947, p <0.001, CV = 2.0%), CHO (r = 0.972, p <0.001, CV = 3.5%), protein (r = 0.914, p <0.001, CV = 6.4%) and fat (r = 0.977, p <0.001, CV = 1.0%) (Atkinson & Nevill, 1998; Koo & Li, 2016).

3.2.4 Anthropometric Data

Body mass and height were determined using electronic scales and a stadiometer before and after lockdown (see Chapter 2, section 2.2.1). During lockdown, however, swimmers provided their body mass remotely using their own home-based electronic scales. To standardise measures, these were requested after breakfast whilst wearing underwear. The use of varying scales at this time likely reduced the accuracy of the measure (Drost, 2011), though this was unavoidable given the restrictions. Height was not measured during lockdown since all swimmers did not have access to a stadiometer at home. Repeat body mass and height measures were collected after lockdown for all swimmers in accordance with the UK Government's close contact guidelines (DCMS, 2020).

3.2.5 Training Information

Weekly swimming volume (i.e., km·week^{-1}) was collected for each participant via communication with the head swimming coach, who kept records of all swimming training sessions before and after lockdown. During lockdown, some swimmers were able to complete swimming volume in open water (n = 6) or private swimming facilities (n = 2), in which the swimming coach recommended training intensities and volumes. Actual swimming volumes were self-reported following the session. Weekly training time (hours·week^{-1}) accounted for the total hours spent in pool and land-based exercise each week. Before lockdown, training consisted of between 5–8 pool (1.5–2.5 hours) and 2–6 gym-based (40–60 min) sessions·week^{-1} dependant on training age and specialist race distances. After lockdown, training consisted of between 5–7 pool (1–1.5 hours) and 2–3 gym-based (60 min) sessions·week^{-1}. The swimmers were asked to self-report additional exercise outside of these scheduled sessions during food diary collection. During lockdown, training was self-governed by the swimmers based upon recommendations made by coaches and support staff.

3.2.6 Nutrition Support

All participants completed three-day food diaries as part of their ongoing sport nutrition support (see Chapter 2, section 2.1.4). The obtained information was used to provide each swimmer with individual feedback and nutrition interventions, whereas group trends were used as topics for classroom-based education sessions (varying topics, 30 min, weekly). The level and frequency of individual support was determined by the swimmer's engagement. In immediate response to the lockdown, electronic resources (PDF files) were created and sent to swimmers and parents/guardians (WhatsApp, Mountain View, CA, USA) on ad hoc basis throughout March and April. These mostly included topics centred around training from home, muscle retention, spontaneous energy reduction, and improving immunity. The April food diary was requested to monitor adherence to the resources and identify possible nutritional interventions. Each swimmer and their parents/guardians received a phone or video call (WhatsApp) from the lead researcher to discuss their results, with the option of

weekly check-ins. Similarly, this support was determined by the swimmers' engagement with the service. From April until June, all swimmers had access to two weekly group nutrition activities (cooking workshop, nutrition quiz) using an online meeting platform (Zoom, San Jose, CA, USA). Attendance at these activities was not monitored. All online group activities ceased in July as swimmers resumed formal training. The weekly check-in option remained in place since face-to-face contact was not prohibited. Resources for pre-, intra-, and post-training nutrition (e.g., meal composition, nutrient timing, hydration) were sent to swimmers and parents/guardians to facilitate the return to sport throughout August 2020.

3.2.7 Statistical Analysis

All statistical tests were completed in accordance with Chapter 2 (section 2.5.2). A one-way ANOVA was used to establish mean differences for all nutrition intake variables and body mass at the three sampling time points (before, during, and after lockdown). A paired samples t-test was used to determine differences in height before and after lockdown. Effect sizes for each ANOVA were reported as $P\eta^2$ and pairwise effect sizes were reported as *g* (see Chapter 2, section 2.5.2 for interpretations). Inter-individual variability in each measure was also shown using CV. Statistics for the pilot tests utilised a two-way mixed effects ICC for reliability analysis (type: consistency) and are reported with *r* value and significance level (*p* value) as per previous recommendations (Atkinson & Nevill, 1988). All data are reported as mean ± SD, and statistical significance was set at $p < 0.05$.

3.3 Results

3.3.1 Training Characteristics

The COVID-19 pandemic caused significant disruptions to swimming volume ($F = 139.8$, $p < 0.001$, $P\eta^2 = 0.92$), with a 91% reduction observed from before (43.3 ± 11.7 km·week^{-1}) to during lockdown

(4.1 ± 5.8 km·week^{-1}; p <0.001, g = 4.11). After lockdown, swimming volume did not fully return compared to before lockdown (33.5 ± 7.0 km·week^{-1}; p <0.001, g = 0.98). The same pattern was also observed for training time (F = 187.8, p <0.001, Pη^2 = 0.94), as swimmers reduced their weekly training duration by 70% during lockdown (19.1 ± 2.2 vs. 5.7 ± 2.5 h·week^{-1}, p <0.001, g = 5.51), whereas a full return of total training hours did not occur after lockdown compared to before lockdown (15.0 ± 1.4 hours·week^{-1}; p <0.001, g = 2.15).

3.3.2 Anthropometric Changes

Body mass increased over the study timeframe (F = 30.9, p <0.001, Pη^2 = 0.72), although this change did not occur from before (58.4 ± 8.5 kg) to during lockdown (59.0 ± 8.6 kg; p = 0.254, g = 0.07). After lockdown, however, body mass was increased (62.7 ± 9.4 kg) compared to both before and during lockdown time points (both p <0.001, g = 0.46 and 0.40, respectively). Height was also increased from before to after lockdown (1.66 ± 0.09 vs. 1.69 ± 0.08 m, p = 0.002, g = 0.27).

3.3.3 Energy and Macronutrients

Changes in absolute and relative intakes of energy, CHO, protein, and fat were observed over the study timeframe (Table 3.2). The most prominent of these changes occurred during lockdown, where large reductions in energy (-14.2 ± 8.2 kcal·kg BM^{-1}·day^{-1}, p <0.001, g = 1.56), CHO (-1.9 ± 1.1 g·kg BM^{-1}·day^{-1}, p <0.001, g = 1.60), protein (-0.6 ± 0.5 g·kg BM^{-1}·day^{-1}, p = 0.002, g = 1.45), and fat (-0.5 ± 0.4 g·kg BM^{-1}·day^{-1}, p = 0.011, g = 1.37) were all reported compared the intakes before lockdown. After lockdown, energy (-12.9 ± 10.5 kcal·kg BM^{-1}·day^{-1}, p = 0.003, g = 1.23), CHO (+1.9 ± 1.1 g·kg BM^{-1}·day^{-1}, p <0.001, g = 1.46), and protein (+0.4 ± 0.6 g·kg BM^{-1}·day^{-1}, p = 0.002, g = 1.45) intakes all increased again compared to during lockdown, with swimmers reporting the same intakes as before lockdown (all p >0.05). Fat intakes reported during lockdown were not statistically significant to those reported after lockdown (+0.4 ± 0.6 g·kg BM^{-1}·day^{-1}), although a large effect size was calculated

between time points (p = 0.106, g = 0.82). The lack of statistical significance was likely caused by an increased inter-individual variance in relative fat intakes at this time (CV = 36%, eight increased, four maintained, one decreased), which was more variable than observed in CHO (CV = 27%, 13 increased) and protein (CV = 28%, 11 increased, two decreased).

Table 3.2. Energy and macronutrient intakes reported by highly trained adolescent swimmers before, during, and after a national lockdown during the COVID-19 pandemic.

Nutrition Variable	Lockdown Period			Interaction effect
	Before	During	After	
Energy				
Absolute (kcal·day^{-1})	2606 ± 507	1796 ± 338*	2712 ± 718$^{\#}$	F = 17.5, p <0.001, Pη^2 = 0.60
Relative (kcal·kg BM $^{-1}$·day^{-1})	46 ± 10	31 ± 8*	44 ± 12$^{\#}$	F = 17.9, p <0.001, Pη^2 = 0.60
CHO				
Absolute (g·day^{-1})	311 ± 68	200 ± 41*	330 ± 77$^{\#}$	F = 26.4, p <0.001, Pη^2 = 0.70
Relative (g·kg BM $^{-1}$·day^{-1})	5.4 ± 1.2	3.5 ± 1.1*	5.4 ± 1.4$^{\#}$	F = 27.5, p <0.001, Pη^2 = 0.70
Protein				
Absolute (g·day^{-1})	135 ± 26	99 ± 24*	132 ± 38$^{\#}$	F = 8.3, p = 0.002, Pη^2 = 0.41
Relative (g·kg BM $^{-1}$·day^{-1})	2.3 ± 0.4	1.7 ± 0.4*	2.1 ± 0.6$^{\#}$	F = 8.4, p = 0.002, Pη^2 = 0.41
Fat				
Absolute (g·day^{-1})	92 ± 22	67 ± 18*	95 ± 34	F = 6.2, p = 0.007, Pη^2 = 0.34
Relative (g·kg BM $^{-1}$·day^{-1})	1.6 ± 0.4	1.1 ± 0.3*	1.5 ± 0.6	F = 5.7, p = 0.009, Pη^2 = 0.32

* = different to before lockdown (p <0.05); $^{\#}$ = different to after lockdown (p <0.05).

Though all energy and macronutrient intakes were similar at the before and after lockdown time points, the inter-individual variance within each measure was increased after lockdown (CV before vs. after lockdown, energy = +6%; CHO: +5%; protein: +9%; fat: +8%; Figure 3.1). Subsequently, the number of individual swimmers who reported consuming less than the recommended protein and fat intakes was increased after lockdown (protein: +8%, fat: +15%). The same number of swimmers reported consuming <35 kcal·kg BM^{-1}·day^{-1} energy at the before and after lockdown time points (23%), although these swimmers' relative intakes were further from the recommendations after lockdown (before: 33.5, 34.5, and 34.8 kcal·kg BM^{-1}·day^{-1} vs. after: 25.3, 29.0 and 34.0 kcal·kg BM^{-}

^{1}·day^{-1}). In contrast, more swimmers reported consuming protein within the 1.5–2 g·kg BM^{-1}·day^{-1} range after lockdown (before: 31%, after: 54%), compared to most swimmers over-consuming protein at the before lockdown time point (before: 69%, after: 30%).

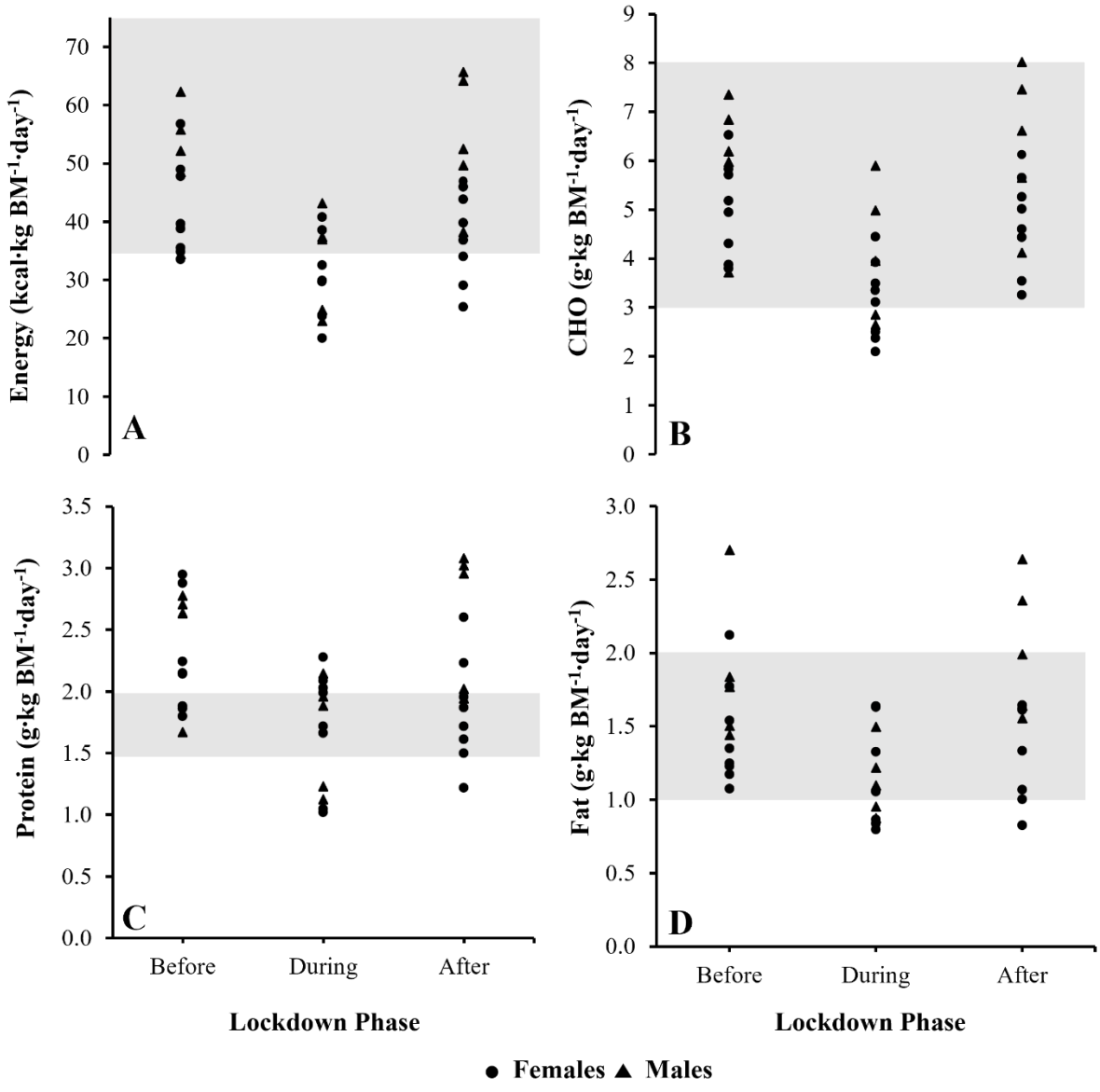

Figure 3.1. The relative A) energy, B) CHO, C) protein, and D) fat intakes reported by individual swimmer before, during, and after a national lockdown during the COVID-19 pandemic. Grey shaded areas represent the recommended energy and macronutrient intakes for swimmers (Mujika et al., 2014; Stellingwerff et al., 2011).

3.3.4 Carbohydrate and Lipid Components

Changes in dietary fibre, sugar, and monounsaturated fat intakes were identified across the study timeframe (Table 3.3). Before lockdown, 92% of swimmers reported consuming the UK RNI for dietary fibre (25 g). During lockdown, however, there was a large reduction in fibre intake ($p = 0.001$, $g = 1.87$), resulting in only 23% of swimmers meeting the UK RNI. While there was no difference in mean fibre intakes between the before and after lockdown time points ($p = 1.000$, $g = 0.16$), only 69% of the cohort reported consuming the UK RNI after lockdown. A 37% reduction in sugar intake also occurred from before to during lockdown ($p = 0.038$, $g = 0.88$), though there was no difference between sugar intakes before and after lockdown ($p = 0.223$, $g = 0.41$). All swimmers exceeded the UK RNI for sugar intake (≤5% of DEI) before (18 ± 6% of DEI), during (16 ± 6% of DEI) and after lockdown (21 ± 6% of DEI). Swimmers also reported consuming 28% less monounsaturated fat after lockdown compared to before lockdown ($p = 0.005$, $g = 0.85$). A large effect size was also calculated for a similar decline in monounsaturated fat intake during lockdown, although this change did not reach statistical significance ($p = 0.068$, $g = 1.12$). Reported saturated fat intakes were close to the UK RNI (≤11% of DEI) at all three time points (before: 11 ± 2%, during: 12 ± 3%, after: 11 ± 2% of DEI). No other CHO or lipid component changed considerably over the study timeframe.

Table 3.3. Carbohydrate and lipid components recorded in the diets of highly trained adolescent swimmers before, during, and after a national lockdown during the COVID-19 pandemic.

Nutrient	Lockdown Period			Interaction Effect
	Before	During	After	
Fibre (g·day^{-1})	29.7 ± 4.3	20.7 ± 5.0*	30.8 ± 8.1$^{\#}$	F = 13.4, p <0.001, Pη^2 = 0.53
Sugar (g·day^{-1})	118 ± 57	75 ± 36*	139 ± 41$^{\#}$	F = 12.6, p <0.001, Pη^2 = 0.51
Saturated Fat (g·day^{-1})	32.3 ± 8.9	24.8 ± 8.3	33.3 ± 12.9	F = 2.9, p = 0.069, Pη^2 = 0.20
Monounsaturated Fat (g·day^{-1})	28.6 ± 9.7	20.6 ± 6.1	20.5 ± 8.8$^{\#}$	F = 5.8, p = 0.009, Pη^2 = 0.33
Polyunsaturated Fat (g·day^{-1})	12.1 ± 4.2	9.6 ± 3.6	9.8 ± 3.3	F = 2.8, p = 0.081, Pη^2 = 0.19
Omega-3 Fatty Acid (g·day^{-1})	2.0 ±1.2	1.7 ± 1.5	2.1 ± 0.9	F = 0.4, p = 0.650, Pη^2 = 0.04
Omega-6 Fatty Acid (g·day^{-1})	6.7 ± 2.6	5.2 ± 2.6	6.1 ± 3.4	F = 1.2, p = 0.327, Pη^2 = 0.10
Trans Fat (g·day^{-1})	1.0 ± 0.4	0.9 ± 0.5	0.8 ± 0.4	F = 0.6, p = 0.564, Pη^2 = 0.05
Cholesterol (mg·day^{-1})	369 ± 145	268 ± 105	313 ± 247	F = 1.8, p = 0.195, Pη^2 = 0.13

* = different to before lockdown (p <0.05), $^{\#}$ = different to during lockdown (p <0.05).

3.3.5 Minerals and Trace Elements

Swimmers reported a reduced intake in seven of the 12 measured minerals and trace elements during the lockdown period, with sodium (p = 0.010, g = 1.32) potassium (p = 0.030, g = 1.14), chloride (p = 0.010, g = 1.39), calcium (p = 0.009, g = 0.99), phosphorus (p = 0.002, g = 1.34), iron (p = 0.004, g = 1.33), and selenium (p = 0.007, g = 1.00) all decreasing compared to before lockdown (Table 3.4). After lockdown, swimmers increased their sodium (p = 0.036, g = 1.05), chloride (p = 0.009, g = 1.36), and calcium (p = 0.027, g = 0.80) intakes compared to during lockdown. In contrast, the intakes of phosphorus (p = 0.956, g = 0.39) and selenium (p = 0.947, g = 0.31) did not increase again after lockdown. The increase in potassium and iron intakes from during lockdown to after lockdown did not reach statistical significance, although moderate (p = 0.445, g = 0.51) and large (p = 0.071, g = 0.91) effect sizes were calculated for these changes, respectively.

Table 3.4. Minerals and trace elements reported in the diets of highly trained adolescent swimmers before, during, and after a national lockdown during the COVID-19 pandemic.

Nutrient	UK RNI	Lockdown Period			Interaction effect
		Before	During	After	
Sodium (mg·day^{-1})	M: 1600 F: 1600	2754 ± 822	1784 ± 587*	2848 ± 1256$^{\#}$	F = 7.7, p = 0.003, Pη^2 = 0.39
Potassium (mg·day^{-1})	M: 3500 F: 3500	3471 ± 776	2615 ± 680*	3052 ± 946	F = 3.6, p = 0.043, Pη^2 = 0.23
Chloride (mg·day^{-1})	M: 2500 F: 2500	4739 ± 1842	2719 ± 738*	4413 ± 1541$^{\#}$	F = 9.0, p = 0.001, Pη^2 = 0.43
Calcium (mg·day^{-1})	M: 1000 F: 800	1247 ± 371	858 ± 389*	1219 ± 484$^{\#}$	F = 7.6, p = 0.003, Pη^2 = 0.39
Phosphorus (mg·day^{-1})	M: 775 F: 625	1749 ± 294	1283 ± 374*	1452 ± 466	F = 5.1, p = 0.014, Pη^2 = 0.30
Magnesium (mg·day^{-1})	M: 300 F: 300	336 ± 63	255 ± 83	432 ± 349	F = 2.4, p = 0.140, Pη^2 = 0.17
Iron (mg·day^{-1})	M: 11.3 F: 14.8	14.5 ± 3.2	10.1 ± 3.2*	14.6 ± 6.0	F = 5.4, p = 0.012, Pη^2 = 0.31
Zinc (mg·day^{-1})	M: 9.5 F: 7.0	10.8 ± 2.3	8.8 ± 3.0	11.6 ± 6.1	F = 1.8, p = 0.183, Pη^2 = 0.13
Copper (mg·day^{-1})	M: 1.0 F: 1.0	1.4 ± 0.4	1.0 ± 0.4	1.5 ± 0.7	F = 3.1, p = 0.062, Pη^2 = 0.21
Manganese (mg·day^{-1})	-	10.2 ± 20.0	2.8 ± 1.1	3.3 ± 1.1	F = 1.6, p = 0.226, Pη^2 = 0.12
Selenium (µg·day^{-1})	M: 70 F: 60	68.2 ± 15.7	49.4 ± 20.4*	57.4 ± 28.2	F = 4.1, p = 0.030, Pη^2 = 0.25
Iodine (µg·day^{-1})	M: 140 F:140	187.3 ± 86.5	138.1 ± 88.6	159.8 ± 101.7	F = 1.2, p = 0.324, Pη^2 = 0.09

* = different to before lockdown (p <0.05), $^{\#}$ = different to during lockdown (p <0.05). M = UK RNI for males; F = UK RNI for females (British Nutrition Foundation, 2021).

Most female swimmers reported consuming inadequate (<14.8 mg·day^{-1}) iron intakes before (75%, mean intake: 13.9 ± 3.2 mg·day^{-1}), during (88%, 9.7 ± 3.0 mg·day^{-1}), and after lockdown (75%, 13.9 ± 3.2 mg·day^{-1}) (Figure 3.2). This was combined with an increased percentage of female swimmers also reported consuming inadequate calcium (<800 mg·day^{-1}) from before (25%, 1327 ± 411 mg·day^{-1}) to during lockdown (50%, 920 ± 466 mg·day^{-1}). After lockdown, an increased percentage of females reported <800 mg·day^{-1} calcium compared to before lockdown (38%, 1099 ± 439 mg·day^{-1}). A further

comparison found that 50% of female swimmers were concurrently reported inadequate energy (<35 kcal·kg BM·day^{-1}), iron, and calcium intakes during lockdown, which was a greater percentage compared to the 13% observed both before and after lockdown. All males achieved the UK RNI for iron (>11.3 mg·day^{-1}) before (15.4 ± 3.3 mg·day^{-1}) and after lockdown (19.3 ± 3.6 mg·day^{-1}). During lockdown, however, 60% of males failed to meet this threshold (10.9 ± 3.7 mg·day^{-1}). Regarding calcium, only 60% of males consumed the UK RNI (>1000 mg·day^{-1}) before lockdown (1120 ± 291 mg·day^{-1}), which further reduced to 20% during lockdown (759 ± 229 mg·day^{-1}). Nonetheless, 80% of males consumed adequate calcium after the lockdown period (1410 ± 539 mg·day^{-1}).

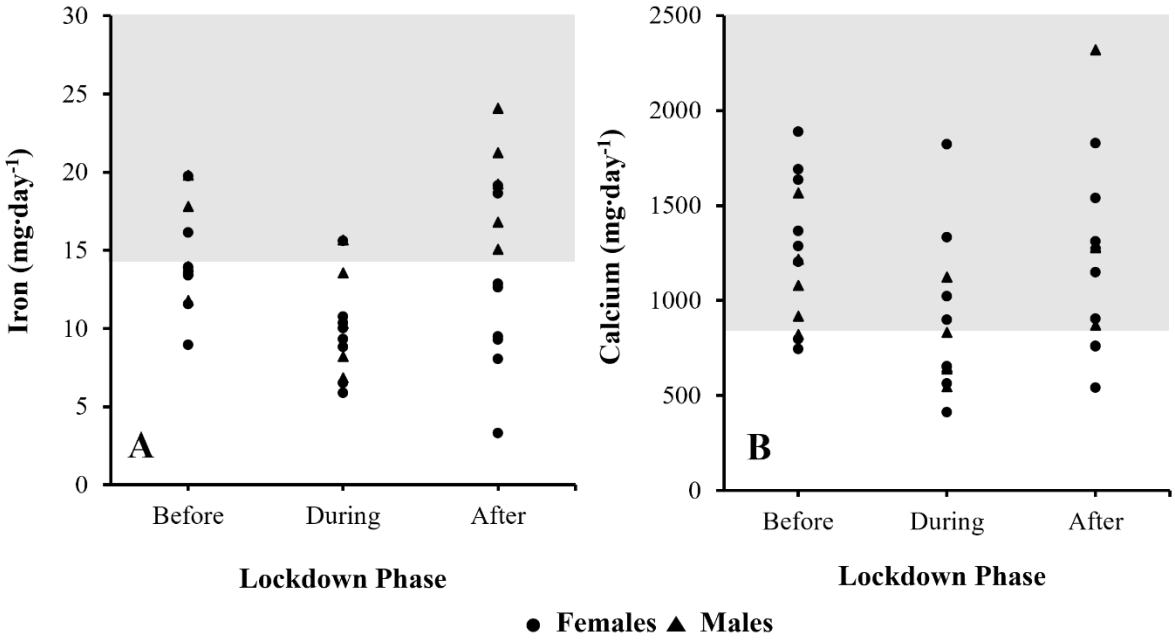

Figure 3.2. The A) iron and B) calcium intakes reported by individual swimmers before, during, and after a national lockdown during the COVID-19 pandemic. Grey shaded areas represent the UK RNI for female adolescents aged 15–18 years (British Nutrition Foundation, 2021).

3.3.6 Vitamins

Only riboflavin (F = 3.9, p = 0.033, $P\eta^2$ = 0.25) and folate (F = 4.1, p = 0.030, $P\eta^2$ = 0.25) intakes were affected by the COVID-19 pandemic (Table 3.5); though, post-hoc analysis could not identify when these changes occurred with statistical significance. Moderate and large effect sizes were calculated for the reduction of these vitamins from before to during lockdown (riboflavin: p = 0.102, g = 0.77; folate: p = 0.117, g = 0.84). Similarly, large effect sizes were also calculated for the increased intake of these vitamins from during to after lockdown (riboflavin: p = 0.060, g = 0.91; folate: p = 0.067, g = 0.98). No swimmer reported consuming the UK RNI for vitamin D (≥10 μg·day^{-1}) before lockdown (range: 1.8–8.9 μg·day^{-1}), but this increased to 15% during lockdown (0.7–16.8 μg·day^{-1}) and 23% after lockdown (3.3–18.0 μg·day^{-1}).

Table 3.5. Vitamin intakes reported in the diets of highly trained adolescent swimmers before, during, and after a national lockdown during the COVID-19 pandemic.

Nutrient	UK RNI	Lockdown Period			Interaction effect
		Before	During	After	
Vitamin A (ret eq·day^{-1})	M: 700 F: 600	758 ± 309	734 ± 363	1023 ± 634	F = 2.0, p = 0.157, $P\eta^2$ = 0.14
Vitamin D (μg·day^{-1})	M: 10 F: 10	4.6 ± 2.3	4.0 ± 5.0	7.2 ± 5.0	F = 2.0, p = 0.155, $P\eta^2$ = 0.14
Vitamin E (mg·day^{-1})	-	9.2 ± 3.5	7.7 ± 2.9	11.4 ± 7.4	F = 2.3, p = 0.118, $P\eta^2$ = 0.16
Vitamin K (mg·day^{-1})	-	80 ± 59	85 ± 81	74 ± 52	F = 0.1, p = 0.876, $P\eta^2$ = 0.01
Thiamin (mg·day^{-1})	M: 1.1 F: 0.8	2.2 ± 0.4	1.8 ± 0.6	2.3 ± 0.8	F = 2.1, p = 0.145, $P\eta^2$ = 0.15
Riboflavin (mg·day^{-1})	M: 1.3 F: 1.1	2.4 ± 0.7	1.8 ± 0.8	2.7 ± 1.1	F = 3.9, p = 0.033, $P\eta^2$ = 0.25
Niacin (mg·day^{-1})	M: 18 F: 14	53 ± 10	50 ± 29	40 ± 14	F = 1.4, p = 0.270, $P\eta^2$ = 0.10
Pantothenic Acid (mg·day^{-1})	-	7.6 ± 1.7	6.9 ± 4.3	7.9 ± 3.5	F = 0.3, p = 0.645, $P\eta^2$ = 0.03
Vitamin B6 (mg·day^{-1})	M: 1.5 F: 1.2	2.6 ± 0.7	2.4 ± 1.2	2.8 ± 0.9	F = 0.6, p = 0.499, $P\eta^2$ = 0.06
Folate (μg·day^{-1})	M: 200 F: 200	311 ± 69	236 ± 100	356 ± 136	F = 4.1, p = 0.030, $P\eta^2$ = 0.25
Vitamin B12 (μg·day^{-1})	M: 1.5 F: 1.5	7.3 ± 2.4	6.0 ± 3.5	6.6 ± 3.4	F = 0.6, p = 0.580, $P\eta^2$ = 0.04
Biotin (μg·day^{-1})	-	40 ± 7	29 ± 10	52 ± 35	F = 3.6, p = 0.076, $P\eta^2$ = 0.23
Vitamin C (mg·day^{-1})	M: 40 F: 40	125 ± 78	105 ± 52	195 ± 164	F = 3.3, p = 0.085, $P\eta^2$ = 0.22

M = UK RNI for males; F = UK RNI for females (British Nutrition Foundation, 2021).

3.3.7 Caffeine

Caffeine intakes did not change over the course of the study ($F = 1.9$, $p = 0.189$, $P\eta^2 = 0.14$), with negligible intakes reported before (0.1 ± 0.1 mg·kg BM^{-1}·day^{-1}), during (0.1 ± 0.3 mg·kg BM^{-1}·day^{-1}) and after lockdown (0.2 ± 0.5 mg·kg BM^{-1}·day^{-1}).

3.4 Discussion

This was the first study to analyse the nutritional intakes of highly trained adolescent swimmers in the UK at three different time points: (a) in normal training before COVID-19; (b) during a national lockdown; and (c) upon a return to sport following a national lockdown. In contrast to prior research (Alméras et al., 1997; Kabasakalis et al., 2007; Montenegro et al., 2017), this study showed that highly trained male and female swimmers appropriately adapted their energy and macronutrient intakes to match their changing training demands. Reductions in DEI during lockdown did, however, cause some micronutrients to be consumed in inadequate amounts, including iron and calcium that are important for growth, development, and athletic performance (Desbrow, 2021). Nonetheless, at both the in-training time points (before and after lockdown), the minimal recommendations for energy, macronutrients, and most micronutrients were reportedly being achieved. A caveat to this observation was that it only considered swimmers who utilised sport nutrition provisions, thus whether these results are generalisable to the wider swimming community with less access/engagement with sport nutrition remains unclear.

The lockdown and social distancing regulations introduced during the COVID-19 pandemic caused a 70% reduction in the weekly training time of highly trained adolescent swimmers, suggesting large decreases in DEE were also present at this time. To account for this reduced training, swimmers reduced their DEI by ~30%, which was deemed appropriate since this cohort were still able to achieve the macronutrient recommendations for swimmers (CHO: 3.5 g·kg BM^{-1}·day^{-1}, protein: 1.7 g·kg BM^{-}

^{1}·day^{-1}, fat: 1.1 g·kg BM^{-1}·day^{-1}). Moreover, no changes in body mass were observed one month into lockdown, demonstrating that energy balance was being achieved (Chow & Hall, 2008). After lockdown, however, swimmers returned to training with mean body mass increase of +4.3 kg, consistent with previous research when adolescent swimmers engaged in a detraining period exceeding two months (+4.8 kg, Alméras et al., 1997). It is therefore plausible that swimmers started to increase their DEI and/or become less motivated to exercise once lockdown conditions extended beyond one month (Pillay et al., 2020). Alternatively, large body mass increases are expected between the ages of 10–20 years, with height (e.g., +3 cm in the present study), skeletal muscle, and bone mass rapidly increasing during adolescence (Brown et al., 2017). With such a prolonged reduction in training volume and intensity, it is possible that this young cohort were instead consuming a sufficient DEI to promote optimal growth during this time (Meyer et al., 2007). Consequently, without access to food diaries at a secondary lockdown time point or a simple metric of body composition (e.g., waist-to-hip ratio; Kuriyan, 2018), it is unclear whether this increased body mass was a result of inadequate dietary intakes (e.g., increased body fat) or growth.

Swimmers had access to sport nutrition support throughout this investigation, possibly explaining why this cohort increased and decreased their daily nutrition intakes in contrast with previous research (Alméras et al., 1997; Kabasakalis et al., 2007; Montenegro et al., 2017; Noland et al., 2001; Sato et al., 2011). On an individual basis, however, heightened inter-individual variation was observed within each nutritional measure after lockdown, indicating that more swimmers started to either over-consume or under-consume energy (e.g., DEI range before lockdown: 34–62 kcal·kg BM·day^{-1} vs. after lockdown: 29–66 kcal·kg BM·day^{-1}) and macronutrients (e.g., protein range before lockdown: 1.5–2.9 g·kg BM·day^{-1} vs. after lockdown: 1.2–3.1 g·kg BM·day^{-1}) upon the return to sport. This could have been the result of some swimmers experiencing a decline in diet quality and motivation as the lockdown persisted, which is in accordance with other sporting populations (Pillay et al., 2020; Roberts et al., 2020). Indeed, anecdotal data from coaches and support staff suggest that adherence and engagement with sport nutrition and training provisions declined over time during lockdown; and

as such, it is speculated that some swimmers developed poor eating behaviors that were carried over into the after lockdown time point. This could be problematic given that diet quality is associated with physical performance capacity and health (Farina et al., 2020; Thomas et al., 2016); hence, a greater proportion of swimmers might now be at greater risks of injuries, illnesses, and poor performances without additional post-lockdown nutrition support. Though this requires further research.

Though a large reduction in DEI was necessary during lockdown, swimmers should be aware that low energy diets increase the risks of developing micronutrient deficiencies (Thomas et al., 2016). The current study adds to this concern by identifying a reduction in the intake of nine different micronutrients during lockdown; including iron, calcium, and potassium; which all fell below the UK RNI for adolescents (British Nutrition Foundation, 2021). More specifically, female swimmers reported consuming suboptimal calcium (684–970 $mg \cdot day^{-1}$) and iron intakes (9.7–13.2 $mg \cdot day^{-1}$) when their DEI decreased ≤40 $kcal \cdot kg\ BM^{-1} \cdot day^{-1}$, which supported previous observations in adolescent female swimmers (da Costa et al., 2013; Martínez et al., 2011; Vallières et al., 1989). On the other hand, male swimmers are considered to be at lower risks of developing nutrient deficiencies due to consistently achieving DEI recommendations (Shaw et al., 2014), though this study suggested otherwise during lockdown conditions. These insights suggest that education and practical skills are of much needed attention within swimming clubs when reductions in DEI are necessary (e.g., injury or future lockdowns). Nonetheless, when in formal training, group mean data suggested that highly trained adolescent swimmers mostly consumed adequate micronutrient intakes (except vitamin D). However, it is currently unclear if three-day food diaries are valid and reliable tools to assess micronutrient intakes in adolescent athletes (Costello et al., 2017), and therefore the data from this study should be interpreted with caution.

The retrospective nature of this study produced a number of limitations. Firstly, energy balance, and therefore the risk of energy deficiency, was not assessed since a consistent DEE calculation was not established. For example, the Harris-Benedict equation was used before lockdown using height, age,

body mass, and daily activity (Jagim et al., 2018), whereas an approach based on metabolic equivalents (METs) was attempted during lockdown to account for changes in daily routines (Ainsworth et al., 2011; Ridley et al., 2008). However, the latter approach demanded an accurate recall of all daily activity, which the current cohort did not adequately provide or engage with. Secondly, 50% of the original cohort did not complete all nutrition assessments, which meant that only the food diaries from swimmers who engaged with the sport nutrition provisions was included in the analysis. Consequently, it is unclear whether these results can be generalised to the wider swimming population at present. Finally, no health or performance measures were collected alongside dietary intakes, restricting any practical outcomes from being observed. Future research should therefore consider utilising simple and non-invasive measures of body composition, exercise performance, well-being, and/or growth; given the possibility of future pandemic situations restricting training and face-to-face engagement in the near future (Mahase, 2021; Thiagarajan, 2021). Nonetheless, the key purpose of this study was to identify any changes that occurred in the dietary intakes of highly trained adolescent swimmers during three different lockdown stages, to which this was achieved.

3.5 Conclusion

With sport nutrition support, highly trained adolescent swimmers in the UK were capable of adjusting their nutrition intakes based on their changing training demands during the COVID-19 pandemic. At the group level, energy and macronutrient recommendations were achieved before, during, and after a national lockdown. However, these intakes were variable at the individual level, suggesting that more swimmers were deviating away from the nutrition recommendations after lockdown. It was suspected that diet quality and motivation decreased in some swimmers as lockdown conditions persisted beyond five weeks, which could therefore place some adolescent swimmers at greater risks of energy and nutrient deficiencies. As such, further research regarding the long-term health and performance implications caused by COVID-19 is required.

Chapter 4 – Nutritional Supplement Use in a UK High-Performance Swimming Club

Chapter can be found at: Newbury, J.W., Sparks, S.A., Cole, M., Kelly, A.L. and Gough, L. A. (2023). Nutritional supplement use in a UK high-performance swimming club. *Nutrients*, 15(15), pp.3306. Available at: https://doi.org/10.3390/nu15153306.

4.1 Introduction

The International Olympic Committee (IOC) define nutritional supplements as ‘food, food components, nutrients, or non-food compounds that are purposefully ingested in addition to the habitually consumed diet with the aim of achieving a specific health and/or performance benefit’ (Maughan et al., 2018, pp.105). This broad definition covers a wide variety of supplements that are commercially available to swimmers, including ‘sports’, ‘health’, ‘ergogenic’, and ‘herbal’ products that were previously described in Chapter 1 (section 1.4). Given each of these supplement categories has suggested health and/or performance benefits, it is no surprise that their use is currently widespread in sport at the elite (Shaw et al., 2016a), junior (Mettler et al., 2022), and recreational levels (Ulery et al., 2022).

Supplement use generally increases with age and training status, though the total number and type of supplements can also be influenced by a sport’s cultural norms (Maughan et al., 2018). For example, swimmers are often placed amongst the highest supplement when compared to other sports (Corrigan & Kazlauskas, 2003; Dascombe et al., 2010; Huang et al., 2006; Jovanov et al., 2019), with between 87–99% of elite swimmers currently thought to be consuming supplements on a regular basis, and ~6–10 different supplements being used at the same time (Moreno et al., 2022; Shaw et al., 2016b). More recently, Moreno et al. (2022) also found that supplement use was equally prevalent between swimmers at the national and international levels, including little differences in the total number (6.3 ± 4.4 vs. 4.9 ± 3.6 supplements) or types of supplements (e.g., sports: 1.4 ± 1.1 vs. 1.4 ± 1.3 supplements; ergogenic aids: 1.3 ± 1.3 vs. 1.2 ± 1.1 supplements) being consumed. These results raise potential concerns given that many national swimmers are adolescents who could therefore be engaging in widespread supplement without understanding safe practices (Dascombe et al., 2010; Mettler et al., 2022). As the current supplement intakes of highly trained adolescent swimmers are unclear (see Chapter 1, section 1.4.1), further research is required to understand this population’s supplement behaviours and motivations.

Approximately 35–100% of highly trained adolescents reportedly engage in supplement use, with reasons being to improve performance (20–65%), enhance recovery (33–40%) and support health (23–56%) (Dascombe et al., 2010; Mettler et al., 2022; Parnell et al., 2016; Petróczi et al., 2008). The intake of sports and some health supplements are justified in this cohort given that a 'food first, but not always food only' approach is thought optimal for health and performance (Close et al., 2022). However, the consumption of ergogenic aids is more dubious, since the possibility of obtaining marginal performance benefits can be outweighed by the risks of adverse side-effects and/or inadvertent doping (Desbrow et al., 2014). Nonetheless, 57–72% of adolescents believe ergogenic aids to be important for sporting success, using them despite knowing the inherent risks and not knowing the correct dosing protocols (Dascombe et al., 2012; Mettler et al., 2022). This could be because supplement knowledge is often obtained from coaches and family members as opposed to qualified nutritionists (Jovanov et al., 2019; Moreno et al., 2022; Petróczi et al., 2008); though this has not been confirmed specifically in adolescent swimming cohorts. This poses key questions regarding supplement use in adolescent swimmers, such as at what age does prevalent use begin; does the total number and type of supplements change with training status; why are these supplements chosen; and who recommends them? The aim of this study was therefore to identify the current supplement practices of three distinct stages in the swimming talent pathway: development (aged 10–14 years); age-group (aged 13–17 years); and national level (aged ≥16 years).

4.2 Methods

4.2.1 Participants

This study took place within a high-performance swimming club in the UK, which consisted of 62 swimmers of national, age-group, and development status (see Chapter 2, section 2.1.2). However, logistical challenges meant that not all swimmers were available for data collection, resulting in a final participant sample of 44 swimmers (Table 4.1). An a priori power calculation with input parameters of $\alpha = 0.05$ and ß = 0.80 determined this sample size appropriate for detecting medium

effect sizes (0.50) in one-way ANOVA tests (three groups, one measure) with a power of 80% (G*Power, v.3.1.9.4, Universität Düsseldorf, Germany). At the time of the study, the national group of swimmers (n = 11) consisted of two national swimming champions and five swimmers who had represented their nations at the junior level. Age-group swimmers (n = 13) were all highly competitive in their respective age categories, including seven of this group who were nationally ranked in the top 10 swimmers for their specialist event. Development swimmers (n = 20) were all highly competitive at the regional level, with ten being nationally ranked in the top 10 swimmers in their age groups for at least one event. Written informed consent was provided by all swimmers and their parents/guardians if aged under 18 years. Ethical approval was granted by BCU (Newbury/7594/R(B)/2020/Aug/HELS FAEC) in accordance with the Declaration of Helsinki.

Table 4.1. The competitive status and training characteristics of the study participants.

Measure	National (n = 11)	Age-Group (n = 13)	Development (n = 20)	Males (n = 21)	Females (n = 23)	Combined (n = 44)
Age (years)	20 ± 2$^{*\#}$	15 ± 1*	13 ± 1	16 ± 3	15 ± 3	15 ± 3
Time competitive (years)	9 ± 2$^{*\#}$	5 ± 1*	3 ± 1	5 ± 3	5 ± 3	5 ± 3
Training volume (sessions·week^{-1})	6.9 ± 1.2*	6.2 ± 0.8*	5.7 ± 0.5	6.0 ± 0.7	6.3 ± 1.1	6.2 ± 0.9
Training time (hours·week^{-1})	17.6 ± 3.2*	15.8 ± 2.4*	12.3 ± 1.2	14.4 ± 2.3	14.9 ± 3.8	14.6 ± 3.1
WA points	698 ± 59$^{*\#}$	622 ± 67*	483 ± 69	555 ± 123	598 ± 99	578 ± 112

World Aquatic (WA) points awarded for the fastest swimming performance in a 50 m pool. Training time includes both pool and land-based activities undertaken at the swimming club. * = increased compared to development swimmers (p <0.05). $^{\#}$ = increased compared to age-group swimmers (p <0.05). Statistical comparisons are described in section 4.3.1.

4.2.2 Experimental Procedures

A descriptive and cross-sectional design was used to investigate supplement practices. Each swimmer underwent a short interview (10–15 min) with the lead researcher, which was previously outlined in Chapter 2 (section 2.2.3). In brief, the interview questions were an adaptation of a validated online nutrition supplement questionnaire (Sanchez-Oliver, 2012), which asked the following questions: (a) what supplements are consumed; (b) why is that supplement consumed; (c) where was the information for that supplement sourced; (d) how frequently is that supplement consumed; and (e) where was the supplement purchased? Swimmers were only asked to detail supplements that were consumed during the 2021/2022 competitive swimming season.

4.2.3 Data Groups for Analysis

Supplement intakes were compared by training status (national vs. age-group vs. development) rather than participant age due to the differing levels of nutrition support they received (see Chapter 2, section 2.1.4). For each individual question, the following categories were applied for data analysis based on the swimmers' responses. *Supplement type*: sports supplements; ergogenic aids; and health supplements, whereby 'health' supplements included vitamins, minerals, medical, and herbal products. *Reasons for use*: increase performance (including 'increasing energy levels for racing'); recovery from exercise; general health; convenient source of nutrients; muscle growth; immune support (avoiding or reducing length of illnesses); hydration; sleep support; and unsure. *Information source*: performance nutritionist; swim coach; other coach (i.e., physiotherapist, personal trainer); teammate; medical doctor; parent/guardian; friends and siblings; media (i.e., internet, social media role models); and national governing bodies (NGB) (i.e., recommended at a development camp, provided by supplement partners). *Supplement frequency*: daily; regularly (1–4 days·week^{-1}); and occasionally (i.e., at competitions). *Supplement source*: grocery stores; general stores online (e.g.,

Amazon); online sport nutrition outlets; health and wellness stores; pharmacies; and supplied directly from a performance nutritionist or a parent/guardian.

4.2.4 Statistical Analysis

All quantitative data (i.e., total supplements, participant characteristics) are presented as mean ± SD, whereas the frequency of the qualitative responses (i.e., individual supplements, information sources, reasons for use) are reported as percentages. All statistical analyses followed the processes outlined in Chapter 2 (section 2.5.2). Based on the data in this chapter violating normality and sphericity, the equivalent non-parametric tests were utilised. These were Kruskal-Wallis tests to analyse group level differences in total supplement intakes (national vs. age-group vs. development), and Mann-Whitney U tests to analyse pairwise differences based on sex (male vs. female). Effect sizes for pairwise comparisons are calculated and reported in accordance with Hedge's *g* bias correction. Differences in frequency distributions between groups were analysed via Pearson's Chi-Square (χ^2) tests, with Cramer's *V* effect sizes calculated and reported. All interpretations of effect sizes can be found in Chapter 2 (section 2.5.2). Statistical significance was set at $p < 0.05$.

4.3 Results

4.3.1 Participants

There were incremental increases in age ($H(2) = 33.7$, $p < 0.001$) and years competitive ($H(2) = 33.9$, $p < 0.001$) between the training phases (Table 4.1), such that national swimmers were older and more experienced than age-group swimmers ($U = 0.0$, $p < 0.001$, $g = 3.14$; and $U = 11.0$, $p < 0.001$, $g = 1.73$, respectively), and age-group swimmers were older and more experienced than development swimmers ($U = 25.0$, $p < 0.001$, $g = 1.95$; and $U = 13.0$, $p < 0.001$ $g = 1.73$, respectively). Moreover, the swimmers' mean WA points were also increased with each training phase ($H(2) = 30.0$, $p < 0.001$),

with national swimmers being higher performers compared to age-group swimmers (U = 27.0, p = 0.10, g = 1.14), and age-group swimmers being higher performers than development swimmers (U = 19.0, p <0.001, g = 1.99). Increases in weekly training sessions (H(2) = 9.6, p = 0.008) and training hours (H(2) = 21.3, p <0.001) also occurred, but these were only evident between swimmers of development and age-group levels (U = 48.0, p = 0.005, g = 1.44; U = 42.0, p <0.001, g = 1.94, respectively). There were no sex-based differences in age (U = 201.0, p = 0.335, g = 0.33), competitive experience (U = 222.5, p = 0.651, g = 0.00), weekly training sessions (U = 254.5, p = 0.745, g = 0.32), weekly training hours (U = 249.5, p <0.848, g = 0.28), or WA points (U = 293.5, p = 0.222, g = 0.38).

4.3.2 Supplement Type and Prevalence

Ninety-eight percent (43 of 44) of swimmers reported using at least one nutritional supplement. These supplement intakes differed between training groups (H(2) = 14.4, p <0.001, Table 4.2), with national swimmers reporting using a greater number of total supplements compared to both age-group (U = 21.0, p = 0.003, g = 1.17) and development swimmers (U = 27.5, p <0.001, g = 1.69). No difference in total supplement intake was observed between development and age-group swimmers (U = 93.5, p = 0.169, g = 0.35).

Group differences in the consumption of ergogenic aids (H(2) = 27.3, p <0.001) and health supplements (H(2) = 9.0, p = 0.011) were also identified; however, all three groups reported using a similar number of sports supplements (H(2) = 0.37, p = 0.982; Table 4.2). With regards to ergogenic aids, beta-alanine ($\chi^2_{(2,\ n\ =\ 44)}$ = 13.00, p = 0.002, V = 0.54); CAF anhydrous ($\chi^2_{(1,\ n\ =\ 44)}$ = 20.49, p <0.001, V = 0.68); CAF drinks and gels ($\chi^2_{(2,\ n\ =\ 44)}$ = 9.56, p = 0.008, V = 0.47); creatine ($\chi^2_{(2,\ n\ =\ 44)}$ = 16.71, p <0.001, V = 0.62); and $NaHCO_3$ ($\chi^2_{(2,\ n\ =\ 44)}$ = 13.20, p = 0.001, V = 0.55) were all more frequently reported by national swimmers. This resulted in national swimmers reporting more ergogenic aids compared to age-group swimmers (U = 12.5, p <0.001, g = 1.81), whereas age-group

swimmers also reported consuming more ergogenic aids compared to development swimmers (U = 76.5, p = 0.005, g = 1.12). An increased intake of health supplements occurred in national swimmers, who reported using more supplements versus swimmers at the age-group (U = 35.0, p = 0.032, g = 0.79) and development levels (U = 40.0, p = 0.003, g = 1.27). This occurred due to an increased proportion of national swimmers reporting using magnesium ($\chi^2_{(2,\ n\ =\ 44)}$ = 6.29, p = 0.043, V = 0.38), omega-3 fatty acids ($\chi^2_{(2,\ n\ =\ 44)}$ = 11.57, p = 0.003, V = 0.51), vitamin D ($\chi^2_{(2,\ n\ =44)}$ = 8.32, p = 0.016, V = 0.44), and zinc supplements ($\chi^2_{(2,\ n\ =44)}$ = 16.92, p <0.001, V = 0.62). No difference in health supplement use was found between age-group and development swimmers (U = 117.0, p = 0.621, g = 0.26). Despite a similar number of sports supplements being reported between groups, a larger distribution of sports drinks was identified in development swimmers ($\chi^2_{(2,\ n\ =\ 44)}$ = 15.38, p <0.001, V = 0.59), whereas protein powders were more frequently reported by national swimmers ($\chi^2_{(2,\ n\ =\ 44)}$ = 11.46, p = 0.003, V = 0.51).

Male and female swimmers both reported using a similar total number of supplements (U = 169.0, p = 0.085, g = 0.45), including a similar number of ergogenic (U = 215.5, p = 0.484, g = 0.07) and health supplements (U = 173.5, p = 0.103, g = 0.44, Table 4.2). A greater proportion of males did, however, report using multivitamin supplements ($\chi^2_{(1,\ n\ =\ 44)}$ = 7.33, p = 0.007, V = 0.41). Male swimmers also reported using more sports supplements compared to females (U = 149.5, p = 0.021, g = 0.76), with a greater proportion of males using protein-enhanced foods ($\chi^2_{(1,\ n\ =\ 44)}$ = 4.39, p = 0.036, V = 0.32). In contrast, a greater proportion of females reported using CAF anhydrous ($\chi^2_{(1,\ n\ =\ 44)}$ = 4.49, p = 0.034, V = 0.32), whereas males used a wider variety of ergogenic supplements.

Table 4.2. Total number and prevalence of nutritional supplements reportedly used by three training tiers within a UK-based, high-performance swimming club.

Category / Individual Supplements	Overall (*n* = 44)	National (*n* = 11)	Age-Group (*n* = 13)	Development (*n* = 20)	Males (*n* = 21)	Females (*n* = 23)
Total (supplements)	5.2 ± 2.9	**8.1 ± 3.4** [ab]	4.8 ± 2.0	3.9 ± 1.7	5.9 ± 2.7	4.6 ± 2.9
Sports (supplements)	**2.5 ± 1.0** [*#]	2.7 ± 1.7	2.6 ± 0.7	2.6 ± 0.9	**2.9 ± 0.8** [†]	2.2 ± 1.0
Dextrose/maltodextrin (%)	0	0	0	5	0	4
Electrolytes (%)	18	18	38	5	29	9
Liquid meals (%)	9	18	0	10	0	**17**[‡]
Protein bars (%)	43	36	54	40	57	30
Protein-enhanced food (%)	45	45	46	45	**62**[‡]	30
Protein powder (%)[†]	45	**82**	**54**	**20**	52	39
Sports bars (%)	2	0	0	5	0	4
Sports drinks (%)[†]	68	**27**	**62**	**95**	67	70
Sports gels (%)	18	9	8	30	19	17
Ergogenic (supplements)	0.8 ± 1.4	**2.4 ± 1.4** [ab]	**0.5 ± 0.5**[b]	0.1 ± 0.2	0.8 ± 1.7	0.9 ± 1.2
Beetroot juice (%)	5	9	8	0	10	0
Beta-alanine (%)[†]	14	**45**	**8**	**0**	14	13
Caffeine anhydrous (%)[†]	30	**82**	**23**	**5**	14	**43**[‡]
Caffeine drinks/gels (%)[†]	9	**36**	**0**	**0**	10	9
Citrulline malate (%)	2	9	0	0	5	0
Creatine (%)[†]	16	**55**	**8**	**0**	19	13
Sodium bicarbonate (%)[†]	9	**36**	**0**	**0**	10	9
Health (supplements)	**1.8 ± 1.6**[*]	**3.0 ± 1.3**[ab]	1.7 ± 1.8	1.3 ± 1.3	2.2 ± 1.4	1.5 ± 1.7
Ginger (%)	2	0	8	0	5	0
Iron (%)	20	27	15	20	24	17
Magnesium (%)[†]	5	**18**	**0**	**0**	10	0
Melatonin (%)	2	9	0	0	0	4
Multi-vitamin (%)	41	36	31	50	**62**[‡]	22
Omega-3 fatty acids (%)[†]	20	**55**	**0**	**15**	19	22
Probiotics (%)	20	9	38	15	24	17
Vitamin C (%)	18	27	31	5	24	13
Vitamin D (%)[†]	39	**73**	**38**	**20**	38	39
Zinc (%)[†]	11	**45**	**0**	**0**	10	13

[*] = overall greater intake compared to health supplements (p <0.05); [#] = overall greater intake compared to ergogenic aids (p <0.05); [a] = greater intake compared to age-group swimmers (p <0.05), [b] = greater intake compared to development swimmers (p <0.05); [†] = percentage difference between training phases (p <0.05); ‡ = percentage difference between sexes (p <0.05).

4.3.3 Reasons for Use

All three groups cited similar reasons for their supplement use, with 'performance' (34 ± 7%, $\chi^2_{(2,\ n\ =\ 228)} = 2.95$, $p = 0.229$, $V = 0.11$) and 'recovery' (19 ± 7%, $\chi^2_{(2,\ n\ =\ 228)} = 4.67$, $p = 0.097$, $V = 0.14$) being the largest motivators (Figure 4.1A). These reasons were followed by 'convenient nutrient sources' (13 ± 3%, $\chi^2_{(2,\ n\ =\ 228)} = 1.38$, $p = 0.502$, $V = 0.08$) and for 'health' purposes (12 ± 2%, $\chi^2_{(2,\ n\ =\ 228)} = 0.40$, $p = 0.820$, $V = 0.04$). Out of all supplements used, swimmers stated that they were 'unsure' why they consumed 18 ± 5% of their total supplements, which was no different between training groups ($\chi^2_{(2,\ n\ =\ 228)} = 3.30$, $p = 0.192$, $V = 0.12$). The reasons for supplement use differed between sexes, such that female swimmers consumed more supplements for 'performance' ($\chi^2_{(1,\ n\ =\ 228)} = 9.04$, $p = 0.003$, $V = 0.20$), whereas male swimmers consumed more supplements for 'muscle growth' ($\chi^2_{(1,\ n\ =\ 228)} = 7.20$, $p = 0.007$, $V = 0.18$) (Figure 4.1B). No other sex-based differences occurred (all $p > 0.05$, $V < 0.10$).

4.3.4 Information Sources

Seventy-five percent of all reported supplements were informed by a parent/guardian or a performance nutritionist, though this distribution was not equal across groups (Table 4.3). Development swimmers were the most reliant on parent/guardian information, whose influence was less present in national swimmers ($\chi^2_{(2,\ n\ =\ 228)} = 57.66$, $p < 0.001$, $V = 0.50$). In contrast, national and age-group swimmers both reported a performance nutritionist as the most influential supplement advisor, compared to no swimmers at the development level ($\chi^2_{(2,\ n\ =\ 228)} = 53.14$, $p < 0.001$, $V = 0.51$). Additionally, a greater proportion of national swimmers reported gaining supplement information from their coach compared to the other training stages ($\chi^2_{(2,\ n\ =\ 228)} = 10.02$, $p = 0.007$, $V = 0.21$), whereas the development group sourced more information from the media ($\chi^2_{(2,\ n\ =\ 228)} = 8.87$, $p = 0.012$, $V = 0.20$). A sex-based difference was also found, whereby a greater proportion of female swimmers sourced their supplement information from a performance nutritionist ($\chi^2_{(1,\ n\ =\ 228)} = 19.47$, $p < 0.001$, $V = 0.29$), compared to males who sourced more information from a parent/guardian ($\chi^2_{(1,\ n\ =\ 228)} = 6.71$, $p = 0.010$, $V = 0.17$) and other coaches ($\chi^2_{(1,\ n\ =\ 228)} = 3.85$, $p = 0.050$, $V = 0.13$).

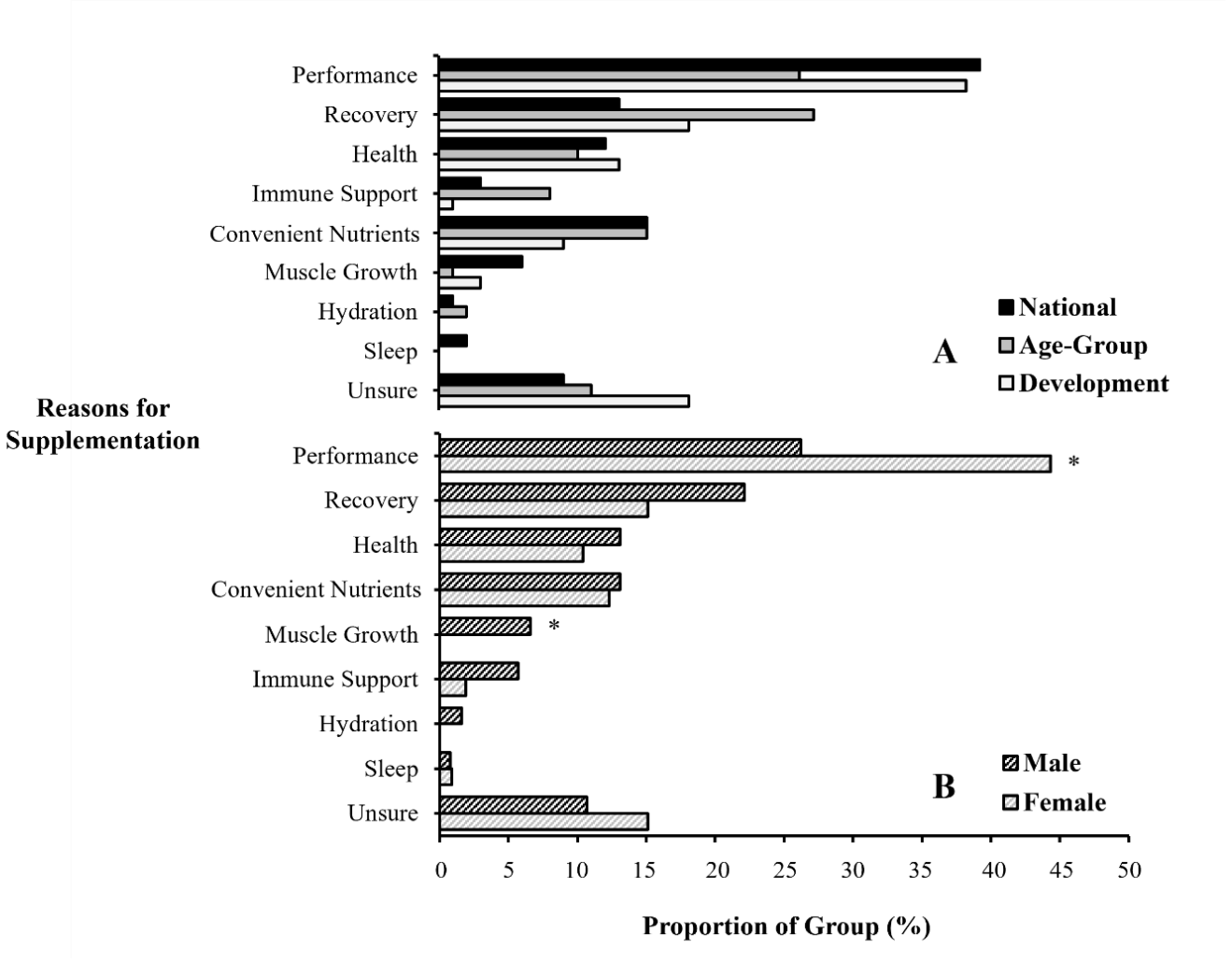

Figure 4.1. Reasons for nutritional supplement use reported by swimmers in accordance with (A) training tier, and (B) sex. * = difference between groups (p <0.05).

Table 4.3. Distribution (%) of supplement information sources reported by swimmers within a high-performance swimming club.

Information Sources	Overall (*n* = 228)	National (*n* = 89)	Age-Group (*n* = 62)	Development (*n* = 77)	Male (*n* = 122)	Female (*n* = 106)
Performance nutritionist (%)*	33	**51**	**50**	**0**	20	**48#**
Swim coach (%)*	6	**12**	**3**	**1**	7	5
Parent/guardian (%)*	42	**16**	**40**	**74**	**50#**	33
NGB (%)	3	4	2	1	4	1
Medical doctor (%)	3	1	3	4	4	1
Other coach (%)	4	7	0	3	**6#**	1
Teammate (%)	3	3	0	4	2	2
Friends and siblings (%)	2	2	0	4	1	0
Media (%)*	3	**1**	**0**	**8**	3	5
Self-Research (%)	2	2	2	1	1	1

* = difference between training groups (p <0.05); # = difference between sexes (p <0.05); NGB = national governing body; n = total number of supplements reported by each group.

4.3.5 Supplement Frequency

The frequency that swimmers consumed nutritional supplements differed by training group ($H(2)$ = 15.38, p <0.001). This change occurred as national swimmers reported consuming more supplements daily (3.8 ± 1.8 supplements), which was more than the swimmers at the age-group (1.8 ± 1.6 supplements, U = 28.0, p = 0.010, g = 1.17) and development levels (0.9 ± 0.9 supplements, U =22.0, p <0.001, g = 2.20). No further differences were identified between groups for the number of supplements consumed regularly (national: 2.4 ± 1.7; age-group: 1.7 ± 1.2; development: 1.5 ± 0.9 supplements; $H(2)$ = 2.7, p = 0.255), or occasionally (national: 1.9 ± 1.3; age-group: 1.3 ± 0.6; development: 1.6 ± 0.9 supplements; $H(2)$ = 1.3, p = 0.526). Between sexes, males reported using more supplements than females on a daily (2.3 ± 1.6 vs. 1.4 ± 1.9 supplements: U = 153.0, p = 0.033, g = 0.49) and regular basis (2.1 ± 1.1 vs. 1.4 ± 1.3 supplements; U = 158.5, p = 0.045, g = 0.52), but

no differences occurred in occasional supplements use (1.4 ± 0.9 vs. 1.7 ± 1.0 supplements; U = 194.0, p = 0.226, g = 0.37).

4.3.6 Supplement Sources

Within national swimmers, an increased proportion of supplements were purchased from online sport nutrition outlets ($\chi^2_{(2,\, n\, =\, 228)}$ = 131.75, p <0.001, V = 0.76), whereas development swimmers purchased most supplements from grocery stores ($\chi^2_{(2,\, n\, =\, 228)}$ = 27.52, p <0.001, V = 0.35) (Figure 4.2A). National swimmers were also the only group to source supplements directly from a performance nutritionist ($\chi^2_{(2,\, n\, =\, 228)}$ = 12.95, p = 0.002, V = 0.24), which were all ergogenic aids. No sex differences were observed for most supplement sources (all p >0.05, V <0.10; Figure 4.2B), though three male swimmers were clinically prescribed supplements from a pharmacy, leading to a proportional difference compared to female swimmers ($\chi^2_{(1,\, n\, =\, 228)}$ = 4.44, p = 0.035, V = 0.14).

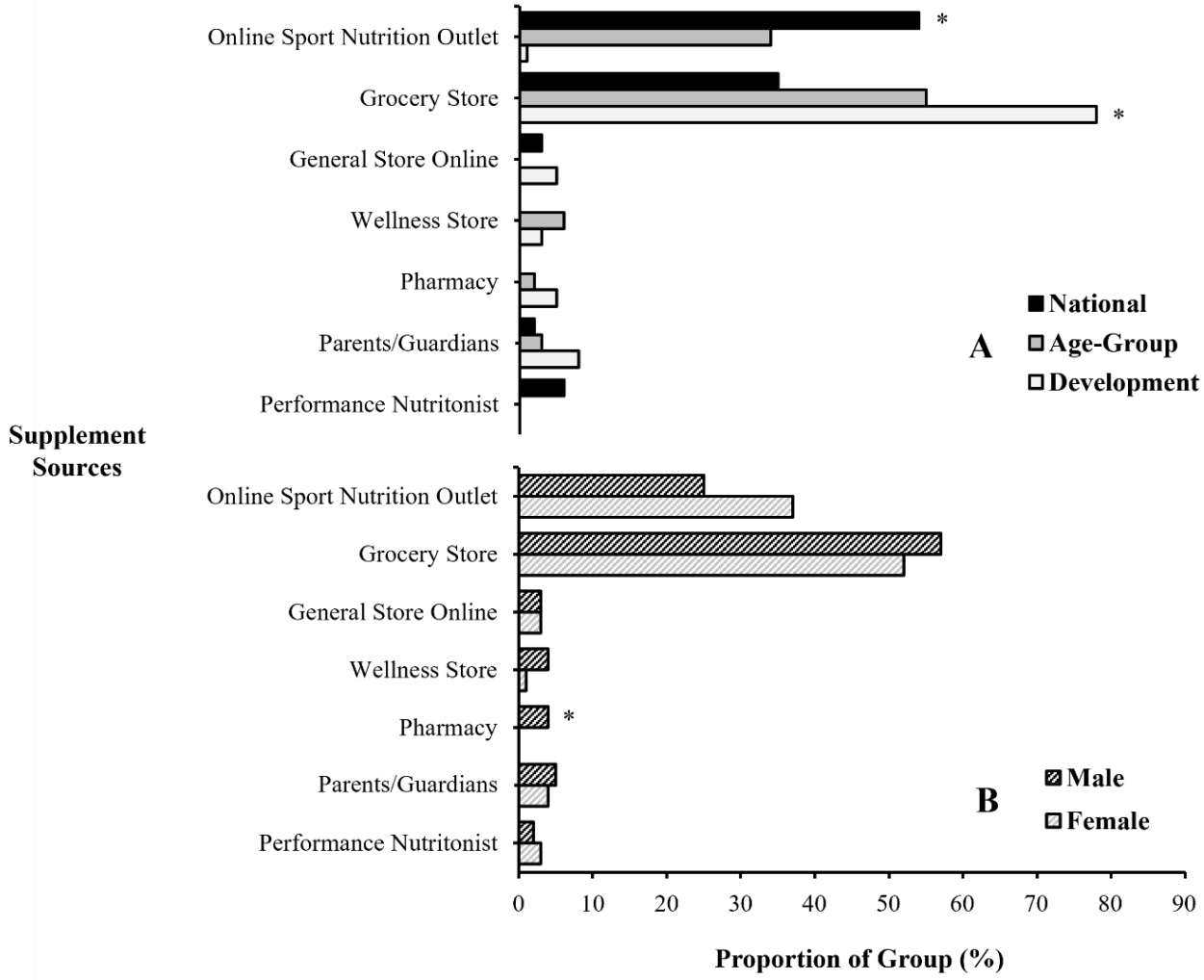

Figure 4.2. The supplement information sources reported by swimmers within a high-performance swimming club based on (A) training tier, and (B) sex. * = difference between groups (p <0.05).

4.4 Discussion

The key finding from this study was that swimmers of all training ages engage in a widespread supplement use, with swimmers at the development phase (aged 11–14 years) utilising sports supplements at competitions, and national swimmers (aged ≥16 years) using an array of health and ergogenic supplements on a more regular basis. Indeed, national swimmers reported consuming a similar number of ergogenic and health supplements as international-level adult swimmers in previous

research (Moreno et al., 2022; Shaw et al., 2016). Moreover, swimmers from all three training stages reported ‘performance’ as a key motivator for supplement use, which was in accordance with other swimming cohorts (Jimenéz-Alageme et al., 2022; Moreno et al., 2022). The prevalent use of ergogenic aids in this study was likely due to swimmers having increasing access to sport nutrition support as they progressed in training status, as evidenced since parents/guardians were replaced by performance nutritionists as supplement informers in swimmers of age-group and national levels. It is therefore prudent to suggest that supplement education could be best implemented to parents/guardians at the development stage, in order to facilitate safe and effective supplement use later in the swimming career.

Development swimmers all reported using nutritional supplements, with approximately four different supplements being used across a swimming season (~1 daily, ~1–2 regularly ~1–2 occasionally). Sports drinks were the most commonly used (95%), followed by multivitamins (50%) and protein supplements (40–45%), which was comparable to the supplement use in adult and adolescent swimmers of international competitive status (sports drinks: 92–100%, multivitamins: 32–46%, protein powder: 46–58%) (Shaw et al., 2016a; Simič & Mohorko, 2018). This early use of supplements was mostly informed by parents/guardians (74%), who were responsible for purchasing supplements and often supplied them to swimmers without rationale (swimmers were unsure why they consumed 18% of all supplements). The primary motivation for supplement use in this cohort was performance (38%), though it was unclear whether this rationale was led by parents/guardians or influenced by swimmers while shopping with parents/guardians at grocery stores. However, the ‘performance supplements’ reported by this cohort were mostly from the sports supplement category (96%) as opposed to ergogenic aids (4%), which was appropriate at this training age given that sports supplements carry lower risks of side-effects and/or inadvertent doping (Garthe & Maughan, 2018). This outcome could therefore be viewed positively as swimmers and their parents/guardians identified nutrition as an important factor for swimming performance. Though, this should be interpreted cautiously as a performance nutritionist provided resources to parents/guardians at the development

level in this study, whereas other swimming parents/guardians might rely on supplement information from coaches and the internet (Jovanov et al., 2019; Petróczi et al., 2008). As such, it is difficult to generalise the outcomes of this study to the wider swimming community, requiring further investigation across multiple swimming clubs with varying levels of nutrition support.

Age-group swimmers consumed a similar number of supplements as development swimmers (~5 supplements·swimmer^{-1}), albeit with a change in their supplement choices, reasoning, and information sources. Indeed, the percentage of swimmers using pill and powder sports supplements was increased compared to the development group (electrolytes: +33%, protein powder: +42%), whereas more swimmers also consumed ergogenic aids (46 vs. 5%). The use of CAF (23%), creatine (8%), beta-alanine (8%), and BRJ (8%) were all reported, which each have strong evidence of a performance-enhancing effect (Maughan et al., 2018), and were consumed in equal proportion to highly trained adolescents from mixed sporting backgrounds (i.e., CAF: 19%, creatine: 25%, beta-alanine: 5%, nitrates: 3%) (Jovanov et al., 2019). However, despite using more ergogenic aids, less age-group swimmers used supplements for 'performance' compared to development swimmers (-12%), instead citing 'recovery', 'immunity', and 'convenience' as motivating factors. This change was partly due to the introduction of formal sports nutrition education, with a performance nutritionist subsequently replacing parents/guardians as the primary source of supplement information (performance nutritionist: +50%, parent/guardian: -34% vs. development swimmers). In turn, this may have enabled age-group swimmers to provide more appropriate reasons for their supplement use. Based on these findings, a transitional stage in supplement use was identified, whereby age-group swimmers become more exposed to sport nutrition and begin trialling ergogenic aids. It is therefore imperative that a 'performance-enhancing' diet is not undermined, which may be supported by practical workshops that develop food literacy and cooking skills (Shaw et al., 2014). Furthermore, strong anti-doping messages would also be of benefit, informing swimmers and guardians of the risks of inadvertently ingesting banned substances when using pill and powder nutritional supplements (Garthe & Maughan, 2018).

National swimmers used an average of eight different nutritional supplements (~3 health, ~3 ergogenic, ~2 sports), which was in line with previous observations in international- and national-level swimmers (6–10 individual supplements) (Moreno et al., 2022; Shaw et al., 2016a). This was, however, higher than the total number of supplements used by age-group swimmers, most notably since more swimmers reported using ergogenic aids (creatine: +47%, beta-alanine: +37%) and health supplements (omega-3 fatty acids: +55%, vitamin D: +35%) on a daily basis. Moreover, national swimmers used more ergogenic aids than age-group swimmers at competitions (CAF: +59% $NaHCO_3$: +36%), some of which were directly sourced from a performance nutritionist. These supplement behaviours follow the step-like process outlined by Garthe and Maughan (2018), whereby an increased training status is accompanied by increased access to professional competence, the use supplements to enhance training adaptations, and more tailored use of ergogenic aids for competition. However, performance nutritionists in this study were of greater influence compared to previous observations in national and international swimmers (51% vs. 20–36%) (Moreno et al., 2022; Shaw et al., 2016a). Indeed, previous studies in swimmers and other highly trained young athletes typically cite their coach as the main supplementation informant (38–40%) (Jovanov et al., 2019; Moreno et al., 2022), which contrasts the present study (12%). This could indicate that sport nutrition support was more prioritised at the investigated swimming club than in others, making it unclear if these supplement practices can be generalised across the UK swimming population. In addition, the national swimmers in this study utilised a large number and variety of ergogenic supplements despite these yet to have strong evidence in applied swimming settings (see Chapter 1, section 1.6); thus, supporting the need further supplement research within this population.

Males and females both utilised a similar number of nutritional supplements, although there were sex-based differences in the individual supplements that were used. Female swimmers were more likely to state ‘performance’ as their primary reason for using supplements (+18% vs. males) and were engaged with greater uses of CAF anhydrous (+29% vs. males). However, this was likely due to the national group of swimmers consisting of a larger proportion of females (8 of 11 swimmers), which

meant that more females would have been receiving ergogenic supplement support directly from a performance nutritionist. In contrast, male swimmers utilised more protein-based products (enhanced foods: +32%, bars: +17%, powder: +13% vs. females) and multivitamin preparations (+40% vs. females), resulting in male swimmers using more supplements on a daily and regular basis. This was in combination with more male swimmers reporting the use of supplements for 'muscle gain' (8% vs. no females), which was in accordance with previous investigations in young athletes (Braun et al., 2009; Jovanov et al., 2019; Wiens et al., 2014). In all, since there were little differences in the supplement behaviours of male and female swimmers, these results suggest that a sex-based differences in supplement education is not required.

A limitation of this study was that supplement interviews were based on a previously validated nutritional supplement questionnaire (Sanchez-Oliver, 2012), which was originally produced and validated for mass dissemination within the Spanish sports population. This therefore limited the number of questions that were included, meaning that participants did not elucidate any information regarding dosing strategies or whether supplements were sourced from batch-tested suppliers; both of which are important considerations for determining whether supplements are being consumed in a safe and effective manner (Garthe & Maughan, 2018). This could have been overcome with the currently used interview method; hence, future investigations should consider utilising this approach with more in-depth questioning surrounding the use of each individual supplement. Nonetheless, the current methods were sufficient to appropriately identify general supplement practices in swimmers of different training status.

4.5 Conclusion

In summary, swimmers were identified as prevalent users of nutritional supplements from the development age (aged 11–14 years) through to those performing consistently at the national level. Development swimmers' supplement practices were largely influenced by parents/guardians, resulting in many sports supplements being consumed for the purpose of 'performance enhancement'. However, access to sport nutrition support was enhanced in swimmers at the age-group (aged 13–17 years) and national (aged ≥16 years) levels, which subsequently led to the influence of parents/guardians being replaced by performance nutritionists. It was at these training stages that a greater uptake of ergogenic aids was identified, likely requiring targeted nutrition interventions at the age-group and national levels to ensure safe practices are being followed. Moreover, since many ergogenic aids were used without much supporting evidence, further research in applied swimming settings is required to understand which, if any, of these supplements can benefit the training and/or competitive performances of highly trained adolescent swimmers.

Chapter 5 – An Observation of the Vitamin D Status in Highly Trained Adolescent Swimmers During the UK Autumn and Winter Months

Chapter can be found at: Newbury, J.W., Brown, M.A., Cole, M., Kelly, A.L. and Gough, L. A. (2023). An observation of the vitamin D status in highly trained adolescent swimmers during the UK autumn and winter months. *Physiologia*, 3(3), pp.442–450. Available at: https://doi.org/10.3390/physiologia3030031.

5.1 Introduction

Vitamin D is a fat-soluble vitamin with an involvement in numerous physiological processes, including bone health, immunity, cardiac function, and skeletal muscle remodelling (Owens et al., 2018); all of which could support long-term health and performance in swimmers. However, obtaining an adequate vitamin D intake through dietary sources can be challenging, given that low amounts of bioavailable vitamin D (i.e., ergocalciferol, cholecalciferol) are naturally found in foods and beverages (Holick et al., 1977). In contrast, large quantities of vitamin D can be naturally produced following direct sun exposure (Carlberg et al., 2013). This occurs as UVB radiation interacts with 7-dehydrocholesterol in the skin to catalyse the formation of cholecalciferol (vitamin D_3), which is later converted into 25(OH)D in the liver (Holick et al., 1977). Although, as this process is dependent on the UVB exposure, it is rate limited by two key factors: (a) living and training in countries of northern latitudes (≥40° N), whereby an 80–100% decrease in UVB availability occurs in the autumn and winter months (Farrokhyar et al., 2015; Webb et al., 1988); and (b) spending large quantities of time indoors either in training, school, and/or employment (Todd et al., 2015). This is problematic for highly trained adolescent swimmers in the UK (latitude: 51–55° N), who do not consume adequate amounts of vitamin D through diet (i.e., Chapter 3, section 3.3.6), and spend ~15–20 hours·week^{-1} training at indoor swimming facilities (i.e., Chapter 3, section 3.3.1 and Chapter 4, section 4.2.1). Thus, for this population, the use of vitamin D_3 supplements is warranted.

Swimming as a sport is associated with large seasonal declines in circulating 25(OH)D concentrations, although this can be offset with vitamin D_3 supplements (i.e., Chapter 1, section 1.3.3). Indeed, Lewis et al. (2013b) showed that 4000 IU·day^{-1} vitamin D_3 maintained the 25(OH)D concentrations of collegiate swimmers over an autumn and winter training period (August to March: +2.5 nmol·L^{-1}), compared to a 31% decline when swimmers who received a PLA (-50 nmol·L^{-1}). Similarly, Rockwell et al. (2020a) found 5000 IU·day^{-1} vitamin D_3 to increase the 25(OH)D of collegiate swimmers across an autumn training period (August to November: +9 nmol·L^{-1}), with a

large decline observed in swimmers who ingested a PLA supplement (-40 nmol·L^{-1}). Although, as the locations (USA: 37–38° N) of these studies enabled swimmers to obtain a summer 25(OH)D ≥120 nmol·L^{-1}, most swimmers were able to maintain a sufficient (≥75 nmol·L^{-1}) vitamin D status year-round without needing supplements (Galan et al., 2012). This finding is not universal, however, as 66% of adolescent swimmers from Israel (31° N) were found to have insufficient 25(OH)D during the autumn months (October: 62 ± 12 nmol·L^{-1}; Dubnov-Raz et al., 2015a). Moreover, while supplementation (2000 IU·day^{-1} vitamin D_3) increased circulating 25(OH)D across the autumn and winter training period (October to January: +12 nmol·L^{-1}), only 48% of this cohort achieved a sufficient vitamin D status. On the other hand, swimmers who were given a PLA supplement all experienced 25(OH)D declines (-11 nmol·L^{-1}), placing them at risk of vitamin D deficiency. This combined evidence shows that large seasonal declines in 25(OH)D are apparent in swimmers regardless of location, although these losses may be mitigated by consuming 2000–5000 IU·day^{-1} vitamin D_3 from August to March.

The importance of vitamin D and the risks of deficiency have become well acknowledged, with a large proportion of athletes (72–97%) recognising the possible health and performance benefits of supplementation (Hollabaugh et al., 2022; Leitch et al., 2021; Walker et al., 2014). Despite this greater education, however, it is currently unclear whether swimmers now adhere to supplement recommendations, or if widespread seasonal declines in serum 25(OH)D still exist. For example, Geiker et al. (2017) found that only 56% of adolescent swimmers in Denmark used vitamin D_3 supplements during the winter months, even though this population was at high risk of deficiency (e.g., latitude: 55° N, indoor training volume: 30 hours·week^{-1} of indoor training; Todd et al., 2015). Furthermore, those that did supplement used a wide variety of vitamin D_3 dosages (mean: 2600 ± 1960 IU·day^{-1}), resulting in both supplement users (57 ± 21 nmol·L^{-1}) and non-users (39 ± 13 nmol·L^{-1}) displaying insufficient and deficient 25(OH)D concentrations, respectively. While education and awareness of vitamin D might have improved since this 2017 study, results from Chapter 4 (section 4.3.2) suggested that only 73% of national swimmers, and 38% of age-group swimmers in the UK

currently utilise vitamin D_3 supplements, even after receiving education and individual nutrition support. Hence, the aim of this study was to assess the serum 25(OH)D concentrations in a cohort of UK-based, highly trained adolescent swimmers at two in-season time points: in the autumn (October), and during the winter (January).

5.2 Methods

5.2.1 Participants

Twenty adolescent swimmers (Caucasian = 18, Black = 2) from a high-performance swimming club in the UK volunteered for this study (Table 5.1), which an a priori power calculation determined to be an appropriate sample size for identifying moderate effect sizes (0.50) in within-between interactions, repeated measures ANOVA tests (two groups, two measurements) with a power >80% (input parameters: $\alpha = 0.05$, $ß = 0.80$, correspondence = 0.3; G*Power, v.3.1.9.4, Universität Düsseldorf, Germany). All swimmers were competitive at the national and age-group levels (see Chapter 2, section 2.1.2), and were all therefore classified as 'highly trained' (McKay et al., 2021). Moreover, seven swimmers from this cohort had recently represented their nations at junior international competitions. At the time of the study, swimmers were completing between 5–9 pool and 2–5 gym-based training sessions·week^{-1} at their training facility in the West Midlands (latitude: 52° N), where they remained throughout the observation period. Informed consent was given prior to the study by all participants, as well their parents/guardians if aged under 18 years. This study was granted ethical approval by BCU (Newbury/7594/R(B)/2020/Aug/HELS FAEC) in accordance with the Declaration of Helsinki.

Table 5.1. Characteristics of the study participants.

Swimmers	Age (years)	Height (m)	Body Mass (kg)	WA points*
Male (*n* = 8)	18 ± 2	1.80 ± 0.04	72.6 ± 8.3	705 ± 83
Female (*n* = 12)	16 ± 2	1.70 ± 0.09	62.1 ± 6.9	690 ± 55
Combined (*n* = 20)	17 ± 2	1.74 ± 0.09	66.3 ± 9.0	696 ± 66

* Mean WA points for the swimmers' best swimming stroke and distance in a 50 m pool.

5.2.2 Experimental Procedures

Based on the adolescent cohort, dried blood spot cards were used to determine serum 25(OH)D concentrations in accordance with the previously described methods (Chapter 2, section 2.2.4). In brief, all swimmers placed four fingertip capillary blood drops (~50–75 µL) onto a filter paper, which was allowed to dry before being sent to an independent laboratory (Sandwell & West Birmingham Hospitals NHS Trust, Birmingham, UK) for LC-MS/MS analysis. This process was completed in the first week of October (autumn; one month into the swimming season), and the first week of January (winter; four months into the swimming season).

For ethical and performance reasons, all swimmers and their parents/guardians were given basic information regarding the importance of vitamin D prior to the winter months as part of their ongoing sports nutrition support (see Chapter 2, section 2.1.4). This was delivered by the lead researcher to all swimmers as part of a classroom-based presentation (~20 min), whereas parents/guardians were sent the presentation slides electronically via a group instant messaging application (WhatsApp, Menlo Park, CA). Within the slides was the recommendation to supplement with 2000–5000 IU·day^{-1} vitamin D_3 from October until March based previous research (Dubnov-Raz et al., 2015a; Lewis et al., 2013b; Rockwell et al., 2020a). Following the winter (January) measurement of 25(OH)D, swimmers were asked whether they had taken any vitamin D_3 supplements over the study timeframe, to which 10 swimmers positively responded but with varying doses (2 x 400 IU·day^{-1}, 1 x 1000 IU·day^{-1}, 1 x

2000 IU·day^{-1}, 5 x 2500 IU·day^{-1}, 1 x 4000 IU·day^{-1}). Conveniently, a sub-group analysis of supplementing (VITD) versus non-supplementing (NONE) swimmers was included in the results.

5.2.3 Statistical Analysis

All statistical analyses were carried out in line with the descriptions in Chapter 2 (section 2.5.2). A 2 x 2 repeated measures ANOVA was used to determine main effects of time for the whole group of swimmers (October vs. January), as well as group level interactions between the VITD (n = 10) and NONE (n = 10) sub-groups. Effect sizes are reported as Pη^2 for the ANOVA test and g for pairwise comparisons (for interpretations, see Chapter 2, section 2.5.2). A SWC in 25(OH)D concentration of 4.3 nmol·L^{-1} was calculated by multiplying the SD of the initial October data set by 0.2 (Bernards et al., 2017). All data are reported as mean ± SD. Statistical significance was set at p <0.05.

5.3 Results

At the group mean level, 25(OH)D concentrations reduced by 13% from October (86 ± 26 nmol·L^{-1}) to January (75 ± 36 nmol·L^{-1}), but this decline did not reach statistical significance (F = 3.4, p = 0.082, Pη^2 = 0.16). However, large individual variances in serum 25(OH)D were observed at both the October (range: 46–124 nmol·L^{-1}, CV: 30%) and January time points (range: 31–172 nmol·L^{-1}, CV: 49%), which masked the changes taking place at the individual level. Overall, 16 swimmers (80%) experienced changes in serum 25(OH)D that exceeded the SWC, including 12 swimmers (60%) who experienced declines (range: -6 to -63 nmol·L^{-1}) and four swimmers (20%) who experienced increases (range: +10 to +52 nmol·L^{-1}). Based on these individual changes, there was an increase in the number of swimmers who developed an insufficient vitamin D status (October = 8 vs. January = 14), including a greater number of swimmers who could be classified as deficient (October = 2 vs. January = 5).

5.3.1 Sub-Group Analysis

The highly variable changes in vitamin D status observed at the group level were due to differences in supplement intakes (F = 7.4, p = 0.014, $P\eta^2$ = 0.29; Figure 5.1). While there was little difference between sub-groups in October (VITD: 92 ± 25 nmol·L^{-1} vs. NONE: 80 ± 25 nmol·L^{-1}, p = 0.228, g = 0.47), the NONE sub-group experienced a significant decline in 25(OH)D by January (mean change: -27 ± 20 nmol·L^{-1}, p = 0.005, g = 1.24), whereas no change occurred in the VITD group (mean change: +5 ± 31 nmol·L^{-1}, p = 0.544, g = 0.15). This resulted in a large difference between the two sub-groups at the January time point (VITD: 97 ± 38 nmol·L^{-1} vs. 53 ± 15 nmol·L^{-1}, p = 0.005, g = 1.47). Nine swimmers in the NONE had a decline in serum 25(OH)D above the SWC, resulting in all of this sub-group having insufficient or deficient vitamin D in January (Table 5.2). In contrast, variable 25(OH)D changes occurred in the VITD group (four increased, three maintained, three declined), which likely occurred because of the variable supplement strategies.

Table 5.2. Individual changes in serum 25(OH)D concentration from October to January in swimmers based on their reported vitamin D_3 supplementation.

NONE			VITD		
Swimmer	**Vitamin D_3 dose (IU·day^{-1})**	**Δ from October (nmol·L^{-1})**	**Swimmer**	**Vitamin D_3 dose (IU·day^{-1})**	**Δ from October (nmol·L^{-1})**
1	0	-26.3	**11**	400	-5.4
2	0	-53.2	**12**	2500	+25.0
3*	0	-53.0	**13**	4000	+41.9
4	0	-54.6	**14**	2000	+9.5
5	0	-23.8	**15**	2500	-3.7
6	0	-5.5	**16**	1000	-62.9
7*	0	-19.9	**17**	2500	+3.1
8	0	+1.0	**18**	2500	+52.0
9	0	-14.3	**19**	2500	-6.3
10	0	-19.9	**20**	400	-1.4

VITD = Vitamin D_3 supplementing sub-group. NONE = Non-supplementing sub-group. Δ = absolute change in serum 25(OH)D from October to January. SWC = 4.3 nmol·L^{-1}. * = swimmer of Black ethnicity.

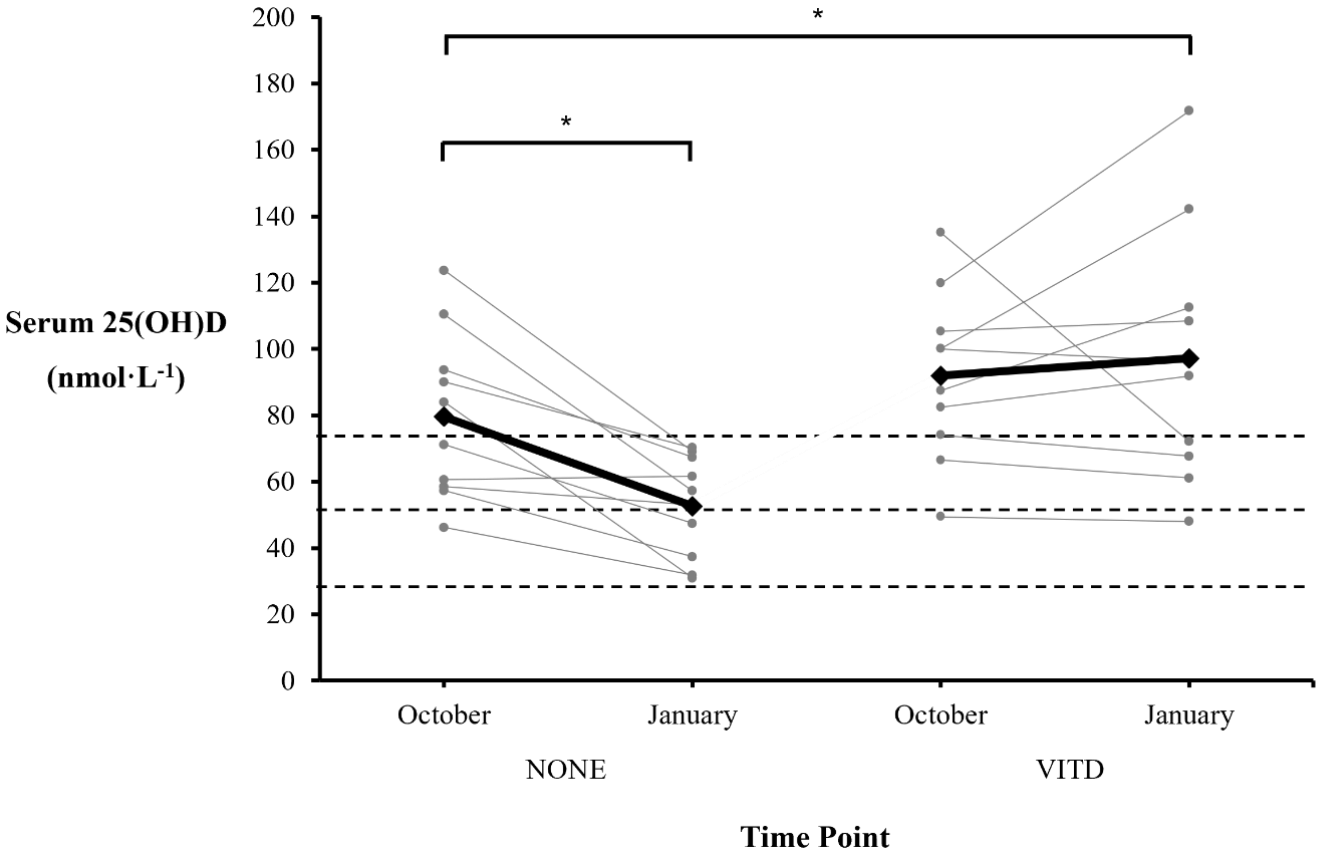

Figure 5.1. Individual changes in serum 25(OH)D concentration from October to January in swimmers who reported using vitamin D_3 supplements (VITD) or no supplements (NONE) over the study timeframe. Black line represents sub-group means. * = between or within group differences (p <0.05). Dotted lines represent vitamin D thresholds: ≤25 nmol·L^{-1} = severely deficient; 25–49 nmol·L^{-1} = deficient; 50–74 nmol·L^{-1} = insufficient; ≥75 nmol·L^{-1} = sufficient (Holick et al., 2011).

5.4 Discussion

This was the first study to observe a seasonal change in the vitamin D status of highly trained adolescent swimmers in the UK. A concerning finding was that only 60% of swimmers displayed a sufficient vitamin D status in October, which was approximately one month following a summer break from training. Moreover, all swimmers were advised to supplement with 2000–5000 IU·day^{-1} across the autumn and winter months in accordance with previous research (Dubnov-Raz et al., 2015a; Lewis et al., 2013b; Rockwell et al., 2020a), although only 50% of the swimmers adhered to

this recommendation. This resulted in highly variable changes in serum 25(OH)D occurring across the study timeframe, with swimmers either increasing (n = 4), maintaining (n = 4), or declining (n = 12) in vitamin D status. Importantly, the majority of swimmers who experienced 25(OH)D declines were identified in the sub-group who reported using no vitamin D_3 supplements (n = 9), resulting in all swimmers in this sub-group having an insufficient (60%) or deficient (40%) vitamin D status at a mid-season winter time point. These results support the requirement for all swimmers in the UK to utilise vitamin D_3 supplements, although further research is needed to identify methods to increase swimmer adherence to the recommendations.

From a group mean perspective, highly trained adolescent swimmers maintained a sufficient vitamin D status at both October and January time points; however, this analysis masked that 80% of the cohort experienced changes in 25(OH)D that exceeded the SWC (±4.3 nmol·L^{-1}). This failure to detect whole group changes in vitamin D status occurred since 50% of cohort avoided using vitamin D_3 supplements in the autumn and winter months, whereas the other 50% used vitamin D_3 supplements of varying doses (400–4000 IU·day^{-1}). This was in accordance with research by Geiker et al. (2017), who also identified that highly trained adolescent swimmers do not adhere to supplement recommendations, which in turn, resulted in a large proportion of swimmers developing an insufficient or deficient 25(OH)D across the winter months. Indeed, based on whole group data, 70% (n = 14) of this UK-based cohort were found to have insufficient vitamin D in January, including 25% (n = 5) who were deficient; supporting similar research in adolescent swimmers (Dubnov-Raz et al., 2015a). This could have important practical implications considering that insufficient vitamin D is associated to impairments in muscle function, recovery, and immunity (Owens et al., 2018); which is an area for further research in swimming populations. It should also be considered that this study only investigated 25(OH)D changes between October and January, thus it is plausible that greater declines in vitamin D status might have occurred if the experimental window was extended across the entire swimming season (Lewis et al., 2013b). Based on these results, highly trained adolescent swimmers in the UK should consider following standardised vitamin D_3 supplement protocols from October until

March (Dai et al., 2021); although given the variable doses used in this study, the exact dose remains unclear.

While the use of vitamin D_3 supplements were mostly found to preserve 25(OH)D concentrations during the autumn and winter months, variable effects were observed with some doses. For example, supplementing with 2500 IU·day^{-1} was thought to be an appropriate dose for adolescent swimmers (Dubnov-Raz et al., 2015a), but upon taking this amount, serum 25(OH)D either increased (n = 2), maintained (n = 2), or declined (n = 1). Such variable responses to this dose may have occurred due to some swimmers: (a) increasing or decreasing their dietary vitamin D and calcium intakes (Lips, 2012); (b) changing their habitual UVB exposure (e.g., tanning beds; Tangpricha et al., 2004); and/or (c) failing to adhere to their reported supplement intake (Hollabaugh et al., 2022). However, these potential explanations are all speculative given these confounding factors were not monitored. Nonetheless, these results support the findings of Dubnov-Raz et al. (2015a), who also found that a 2000 IU·day^{-1} strategy was only effective in 48% of adolescent swimmers. In contrast, vitamin D_3 doses ≥4000 IU·day^{-1} are thought to maintain a sufficient 25(OH)D more consistently than 1000–2000 IU·day^{-1} doses (Lewis et al., 2013a; Mazahery & von Hurst, 2015), suggesting the standardised ingestion of higher vitamin D_3 doses (4000–5000 IU·day^{-1}) may be a more appropriate when lifestyle factors are unknown (e.g., dietary intakes, UVB exposure). Such doses are well below the 'no observed adverse effect level' of 10,000 IU·day^{-1} and are considered safe for children and adolescents (Brustad et al., 2022; Hathcock et al., 2007).

Due to the variable vitamin D_3 supplement intakes that were observed, the importance of nutrition education is also highlighted. All swimmers in this study received a ~20 min classroom-based education session regarding the roles of vitamin D and the challenges of maintaining vitamin D status in the winter, including a specific recommendation to supplement with 2000–5000 IU·day^{-1} vitamin D_3 from October until March (Dubnov-Raz et al., 2015a; Lewis et al., 2013b; Rockwell et al., 2020a). In addition, all parents/guardians received the educational material electronically, including the

supplement advice. However, this education method only resulted in 35% (n = 7) of swimmers reporting the use of vitamin D_3 supplements within the recommended range. Interestingly, this low adherence to vitamin D_3 supplement recommendations is commonplace, with many athletes either not perceiving themselves at risk of deficiency (Leitch et al., 2021), lacking appropriate supplement knowledge to confidently buy the correct supplements (Walker et al., 2014), and/or not valuing the cost of vitamin D_3 supplements as a worthwhile investment (Rockwell et al., 2020b); all of which point towards a flaw in the current methods used to transfer practical nutrition knowledge to athletes. Indeed, previous work in this cohort has identified that 20–30 min classroom-based education sessions increased sport nutrition knowledge (Foo et al., 2021), though whether this knowledge translates into meaningful dietary changes remains less clear (Heaney et al., 2011). Alternatively, future education strategies might have greater success at improving practical nutrition behaviours by co-educating athletes alongside their parents/guardians, coaches, and support networks (Phillippou et al., 2017); especially since swimmers are likely to be reliant on their parents/guardians to purchase and administer vitamin D_3 supplements.

A limitation of this study was the use of dried blood spot cards, which were selected based on logistical and ethical considerations with this study cohort (Fryer et al., 2014). Previous research of vitamin D status in swimmers has analysed venous blood samples, given that 25(OH)D is largely found in the plasma (Dubnov-Raz et al., 2015a; Geiker et al., 2017; Lewis et al., 2013b; Rockwell et al., 2020a). However, this method requires specialist equipment and expertise to perform venepuncture on adolescents, followed by the timely transportation of blood to a processing laboratory that was not possible in this study (Binks et al., 2021). The alternate use of blood spot cards meant that 25(OH)D was analysed from whole capillary blood collected from the fingertip, which had to be corrected to account for sex-specific haematocrit levels (Heath et al., 2014). This process often results slightly lower 25(OH)D concentrations than found in plasma (~1.7–8.0 $nmol \cdot L^{-1}$), although the agreement between both measures is generally good (Heath et al., 2014; Larkin et al., 2011; Man et al., 2019). Therefore, while this study's classification of swimmer's vitamin D status should be

interpreted cautiously, the absolute changes in serum 25(OH)D that were observed were thought to be reliable. A second limitation was that the participant cohort was predominantly of Caucasian ethnicity, making it difficult to adequately assess the 25(OH)D changes experienced by Black swimmers. Interestingly, both Black swimmers displayed deficient 25(OH)D at the winter time point (participant 5: 84.0 to 31.0 nmol·L^{-1}; participant 17: 57.3 to 37.4 nmol·L^{-1}); although neither of these swimmers utilised vitamin D_3 supplements, nor were these declines any greater than those experienced by Caucasian swimmers, thus requiring further research in swimmers of ethnic minorities.

5.5 Conclusion

Overall, this study showed that highly trained adolescent swimmers in the UK are at risk of seasonal declines and insufficient 25(OH)D concentrations during winter months, highlighting potential risks to health and performance during this time. A secondary finding was that swimmers did not adhere to supplement recommendations, with only 50% of the cohort reporting the use of vitamin D_3 across the study timeframe (which were also highly variable in the doses used). Nonetheless, this supplementing sub-group better preserved their vitamin D status versus non-supplement users, supporting the use of standardised supplementation strategies for all swimmers across the autumn and winter training periods. Further research may therefore be required to develop contemporary vitamin D education strategies to improve adherence to supplement recommendations.

Chapter 6 – The Effects of Caffeine on Swimming Time-Trial Performances in the Evening, and the Next Morning After Sleep

Chapter can be found at: Newbury, J.W., Saunders, B. and Gough, L.A. (2022). Evening caffeine did not improve 100-m swimming time trials performed 60 min post-ingestion or the next morning after sleep. International Journal of Sport Nutrition and Exercise Metabolism, 32(6), pp.453–461. Available at: https://doi.org/10.1123/ijsnem.2022-0042.

6.1 Introduction

Caffeine is the most commonly used ergogenic aid by swimmers, with approximately 49–54% of swimmers at the national and international levels reporting its use (Moreno et al., 2022; Shaw et al., 2016). Interestingly, this intake may be higher in the UK swimming population, such that 82% of national swimmers (aged ≥16 years) and 23% of age-group swimmers (aged 13–17 years) declared its use at competitions (see Chapter 4, section 4.3.2), supporting the notion that adolescents perceive ergogenic supplements as critical for their performance and are willing to consume them despite knowing the potential health risks (Jovanov et al., 2019). However, the use of CAF by adolescent swimmers may be justified considering that: (a) they may already be consuming a performance-enhancing diet (i.e., Chapter 3); and (b) their swimming careers can be very short, often resulting in attrition from the sport before reaching adulthood (Monteiro et al., 2017). Discouragement of CAF may therefore be counterintuitive, and instead research should focus on identifying safe and effective ways for CAF to be used by adolescent swimmers to further their swimming careers.

A daily CAF ingestion of 3 mg·kg BM^{-1}·day^{-1} is currently thought to be safe for adolescents (ESFA, 2015), enabling a small-to-moderate bolus dose (i.e., 3 mg·kg BM^{-1}) to be supplemented for training and competition performances. The mechanisms of CAF have previously been discussed in detail (Chapter 1, section 1.5.1); though in short, it is generally accepted that the key ergogenic action occurs through adenosine antagonism (Guest et al., 2021). Indeed, by blocking adenosine receptor binding sites, CAF can decrease perceptions of tiredness and pain, as well as increase alertness and arousal (Davis & Green, 2009); both of which can increase exercise performance. This effect is thought to be more pronounced in athletes who habitually consume low CAF intakes (Pickering & Kiely, 2019b), such as those observed in highly trained adolescent swimmers (i.e., ~0.1 mg·kg BM^{-1}·day^{-1}; Chapter 3, section 3.3.7). A second consideration is that CAF is associated with adverse side-effects, which appear to increase with higher doses (>6 mg·kg BM^{-1}, Graham & Spriet, 1995; Pasman et al., 1995). Such symptoms include tachycardia, anxiety, headaches, jitters, and over arousal

(Sökmen et al., 2008); which could all negate swimming performance at competitions. For example, swimmers who already experience pre-race anxiety might have their feelings exacerbated with CAF supplementation, whereas over-arousal and/or jitters could result in a reduction in skill-based movements (i.e., starts and turns) that lead to disqualification (Guest et al., 2021). Therefore, based on the low habitual intakes and the apparent safety of 3 mg·kg BM^{-1}·day^{-1} doses for adolescents, this CAF strategy is thought to be safe and effective for improving competition swimming performances.

Despite CAF being highly popular amongst swimmers, there is currently limited evidence to support its use as ergogenic aid (see Chapter 1, section 1.5.1). This is particularly true in the case of adolescents, as only Collomp et al. (1992) have showed a performance benefit in regional-level swimmers (age: 17 ± 2 years). This occurred across 2 x 100 m time-trial performances with 20 min passive recovery (vs. PLA: +0.04 m·s^{-1}, g = 0.82 and +0.06 m·s^{-1}, g = 1.23, respectively); although, this feat was only achieved when exceeding the ESFA safety recommendation (~4 mg·kg BM^{-1}). Alternatively, another study found that regional-level adolescents (age: 14 ± 1 years) received no CAF benefits when 3 mg·kg BM^{-1} was ingested prior to a 400 m time-trial (-3.6 s, g = 0.08; Azizimasouleh et al., 2014). However, this lack of effect was likely due to CAF being ingested just 30 min before exercise, which is a suboptimal ingestion strategy (Maughan et al., 2018). All other CAF research has been conducted in adults, finding equivocal results in short-distance swimming (i.e., 45–75 m) time-trials with 3 mg·kg BM^{-1} CAF (Goods et al., 2017; Lara et al., 2015; Vanata et al., 2014). On the other hand, middle- (i.e., 200 m; Pruscino et al., 2008) and long-distance (1500 m; MacIntosh & Wright, 1995) swimming events appeared to be enhanced by CAF, albeit with doses twice the ESFA safety guideline (6 mg·kg BM^{-1}). Combined, the current evidence shows CAF to have ergogenic potential for most competitive swimming distances (i.e., 100–1500 m; Grgic, 2022); yet further research is required with smaller CAF doses before this supplement can be recommended as an efficacious ergogenic aid for highly trained adolescents.

A factor that has consistently been overlooked in research involving CAF and swimming is its effects on sleep, which is an important consideration given that competitions are typically held over 3–7 days. Indeed, CAF has a half-life lasting approximately 4–6 hours post-ingestion (Guest et al., 2021), potentially delaying tiredness and causing insomnia if ingested before evening performances (Dunican et al., 2018; Ramos-Campo et al., 2019). This is concerning from a recovery perspective, where high levels of performance are required in morning heats, as well as evening finals (Shaw et al., 2014). It is therefore claimed that a strategic trade-off between sleep and CAF needs to be made when preparing for competitive swimming finals. However, whether these purported side-effects are experienced by highly trained adolescent swimmers are yet to be determined, especially when low-to-moderate CAF doses are consumed. The purpose of this research was therefore to investigate the effects of 3 mg·kg BM^{-1} CAF on: (a) the evening 100 m swimming time-trial performance of highly trained adolescents; (b) the subjective side-effects and sleep parameters following ingestion; and (c) performance in a follow-up 100 m swimming time-trial performed the next morning.

6.2 Methods

6.2.1 Participants

An a priori power calculation (input parameters: repeated measures ANOVA test for within-between interactions, two groups, two measures; $\alpha = 0.05$; ß = 0.80; correspondence = 0.95, based on repeatability data presented in section 6.2.3) determined that a sample of size of eight swimmers was required to identify a small effect size (0.20) in 100 m swimming performance with a power of 84% (G*Power, v.3.1.9.4, Universität Düsseldorf, Germany). Twelve national swimmers from a high-performance swimming club originally volunteered for this study, who were all aged ≥16 years and classified as ‘highly trained’ (see Chapter 2, section 2.1.2). However, due to strict logistical and time challenges (i.e., pool availability morning and evening, altering the training regime of highly trained swimmers), four swimmers were not able to complete all data collection trials and were subsequently excluded from analysis. Resultantly, this study utilised a final study sample of eight highly trained

adolescent swimmers (five males, three females, age: 18 ± 1 years, body mass: 69.4 ± 6.4 kg, height: 1.76 ± 0.06 m, WA points for best 100 m event: 668 ± 81), who were all swimmers were completing eight pool (swimming volume: 42.7 ± 0.9 km·week^{-1}) and four land-based training sessions·week^{-1} (training time: 20.5 ± 1.2 hours·week^{-1}) during the experimental period. Written informed consent was provided by all swimmers (and their parents/guardians if under the age of 18 years). Ethical approval was granted by BCU (Newbury/9797/R(B)/2021/Oct/HELS FAEC) in accordance with the Declaration of Helsinki.

6.2.2 Pre-Experimental Procedures

The study took place during the swimmers' normal training regime (evening: 17:30–20:30 PM, morning: 04:45–07:00 AM). In consideration of swimming pool availability and the education commitments of the adolescent swimming cohort, these were the nearest possible times to replicate finals (18:00–20:00 PM) and heats (09:00–12:00 AM) at swimming competitions. Swimmers were requested to follow the pre-experimental dietary and activity controls as per Chapter 2 (section 2.1.4). Dietary records showed that low CAF intakes were consumed by all swimmers in this study (<50 mg·day^{-1}), consistent with the low habitual intakes reported in Chapter 3, section 3.3.7 (0.1 ± 0.2 mg·kg BM^{-1}·day^{-1}). Despite this, all swimmers reported the occasional ingestion of 100–450 mg CAF during competitions, which equalled to relative supplement doses ranging from 1.3–5.9 mg·kg BM^{-1}. No swimmers reported ingesting creatine or beta-alanine in the six months preceding the study. The familiarisation trial identified that swimmers were performing at 99% of their personal best 100 m swimming times.

6.2.3 Experimental Procedures

This study involved two experimental trials in a randomised, double-blind, and crossover design. Upon arrival at the training venue (time: 17:30 PM), each swimmer engaged in five min seated rest

before giving a 5 µL sample of capillary blood from the fingertip to assess resting blood La^- concentration (Lactate Pro 2, Arkray, Kyoto, Japan). The swimmers were then presented with a VAS to quantify baseline perceptions of nine psychological (mood, alertness, tiredness, anxiety, readiness to exercise) and physiological (tachycardia, jitters, headache, stomach upset) side-effects associated with CAF ingestion (Guest et al., 2021; Sökmen et al., 2008), which were completed in accordance with Chapter 2 (section 2.3.1). Following baseline measures, swimmers were then given a single hydroxypropyl methylcellulose capsule (size 00, Bulk Powders, Colchester, UK) consisting of either 3 $mg \cdot kg\ BM^{-1}$ CAF (anhydrous powder; Bulk Powders, Colchester, UK) or a cornflour PLA (ASDA, Leeds, UK). Capsules were created and randomised by a sport and exercise technician, and were administered to swimmers 60 min before the evening time-trial by the lead researcher.

Swimmers then prepared for exercise between 17:45–18:55 PM by first engaging in a self-selected, land-based warm-up (~10–20 min). Afterwards, all swimmers entered a 25 m pool for a 30 min standardised swimming warm-up that was prepared by the head coach. Further details of the warm-up procedures can be found in Chapter 2 (section 2.4.1). The remaining 10–20 min of the 60 min ingestion window was spent changing into race suits, in passive rest, and/or in pre-race activation work (3–5 min before exercise). Swimmers were then instructed to swim a 100 m distance as quickly as possible in their specialist stroke (i.e., four freestyle, two breaststroke, one backstroke, one butterfly). After the evening time-trial was complete, all swimmers completed a 30 min cool-down consisting of low-intensity, aerobic swimming. To maximise competitiveness, each time-trial was performed in two ‘heats’ of four swimmers based upon their 100 m personal best times. All warm-ups, heats, and swimming lanes were recorded and kept consistent for each subsequent time-trial.

The exact same routines were followed the next morning in preparation for a follow-up 100 m swimming time-trial (time: 04:45–05:55 AM). No CAF was supplemented in the morning to assess the possible effects that evening supplementation had on next-day performances. During both trials, swimmers were asked to predict which supplement they had ingested: (a) immediately after the

evening time-trial: and (b) in preparation for the morning time-trial. An analysis of this cohort's past data suggesting that this cohort had a high test-retest reliability in 100 m swimming time-trials (CV: 0.6–1.6%), with an 'excellent' reproducibility over their previous four attempts (ICC: r = 0.984, p <0.001) (Atkinson & Nevill, 1998; Koo & Li, 2016).

6.2.4 Experimental Measures

Swimming was timed by two experienced swimming coaches and the mean of both times was used as the performance measure. Ratings of perceived exertion (RPE) for the whole body were collected immediately after the warm-ups (WARM-UP PM, WARM-UP AM), and after each 100 m swimming time-trial (100 m PM, 100 m AM) using a CR10 Borg scale (Borg, 1998). The previously described methods to collect blood La^- and perceptual side-effects (section 6.2.3) were conducted at seven time points: resting baseline on the evening (BASE PM); immediately after the evening pool warm-up (PRE-TT PM); immediately after the evening 100 m time-trial (POST-TT PM); immediately after the evening cool-down (COOL-DOWN PM); at rest in the morning (BASE AM); immediately after the morning warm-up (PRE-TT AM); and immediately after the morning 100 m time-trial (POST-TT AM).

6.2.5 Subjective Sleep Parameters

All swimmers were requested to follow their normal sleep routines, environments, and timings throughout the duration of the study. Upon waking on the morning of the experiment, swimmers completed an electronic adaptation of the CCSD (Carney et al., 2012), which is discussed in greater detail in Chapter 2 (section 2.3.3). In short, the questionnaire involved six short-answer questions and one 1–5 Likert scale for subjective sleep quality, which together gave the following subjective information: (a) bedtime; (b) intended time to fall asleep; (c) sleep latency; (d) time awake in the night; (e) wake up time; (f) out of bed time; (g) total time in bed; (h) total sleep time; (i) sleep

efficiency; and (j) sleep quality. Questionnaires were completed twice per experimental trial: the night before the evening 100 m time-trial (night one, control), and the night of the evening 100 m time-trial (night two, experimental). Answers to the questionnaires were followed up with the swimmers during measurements at BASE PM and BASE AM to confirm the accuracy of reporting.

6.2.6 Statistical Analysis

All statistical tests were carried out in accordance with Chapter 2 (section 2.5.2). A 2 x 2 repeated measures ANOVA was used to determine CAF and PLA interactions for 100 m time-trial performances (100 m PM, 100 m AM) and all sleep variables (night one, night two). A 2 x 4 repeated measures ANOVA was used to analyse differences in RPE (WARM-UP PM, WARM-UP AM, 100 m PM, 100 m AM). A 2 x 7 repeated measures ANOVA was conducted to identify changes in blood La^- and all physiological and psychological side-effects across the study timeframe (BASE PM, PRE-TT PM, POST-TT PM, COOL-DOWN PM, BASE AM, PRE-TT AM, POST-TT AM). Effect sizes are reported as $P\eta^2$ for all ANOVA tests, whereas *g* was calculated and reported for all pairwise comparisons (for interpretations, see Chapter 2, section 2.5.2). A SWC in 100 m time-trial performance was determined to be 1.5 s, which was calculated by multiplying the SD in the PLA condition x 0.2 (Bernards, et al., 2017). Reported time data were quantified for sleep analysis. This involved translating hours into whole numbers out of 24 (e.g., 9 PM = 21.00), and translating min into decimals by dividing by 60 (e.g., 20 min = 0.33). Test-retest reliability for 100 m performance was calculated using CV, whereas reproducibility was analysed via ICC (Chapter 2, section 2.5.3). All data are reported as mean ± SD. Statistical significance was set at $p < 0.05$.

6.3 Results

6.3.1 Swimming Performance

No differences were observed in mean 100 m time-trial performances across the study timeframe (F = 0.1, p = 0.911, $P\eta^2$ <0.01; Figure 6.1), resulting in trivial effect sizes being calculated for CAF versus PLA performances at 100 m PM (59.5 ± 7.8 s vs. 59.9 ± 7.9 s, g = 0.07) and 100 m AM (59.7 ± 7.7 s vs. 60.2 ± 7.9 s, g = 0.06). Only one swimmer had a performance difference exceeding the SWC, which was achieved during 100 m PM following CAF ingestion (59.0 s vs. 60.6 s).

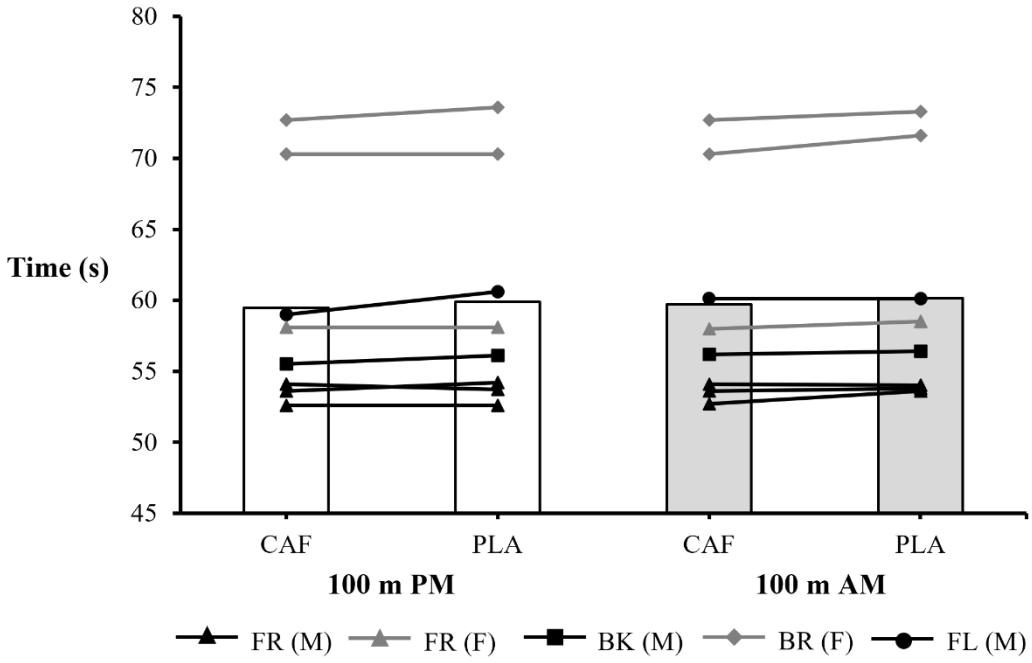

Figure 6.1. Individual and mean 100 m swimming time-trial performances in the evening (100 m PM) and following morning (100 m PM) after CAF or PLA ingestion.

6.3.2 Physiological and Perceptual Measures

Blood La^- production did not differ between CAF or PLA conditions at any time point (F = 0.7, p = 0.649, $P\eta^2$ = 0.09; Figure 6.2), with only trivial or small effect sizes being produced (all g <0.50).

Moreover, no differences were observed in the swimmers' RPE scores (F = 0.4, p = 0.757, $P\eta^2$ = 0.05), including at WARM-UP PM (CAF: 4.5 ± 1.1 units vs. PLA: 4.5 ± 1.3 units, g = 0.00), WARM-UP AM (4.0 ± 0.8 units vs. 4.3 ± 1.0 units, g = 0.31), 100 m PM (CAF: 9.5 ± 0.8 units vs. PLA: 9.5 ± 0.8 units, g = 0.00), and 100 m AM (9.5 ± 0.8 units vs. 9.9 ± 0.4 units, g = 0.60); although a moderate effect size was calculated for the latter time point.

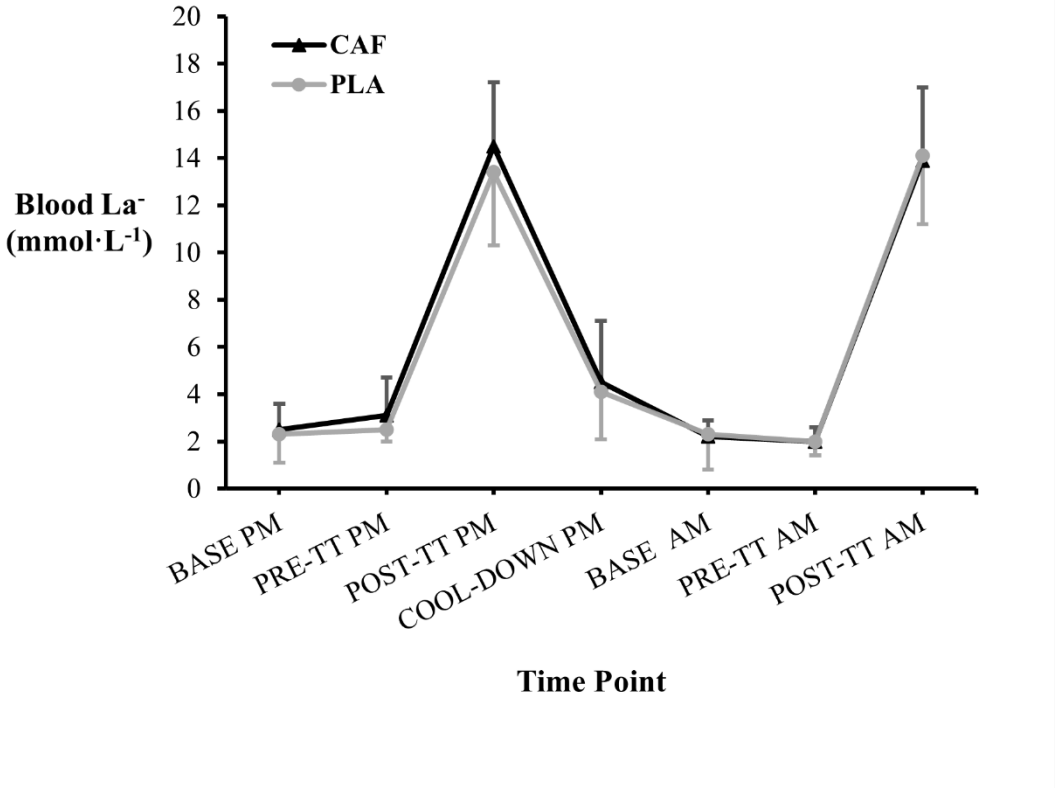

Figure 6.2. Group mean changes in blood La^- concentration across the study timeframe.

6.3.3 Perception of Side-Effects

No CAF versus PLA effects occurred across the seven sampling time points for the perceived ratings of tachycardia (F = 0.4, p = 0.859, $P\eta^2$ = 0.06), jitteriness (F = 0.4, p = 0.888, $P\eta^2$ = 0.05), stomach upset (F = 1.0, p = 0.456, $P\eta^2$ = 0.12), or headaches (F = 0.4, p = 0.635, $P\eta^2$ = 0.06) (Figure 6.3). One occurrence of severe stomach upset was reported, which appeared to occur after exercise and overnight following CAF ingestion (COOL-DOWN PM: CAF = 7.6 units, PLA = 4.4 units; BASE AM: CAF = 9.8, PLA = 1.7 units).

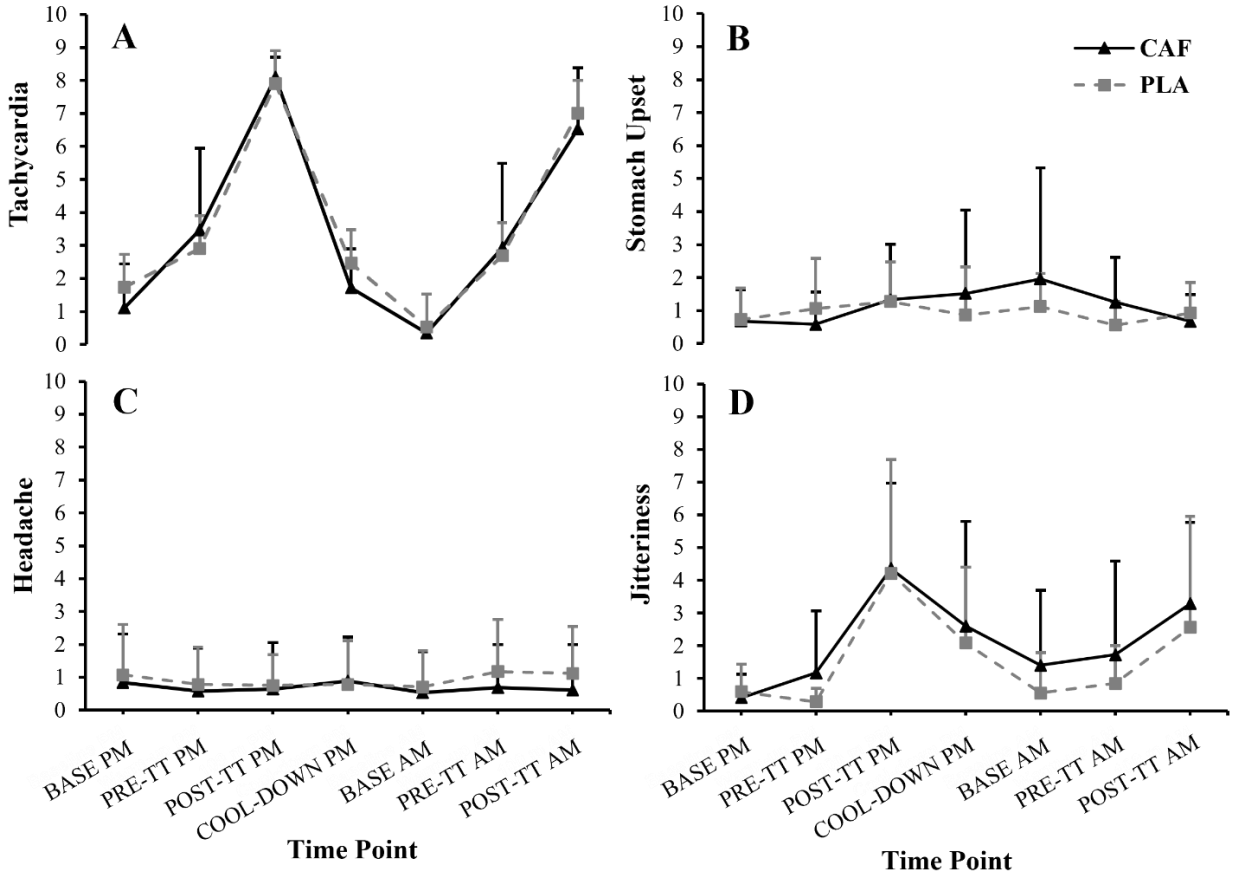

Figure 6.3. The subjective ratings of A) tachycardia, B) stomach upset, C) headache, and D) jitteriness experienced by swimmers across the study timeframe. Subjective ratings out of 10 arbitrary units, where 0 = 'no symptom' and 10 = 'very severe symptom'.

Similarly, no supplement effects occurred within the subjective psychological side-effects of anxiety ($F = 0.9$, $p = 0.486$, $P\eta^2 = 0.12$), tiredness ($F = 0.9$, $p = 0.497$, $P\eta^2 = 0.12$), alertness ($F = 0.2$, $p = 0.959$, $P\eta^2 = 0.03$), readiness to exercise ($F = 1.6$, $p = 0.168$, $P\eta^2 = 0.19$), or mood ($F = 1.0$, $p = 0.451$ $P\eta^2 = 0.12$) (Figure 6.4).

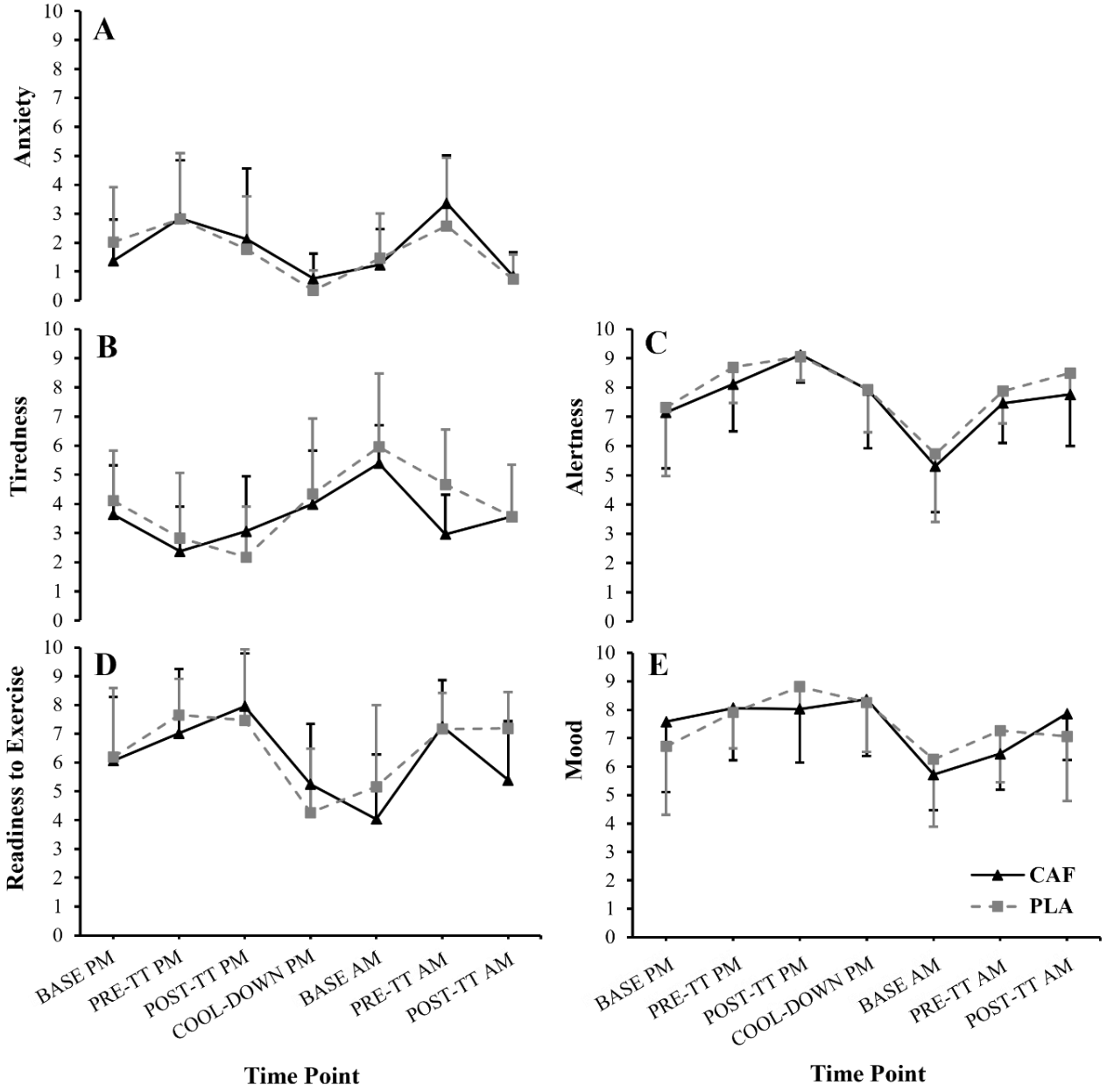

Figure 6.4. The subjective ratings of A) anxiety, B) tiredness, C) readiness to exercise, D) alertness, and E) mood experienced by swimmers across the study timeframe. Subjective ratings out of 10 arbitrary units, where 0 = 'no symptom' and 10 = 'very severe symptom'.

6.3.4 Subjective Sleep Parameters

No differences were observed in any subjective sleep variable following evening CAF or PLA ingestion (Table 6.1). During night two, however, moderate and large effect sizes were calculated in the mean CAF versus PLA differences for bedtime (+23 min, g = 1.10), time intended to fall asleep (+19 min, g = 0.61), sleep latency (+14 min, g = 0.50), total time spent in bed (-26 min, g = 1.09), and total sleep time (-32 min, g = 0.71). An observation of all data showed that main effects occurred for time between night one and night two, with night two having an earlier wake up time (-3 hours 45 min, F = 49.8, p <0.001, $P\eta^2$ = 0.88), an earlier time to leave bed (-3 hours 58 min, F = 55.0, p <0.001, $P\eta^2$ = 0.89), a longer sleep latency (+16 min, F = 9.5, p = 0.018, $P\eta^2$ = 0.58), less overall time in bed (-4 hours 10 min, F = 32.3, p = 0.001, $P\eta^2$ = 0.82), less time spent asleep (-3 hours 36 min, F = 35.3, p = 0.001, $P\eta^2$ = 0.84), and reduced sleep quality (-1.0 units, F = 16.0, p = 0.005, $P\eta^2$ = 0.67).

Table 6.1. Sleep parameters for the night one (before) and night two (after) of the experimental trials.

Sleep Parameter	Night One		Night Two		Interaction
	CAF	PLA	CAF	PLA	
Bedtime (h:min)	21.58 ± 1:39	21:55 ± 0:25	22:20 ± 0:12	21:58 ± 0:24	F = 0.5, p = 0.483, $P\eta^2$ = 0.07
Intend to sleep (h:min)	22:55 ± 0:30	22:30 ± 0:23	22:36 ± 0:20	22:17 ± 0:32	F = 0.9, p = 0.376, $P\eta^2$ = 0.11
Sleep latency (min)	19 ± 26	21 ± 19	43 ± 29	29 ± 24	F = 0.8, p = 0.395, $P\eta^2$ = 0.11
Awake in the night (min)	20 ± 41	5 ± 11	2 ± 4	6 ± 8	F = 1.7, p = 0.240, $P\eta^2$ = 0.19
Wake up time (h:min)	08:17 ± 1:22	07:35 ± 2:19	04:10 ± 0:08	04:13 ± 0:10	F = 0.7, p = 0.426, $P\eta^2$ = 0.09
Out of bed time (h:min)	08:41 ± 1.29	07:47 ± 2:25	04:14 ± 0:07	04:17 ± 0:08	F = 1.0, p = 0.356, $P\eta^2$ = 0.12
Total time in bed (h:min)	10:43 ± 2:02	9:52 ± 2:37	5:55 ± 0:17	6:19 ± 0:24	F = 1.8, p = 0.218, $P\eta^2$ = 0.21
Total sleep time (h:min)	8:44 ± 1:20	8:39 ± 2:10	04:49 ± 0:34	5:20 ± 0:49	F = 0.3, p = 0.574, $P\eta^2$ = 0.05
Sleep efficiency (%)	83.3 ± 14.6	81.4 ± 8.2	88.1 ± 6.5	84.4 ± 10.3	F = 0.1, p = 0.781, $P\eta^2$ = 0.01
Sleep quality (*n*/5)	4.1 ± 0.4	4.2 ± 0.6	3.3 ± 0.9	3.0 ± 0.5	F = 0.4, p = 0.563, $P\eta^2$ = 0.05

Mean ± SD.

6.3.5 Participants and Supplement Predictions

Of the four swimmers who did not complete all data collection, three were uncontrollable by this study (one injury, one illness, one change in education schedule). The final swimmer had to be excluded from the study due to oversleeping and missing the morning experimental trial following CAF ingestion (reported sleep time: 03:15–10:30 AM, sleep latency: 195 min), which might have been related to the supplement ingestion. Only the eight swimmers who completed all trials predicted their supplement ingestion, with correct predictions only occurring on 38% of occasions.

6.4 Discussion

The purpose of this study was to investigate the effects of a small-to-moderate CAF dose (3 mg·kg BM^{-1}) on the evening swimming performances of highly trained adolescent swimmers, and whether this supplementation had carryover effects on subjective sleep and next-day performances. In contrast to previous work, CAF did not improve 100 m swimming time-trial performance (Collomp et al., 1992), nor did it induce any significant effects on side-effects or sleep compared to a PLA supplement (Dunican et al., 2018; Ramos-Campo et al., 2019). Moreover, there did not appear to be any difference in 100 m time-trial performance between the evening and morning trials, suggesting that neither CAF nor total sleep (i.e., ~8–9 hours on night one vs. ~4–6 hours on night two) are critical factors for short-distance swimming performance in adolescents; at least over one night.

The ingestion of a CAF dose thought to be safe for adolescents (3 mg·kg BM^{-1}) had no ergogenic benefits to 100 m swimming performance. This directly contrasts previous research, where trained adolescent swimmers improved their 100 m time-trial swimming speeds after ingesting 4 mg·kg BM^{-1} CAF (Collomp et al., 1992). The difference in study outcomes potentially lied in the different dosing strategies used, such that the larger dose used by Collomp et al. (1992) may have been necessary to activate both central and peripheral ergogenic mechanisms to enhance performance (Spriet, 2014).

Indeed, Collomp et al. (1992) also observed greater post-exercise increases in blood La^- than the present study, a change that could infer that swimmers either: (a) had a greater glycolytic energy contribution (Nevill et al., 1989); (b) experienced a delay in fatigue due to muscular Ca^{2+} and K^+ movements (Guest et al., 2021); and/or (c) gave a greater effort after experiencing more intense CAF side-effects (Shabir et al., 2018); though as neither of these potential mechanisms were measured directly, the actual reason for the differing performance outcomes remains unclear. Alternatively, the highly trained swimmers in this study were not blinded of their performance times, giving them a motivational target that may have been achievable with or without CAF ingestion. This was evidenced as all swimmers were capable of reproducing their 100 m performances (CV = 0.6–1.6%) and were performing at ~99% of their personal best times at the time of the study, thus reducing their 'potential for improvement' following CAF ingestion (Pickering & Grgic, 2019). However, as this scenario replicates how adolescent swimmers would ingest CAF at real-world competitions, these results question the efficacy of using the safe 3 mg·kg BM^{-1} dose as a pre-race nutrition strategy.

The ingestion strategy used in this study has long been suggested to be the most ergogenic CAF protocol (3–6 mg·kg BM^{-1}, 60 min before exercise; Maughan et al., 2018); however, using this approach for all swimmers might not be appropriate. For example, factors such as dietary intake (Abuhelwa et al., 2017), preferred CAF source (Wickham & Spriet, 2018), habitual CAF intake (Pickering & Kiely, 2019b), inter-individual CAF absorption characteristics (Pickering & Kiely, 2019b), and sex hormones (Temple & Ziegler, 2011) can each affect the optimal CAF dose and/or timing required to induce an ergogenic response. Considering the current study did not control for genotypes, menstrual cycle stage, or dietary composition between swimmers, it is suspected that a combination of these individual factors could have negated the CAF effects during the experimental trials. Moreover, each swimmer also reported using CAF in practice, with a variety of doses (range: ~1–6 mg·kg BM^{-1}) and sources (energy drink = 1, energy shot = 1, gum = 1, tablets = 5) being consumed. Thus, administering a different CAF source compared to what the swimmers were familiar with (e.g., a singular capsule vs. six tablets) might also have had an effect, possibly preventing

swimmers from ‘feeling’ like an ergogenic effect was going to occur (Shabir et al., 2018). Higher CAF doses (i.e., 4–6 mg·kg BM^{-1}) could therefore be an alternative for future research, as these appear to show more consistent effects on swimming performance (Collomp et al., 1992; MacIntosh & Wright , 1995; Pruscino et al., 2008). Although further research is needed to determine if these doses are well tolerated and safe for adolescents.

The ingestion of CAF before an evening time-trial also had little impact upon sleep or a next-day performance. The results from this study should be interpreted cautiously, however, given that only subjective measures were used, and there was only limited time (8.5 hours) available for sleep between the evening and morning time-trials. For example, moderate effect sizes were calculated for a shortened sleep duration (-32 min, g = 0.71) and increased sleep latency (+14 min, g = 0.50) with CAF ingestion, which are both frequently observed when CAF supplements are ingested up to six hours before attempting to sleep (Drake et al., 2013; Dunican et al., 2018; Ramos-Campo et al., 2019). Importantly, Drake et al. (2013) has previously compared subjective versus objective (polysomnography) sleep parameters, identifying that participants achieved less total sleep and were awake for longer during the night than they perceived following CAF ingestion, whereas no differences were found after ingesting PLA. Therefore, based on these effect sizes, it is suspected that significant CAF versus PLA effects may have been observed if objective sleep measures and *ad libitum* sleeping hours were available. This is further supported since the sleep data from one swimmer was excluded from the study after they overslept and missed the morning time-trial after evening CAF ingestion, reporting an exacerbated sleep latency (195 vs. 75 min) as the reason behind the inability to wake. Though while these results suggest that CAF might negatively impact the sleep of adolescent swimmers in practice, this requires further research using objective sleep measures to be confirmed.

Conducting this research in an applied setting produced logistical challenges that could not be controlled, thus restricting the total sleep (~4–6 hours) that could be achieved by each swimmer.

However, while this amount of sleep is commonplace in highly trained swimming populations (Sargent et al., 2014), and did not appear to affect the next-day performances, all swimmers reported a 3–4-hour reduction in total sleep time between the control (night one) and experimental sleeps (night two) that made it difficult to examine any CAF-related effects. A second challenge concerned swimmers being in a critical training phase in preparation for a national competition, which restricted the flexibility of the swimmers' training schedules. Indeed, the head coach only permitted three opportunities (familiarisation and two experimental trials) to implement time-trial swimming and collect research data, restricting the control of menstrual cycle stage in female swimmers that could have altered sleep variables (Baker & Lee, 2018) and the perception of CAF side-effects (Temple & Ziegler, 2011). Finally, depending on their education schedules, some swimmers either went back to sleep (n = 2), had a nap prior to higher education (n = 2), or went straight to school (n = 2) after morning time-trials. These different actions restricted the ability to compare measures of daytime sleepiness, mood, and mental performance the day after CAF ingestion, which could all be limiting factors to performance at multi-day swimming competitions (Fullagar et al., 2015; Roehrs & Roth, 2008). In all, further research with greater experimental controls is required to fully elucidate the effects of CAF on sleep and performance in highly trained adolescent swimmers. Due to logistical challenges, however, this research may need to take place during real-world competitions, where education and training commitments have less impact on sleep.

6.5 Conclusion

In summary, a small-to-moderate CAF dose (3 mg·kg BM^{-1}) had no effect on the 100 m swimming performances of highly trained adolescents when ingested an hour before an evening time-trial. Moreover, minimal physical or psychological side-effects were produced before, during, or after exercise, suggesting that no ergogenic mechanisms were active. There also appeared to be little differences in subjective sleep parameters following evening CAF ingestion, though possible effects on total sleep duration and sleep latency require further exploration using objective measures. Nonetheless, all swimmers were able to replicate their 100 m swimming performance the following morning despite only achieving 4–6 hours' sleep, suggesting that a single night of sleep disturbance may not be a concern for next-day performance in highly trained adolescent swimmers. Overall, the lack of CAF benefits in this study might have likely occurred since each swimmer had different dietary intakes, previous CAF experience, genetics, and sex hormones; factors that all affect CAF absorption and perceived effects. Further research should therefore determine whether higher CAF doses are safe for adolescent consumption, given these appear to show more consistent ergogenic effects in time-trial swimming.

Chapter 7a – The Effects of Sodium Bicarbonate on Blood Acid-Base Variables in Highly Trained Adolescent Swimmers

Chapter can be found at: Newbury, J.W., Cole, M., Kelly, A.L., Chessor, R.J., Sparks, S.A., McNaughton, L.R. and Gough, L.A. (2021). The time to peak blood bicarbonate (HCO_3^-), pH, and the strong ion difference (SID) following sodium bicarbonate ($NaHCO_3$) ingestion in highly trained adolescent swimmers. *PLoS One*, 16(7), pp.e0248456. Available at: https://doi.org/10.1371/journal.pone.0248456.

7a.1 Introduction

Sodium bicarbonate ($NaHCO_3$) is one of few nutritional ergogenic aids with strong ergogenic potential (Maughan et al., 2018). The acting mechanisms relating to $NaHCO_3$ ingestion have been discussed in detail (Chapter 1, section 1.5.2), which appear to be contested between either: (a) an increased blood buffering capacity (i.e., HCO_3^-, pH), that accelerates H^+ removal during exercise to delay fatigue (Fitts, 2016; Lancha Junior et al., 2015); or (b) an increased intramuscular SID, that enhances excitation-contraction coupling and delays the depolarisation of skeletal muscles during exercise (Siegler et al., 2016; Westerblad, 2016). At present, the most well acknowledged mechanism is the former, with $NaHCO_3$-induced increases in blood HCO_3^- of ≥5 mmol·L^{-1} and ≥6 mmol·L^{-1} associated with 'potential' and 'almost certain' ergogenic benefits, respectively (Heibel et al., 2018). A caveat to this, however, is that the time taken to reach these ergogenic thresholds is highly variable between individuals, occurring anywhere between 40–125 min post-ingestion with $NaHCO_3$ solutions (Gough et al., 2017, 2018b, 2019a), or between 60–240 min post-ingestion with $NaHCO_3$ capsules (Jones et al., 2016; de Oliveira et al., 2021). This highlights a flaw in the current dosing guidelines (e.g., 60–150 min pre-exercise for all athletes; Maughan et al., 2018), which partly explains why historical $NaHCO_3$ research has found equivocal performance outcomes (McNaughton et al., 2016).

Research is attempting to solve the $NaHCO_3$ timing issue by administering ingestion based on individual peaks in blood HCO_3^- or pH, showing consistent performance benefits versus PLA supplements to date (Miller et al., 2016; Gough et al., 2018a, 2019b, 2022). However, only Boegman et al. (2020) have directly compared whether $NaHCO_3$ is more effective when ingested at an individualised (e.g., 40–160 min pre-exercise) or standardised time point (60 min pre-exercise for all participants), finding an ergogenic effect in 18 of 23 world-class rowers during a 2000 m time-trial performance (mean improvement: -2 s; g = 0.19). Interestingly, this result occurred despite only a small difference in pre-exercise blood HCO_3^- concentrations (individualised: +6.0 mmol·L^{-1} vs. standardised: +5.5 mmol·L^{-1}), potentially inferring that the proposed SID mechanism was more active

with the individualised approach. Indeed, studies have displayed an increase in the apparent SID (+6–10 mEq·L^{-1}) when $NaHCO_3$ improves exercise performance (Gough et al., 2018b; 2019b), therefore it is plausible that the movement of strong ion changes could be the primary ergogenic mechanism. As studies have not yet monitored the time course changes in the SID following $NaHCO_3$ ingestion, it is currently unclear when a peak SID occurs in relation to peaks in blood HCO_3^- or pH, which could have important implications for the future of $NaHCO_3$ supplementation if these times were to differ in practice.

Chapter 4 (section 4.3.2) found $NaHCO_3$ to be a popular ergogenic aid amongst highly trained adolescent swimmers (36%), despite the efficacy of this supplement being unclear for this age group. Only two studies to date have investigated $NaHCO_3$ in highly trained adolescents, both of which found contrasting performance outcomes. Firstly, Zajac et al. (2009) observed a 1.3% faster sprint swimming performance across 4 x 50 m efforts with a 0.3 g·kg BM^{-1} $NaHCO_3$ solution (standardised 90 min pre-exercise). Although, this improvement was mostly due to a faster swimming speed in the first bout (+0.05 m·s^{-1}), which is a timeframe (~25 s) not typically thought to benefit from $NaHCO_3$ ingestion (Maughan et al., 2018). In the second study, Guimarães et al. (2020) found no ergogenic benefit of a 0.3 g·kg BM^{-1} $NaHCO_3$ solution (standardised 90 min pre-exercise) across 6 x 35 m running sprints. Both studies also found that blood HCO_3^- concentrations were not raised above the mooted +5 mmol·L^{-1} ergogenic threshold (+3.4 mmol·L^{-1} in both studies), which the authors speculated might not be able to be achieved in adolescents due to differences in gastrointestinal physiology (Merchant et al., 2016), or carbon dioxide elimination rates (Ratel et al., 2002), compared to adults. However, these speculations cannot be confirmed since neither study utilised an individualised $NaHCO_3$ strategy. Therefore, in order for adolescent swimmers to benefit from $NaHCO_3$ supplementation, it is first necessary to understand the possible acid-base balance alterations that occur following ingestion. The purpose of this study was to explore the time course changes and peak blood concentrations of HCO_3^-, pH, and the apparent SID after highly trained adolescent swimmers ingested 0.3 g·kg BM^{-1} $NaHCO_3$.

7a.2 Methods

7a.2.1 Participants

Twelve national swimmers from a high-performance swimming club volunteered to participate in this study, all of whom were classified as 'highly trained' (see Chapter 2, section 2.1.2). At the time of the study, three of the cohort had recently represented their nations at either the European Junior Swimming Championships or the European Youth Olympic Festival, while seven had qualified for Olympic trials in the UK. Moreover, all participating swimmers were ranked in the top 25 swimmers in the UK for at least one event within their respective age categories (mean WA points: 696 ± 62). Further characteristics of the study cohort can be found in Table 7a.1. At the time of data collection, swimmers were completing 7–9 pool (swimming volume: 50.9 ± 3.4 km·week^{-1}) and 2–5 gym-based training sessions·week^{-1} while in a specific race preparatory training period. The study was granted ethical approval by BCU (Newbury/3649/R(B)/2019/Nov/HELS FAEC), while both the swimmers and their parents/guardians provided written informed consent prior to their participation in the study.

Table 7a.1. Characteristics of the study participants.

Characteristic	Males (*n* = 5)	Females (*n* = 7)	Combined (*n* = 12)
Age (years)	16 ± 1	16 ± 1	16 ± 1
Height (m)	1.78 ± 0.06	1.70 ± 0.04	1.73 ± 0.06
Body mass (kg)	72.4 ± 10.7	60.3 ± 4.8	65.3 ± 9.6
Time competitive (years)	8 ± 2	8 ± 1	8 ± 1

Mean ± SD.

7a.2.2 Pre-Experimental Procedures

Each swimmer attended training as per their normal daily routine (time: 17:00–20:30 PM) having been instructed to eat as they normally would prior to a competitive race. These instructions were

given since previous investigations have assessed time course changes in HCO_3^- and pH when fasted (Gough et al., 2017; Jones et al., 2016) or following a standardised meal (Boegman et al., 2021; de Oliveira et al., 2020), which do not replicate the variance in baseline acid-base balance, electrolyte status, and absorption rates that would occur in practice (Abuhelwa et al., 2017; Remer & Manz, 1995). Moreover, the ingestion of $NaHCO_3$ capsules alongside a meal was also thought to reduce the occurrence and severity of potential gastrointestinal side-effects (Carr et al., 2011b), therefore this ingestion approach was most appropriate for this adolescent cohort. The dietary intakes reported by the swimmers in the 24 hours swimmers prior to $NaHCO_3$ ingestion are presented in Table 7a.2, which were collected and analysed via the previously described methods (see Chapter 2, section 2.2.2). Water was permitted to be consumed *ad libitum* following $NaHCO_3$ ingestion (mean intake: 1.2 ± 0.5 L, range: 0.5–2 L), though the intake of further nutrients was restricted. Swimmers were also asked to refrain from additional exercise outside of their regular swim training programme in the 48 hours prior to the study. No swimmers ingested CAF, although some swimmers reported having ingested creatine (swimmers 8–12) and beta-alanine (swimmers 11 and 12) in the preceding six months. However, neither of these supplements are thought to influence acid-base balance characteristics in the blood (Hobson et al., 2013; Sale et al., 2011), therefore any observed changes would be caused by the acute $NaHCO_3$ ingestion.

Table 7a.2. Dietary intakes reported by the swimmers prior to $NaHCO_3$ ingestion.

Nutritional Variable	24 hours pre-ingestion	1–3 hours pre-ingestion
Total energy intake (kcal·day^{-1})	2852 ± 926	655 ± 285
Relative energy intake (kcal·kg BM^{-1}·day^{-1})	43.3 ± 9.8	10.0 ± 3.7
Total carbohydrate (g·day^{-1})	362 ± 135	75.4 ± 46.0
Relative carbohydrate (g·kg BM^{-1}·day^{-1})	5.5 ± 1.4	1.2 ± 0.6
Total protein (g·day^{-1})	153 ± 37	30.9 ± 9.0
Relative protein (g·kg BM^{-1}·day^{-1})	2.3 ± 0.4	0.5 ± 0.1
Total fat (g·day^{-1})	88.4 ± 31.1	25.6 ± 13.4
Relative fat (g·kg BM^{-1}·day^{-1})	1.3 ± 0.4	0.4 ± 0.2
Total Na^+ (mg·day^{-1})	3211 ± 1110	901 ± 409
Total K^+ (mg·day^{-1})	3546 ± 1185	559 ± 560
Total Ca^{2+} (mg·day^{-1})	1428 ± 501	276 ± 229
Total Cl^- (mg·day^{-1})	4755 ± 1558	1374 ± 601

Mean ± SD.

7a.2.3 Protocol and Measurements

The process of measuring blood concentrations of HCO_3^-, pH, and the apparent SID has been previously described (Chapter 2, section 2.2.5). Briefly, swimmers immediately engaged in five min seated rest upon arrival at their training facility, before giving a 70 μL capillary blood sample. This sample was immediately analysed using a portable blood gas analyser (ABL9, Radiometer Medical, Copenhgen, Denmark), which determined the circulating values of HCO_3^-, pH, K^+, Na^+, Ca^{2+}, and Cl^-. A further 5 μL was drawn for the analysis of blood La^- (Lactate Pro 2, Arkray, Kyoto, Japan), which subsequently enabling the calculation of the apparent SID as per Lloyd (2004): $K^+ + Na^+ + Ca^{2+} - Cl^- - La^-$. Gastrointestinal side-effects were also monitored at baseline using a VAS for nine possible symptoms: nausea, flatulence, stomach cramping, belching, stomach ache, bowel urgency, diarrhoea, vomiting and stomach bloating (see Chapter 2, section 2.3.2 for interpretation). These scales are frequently used to determine gastrointestinal side-effects in $NaHCO_3$ research (Cameron et al., 2010; Gough et al., 2017).

After baseline samples, participants then ingested 0.3 g·kg BM^{-1} $NaHCO_3$ (Dr. Oetker, Bielefeld, Germany) contained in gelatine capsules (1 g·$capsule^{-1}$, Size 00, Bulk Powders, Colchester, UK) within a five min period. All swimmers then remained quietly seated for 165 min, with repeated blood samples obtained and analysed on at least eight more occasions (60, 75, 90, 105, 120, 135, 150, and 165 min post-ingestion). Further samples were taken at 180 min (n = 4) and 195 min (n = 1) post-ingestion to ensure that a peak HCO_3^- was determined in all swimmers. No samples were taken within the first 60 min since 0.3 g·kg^{-1} BM $NaHCO_3$ was not expected to elicit peak blood alkalosis within this time when ingested in capsules (de Oliveira et al., 2020; Jones et al., 2016).

7a.2.4 Statistical Analysis

All statistical tests were carried out in accordance with Chapter 2 (section 2.5.2). Repeated measures ANOVA tests were conducted to establish mean differences between time to peak blood HCO_3^-, pH, and the SID, as well as group mean changes that occurred within each blood metabolite (HCO_3^-, pH, SID, K^+, Na^+, Ca^{2+}, and Cl^-) across the 165 min sampling timeframe. Effect sizes for ANOVAs were reported as $P\eta^2$, whereas pairwise comparisons are reported as g (for interpretations, see Chapter 2, section 2.5.2). Inter-individual variance between swimmers' time course and absolute changes in blood analytes was described using CV (see Chapter 2, section 2.5.3). A Spearman's rank-order correlation (r_s) was also used to investigate associations between dietary intake (energy, macronutrients, and electrolytes consumed 24 and 3 hours before $NaHCO_3$ ingestion) and the time to peak, absolute change, and baseline measures of blood HCO_3^-, pH, and SID. This non-parametric correlation was selected due to violations in the sphericity of nutritional data. All data are reported as mean ± SD. Statistical significance was set at p <0.05.

7a.3 Results

7a.3.1 Blood Analyte Changes

No statistical differences were found in the time to peak concentrations of blood HCO_3^-, pH, or the apparent SID (F =3.2, $p = 0.063$, $P\eta^2 = 0.22$). Despite this, a large effect size ($g = 0.94$) was identified between time to peak blood HCO_3^- (130 ± 35 min) and SID (96 ± 35 min). A moderate effect size ($g = 0.63$) was also calculated between time to peak pH (120 ± 38 min) and SID, though the effect size for peak pH versus HCO_3^- was small ($g = 0.26$). Individual data are presented in Table 7a.3, demonstrating large inter-individual variations within time to peak data for HCO_3^- (CV = 27%), pH (CV = 32%) and SID (CV = 37%), and in the absolute increases from baseline for HCO_3^- (CV = 35%), pH (CV = 42%) and the SID (CV = 61%). The complete blood HCO_3^- (Figure 7a.1) and SID (Figure 7a.2) time course changes for four selected participants have been plotted and displayed to emphasise the individuality in blood responses.

Group mean increases in blood HCO_3^- (F = 17.2, $p < 0.001$, $P\eta^2 = 0.61$), pH (F = 14.7, $p < 0.001$, $P\eta^2 = 0.60$), and SID (F = 3.0, $p = 0.005$, $P\eta^2 = 0.22$) were observed across the study timeframe (Figure 7a.3). Compared to baseline values, blood HCO_3^- was increased 60 min post-ingestion (+3.2 ± 2.6 $mmol \cdot L^{-1}$, $p = 0.046$, $g = 1.40$, CV = 9.8%) and remained elevated at all following time points (all $p < 0.05$, $g > 0.80$). The proposed ergogenic threshold of +5 $mmol \cdot L^{-1}$ was reached 105 min post-ingestion (5.2 ± 2.5 $mmol \cdot L^{-1}$, CV = 8.9%) and was sustained until the end of the observation period (group HCO_3^- peak: 150 min, +5.9 ± 2.7 $mmol \cdot L^{-1}$, CV = 9.3%). An increased pH was observed 75 min post-ingestion (+0.06 ± 0.04 units, $p = 0.021$, $g = 1.83$, CV = 0.6%), which then remained elevated by +0.06–0.08 units for the sampling timeframe (all $p < 0.05$, $g > 0.80$). Peak blood pH occurred 90 min post-ingestion (+0.08 ± 0.05 units, CV = 0.6%). The SID was only increased with statistical significance 60 min post-ingestion (+2.0 ± 1.5 $mEq \cdot L^{-1}$, $p = 0.017$, $g = 1.32$, CV = 4.0%); however, large effect sizes were calculated at all subsequent time points ($g > 0.80$) with the group mean SID peaking at 135 min post-ingestion (+2.4 ± 2.6 $mEq \cdot L^{-1}$, $p = 0.288$, $g = 1.34$, CV = 5.1%).

Table 7a.3. The individual time peak and absolute increases in in blood HCO_3^-, pH, and the apparent SID observed in highly trained adolescent swimmers.

Blood Acid-Base Variable	Swimmer (Sex)											
	1 (M)	**2 (M)**	**3 (F)**	**4 (F)**	**5 (M)**	**6 (F)**	**7 (F)**	**8 (F)***	**9 (F)***	**10 (M)***	**11 (M)#**	**12 (F)#**
						HCO_3^-						
Baseline (mmol·L^{-1})	26.5	28.0	23.3	23.9	25.6	24.8	23.6	25.9	26.4	26.0	26.4	24.7
Peak (mmol·L^{-1})	34.3	35.3	32.3	34.5	33.9	31.4	26.4	28.3	34.8	32.8	32.7	30.5
Absolute change (mmol·L^{-1})	+7.8	+7.3	+9.0	+10.6	+8.3	+6.6	+2.8	+2.4	+8.4	+6.8	+6.3	+5.8
Time to peak (min)	90	75	120	150	165	75	180	120	135	150	150	150
						pH						
Baseline (mmol·L^{-1})	7.41	7.46	7.40	7.40	7.41	7.39	7.43	7.41	7.38	7.40	7.40	7.41
Peak (mmol·L^{-1})	7.57	7.52	7.52	7.54	7.53	7.54	7.47	7.45	7.49	7.49	7.48	7.51
Absolute change (mmol·L^{-1})	+0.16	+0.06	+0.12	+0.14	+0.12	+0.15	+0.04	+0.04	+0.11	+0.09	+0.08	+0.10
Time to peak (min)	90	75	90	135	165	90	75	105	120	180	150	165
						Apparent SID						
Baseline (mEq·L^{-1})	33	37	33	32	35	33	32	33	34	33	30	31
Peak (mEq·L^{-1})	36	38	38	38	35	38	34	35	38	37	38	35
Absolute change (mEq·L^{-1})	+3	+1	+5	+6	0	+5	+2	+2	+4	+4	+8	+4
Time to peak (min)	90	60	90	135	60	165	60	120	75	120	135	60

* = swimmers who were concurrently ingesting creatine. # = swimmers who were concurrently ingesting creatine and beta-alanine. M = male swimmers. F = female swimmers.

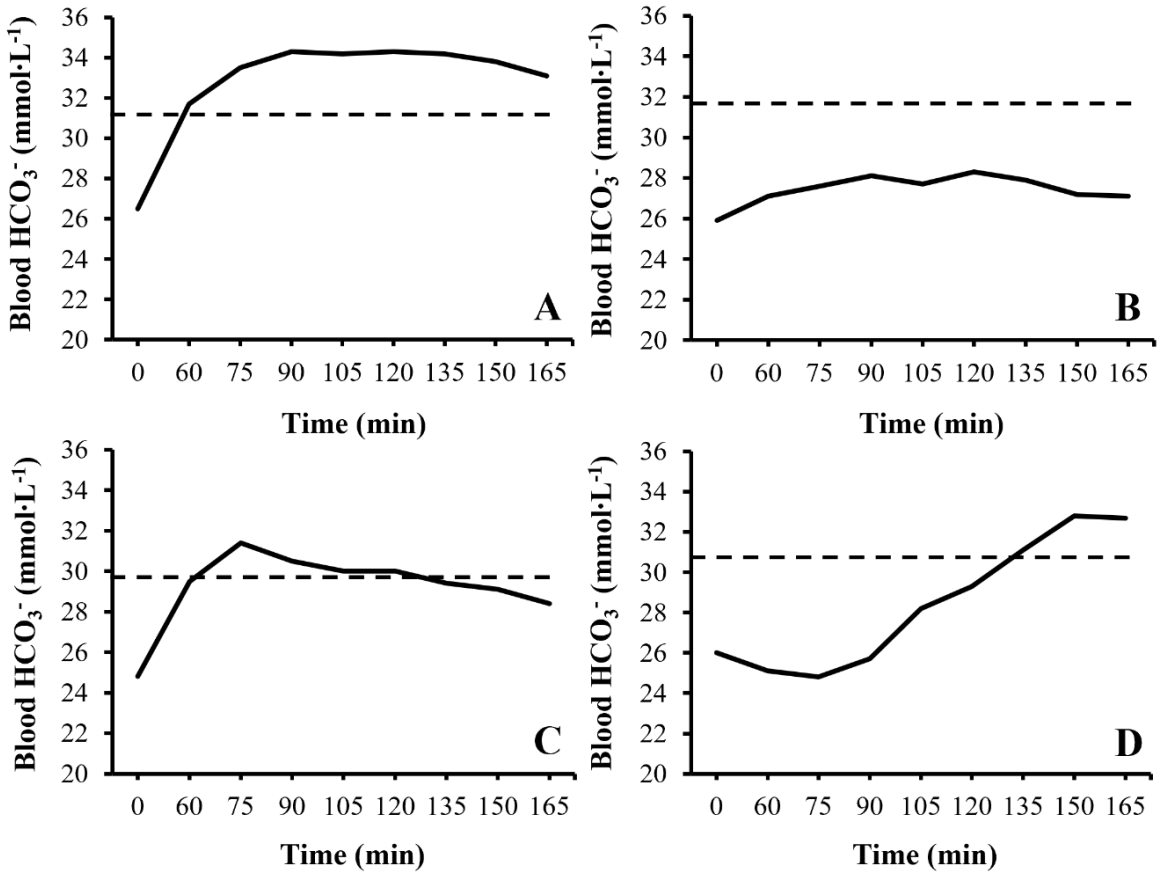

Figure 7a.1. Four unique blood HCO_3^- time course behaviours observed in A) swimmer 1, B) swimmer 8, C) swimmer 6, and D) swimmer 10. The dotted line represents a +5 mmol·L^{-1} increase from baseline blood HCO_3^-.

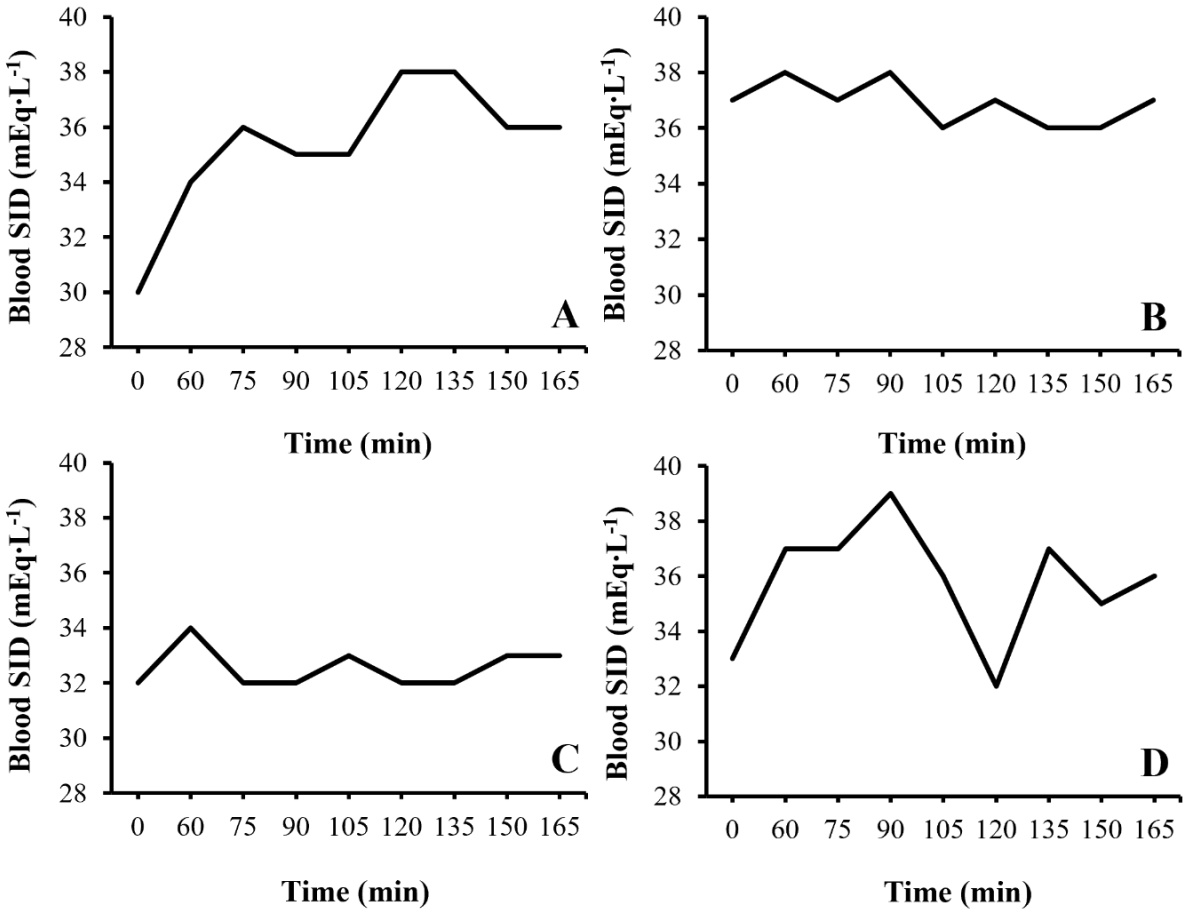

Figure 7a.2. Four unique time course behaviours in the apparent SID observed in A) swimmer 11, B) swimmer 2, C) swimmer 7, and D) swimmer 3.

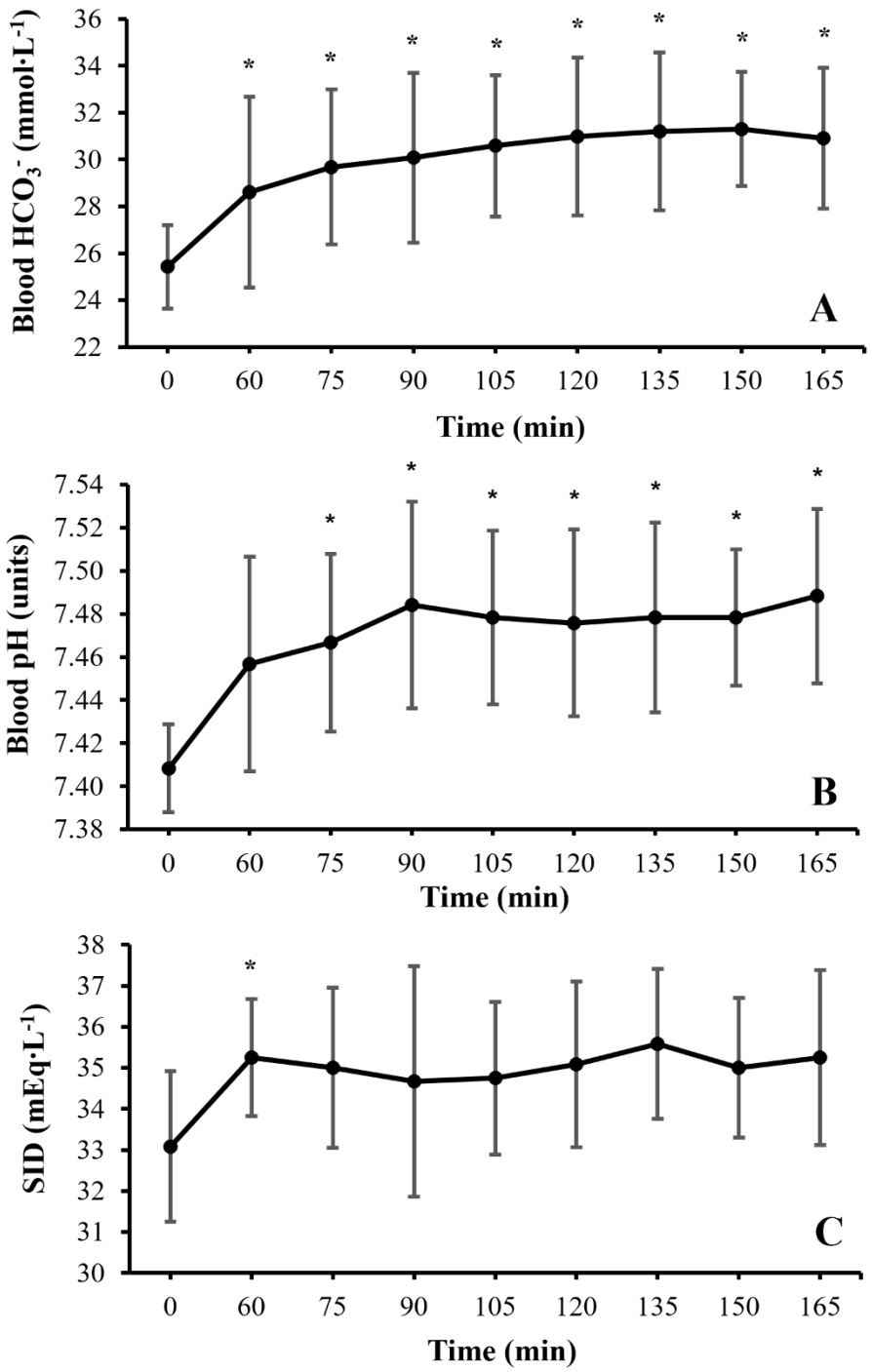

Figure 7a.3. Group mean changes observed in blood A) HCO_3^-, B) pH, and C) apparent SID observed over the sampling timeframe. * = increased compared to baseline concentration (p <0.05).

Strong ion shifts were also observed across the sampling period, with group level changes in Ca^{2+} (F = 15.4, p <0.001, $P\eta^2$ = 0.58), Cl^- (F = 5.9, p = 0.003, $P\eta^2$ = 0.35), K^+ (F = 3.0, p = 0.005, $P\eta^2$ = 0.21), and Na^+ (F = 2.1, p = 0.048, $P\eta^2$ = 0.16) all being detected (Figure 7a.4). Blood Ca^{2+} concentrations were decreased compared to baseline at 90 min post-ingestion (-0.10 ± 0.06 mmol·L^{-1}, p = 0.006, g = 1.48, CV = 5.0%) and remained decreased at all remaining time points (all p <0.05, g >0.80). The lowest group mean Ca^{2+} concentration occurred at 150 min post-ingestion (1.15 ± 0.03 mmol·L^{-1}, p = 0.001, CV = 3.0%). A decrease in Cl^- did not occur until 135 min post-ingestion (-2.9 ± 2.2 mmol·L^{-1}, p = 0.024, g = 1.26, CV = 1.8%), before reaching a peak decline at 150 min post-ingestion (106.5 ± 2.1 mmol·L^{-1}, p = 0.002, CV = 1.9%). No other group mean Cl^- measurement reached statistical significance. Post hoc observations failed to find any statistical significance within the K^+ time course changes, though there was a trend for significance and a large effect size calculated at 150 min post-ingestion (-1.03 ± 0.93 mmol·L^{-1}, p = 0.099, g = 1.42, CV = 9.1%). Similarly, post-hoc observations could not determine the precise time point for a change in Na^+ concentration, though the largest group level change appeared to occur at 60 min post-ingestion (+1.0 ± 1.2 mmol·L^{-1}, p = 0.546, g = 0.77, CV = 0.8%).

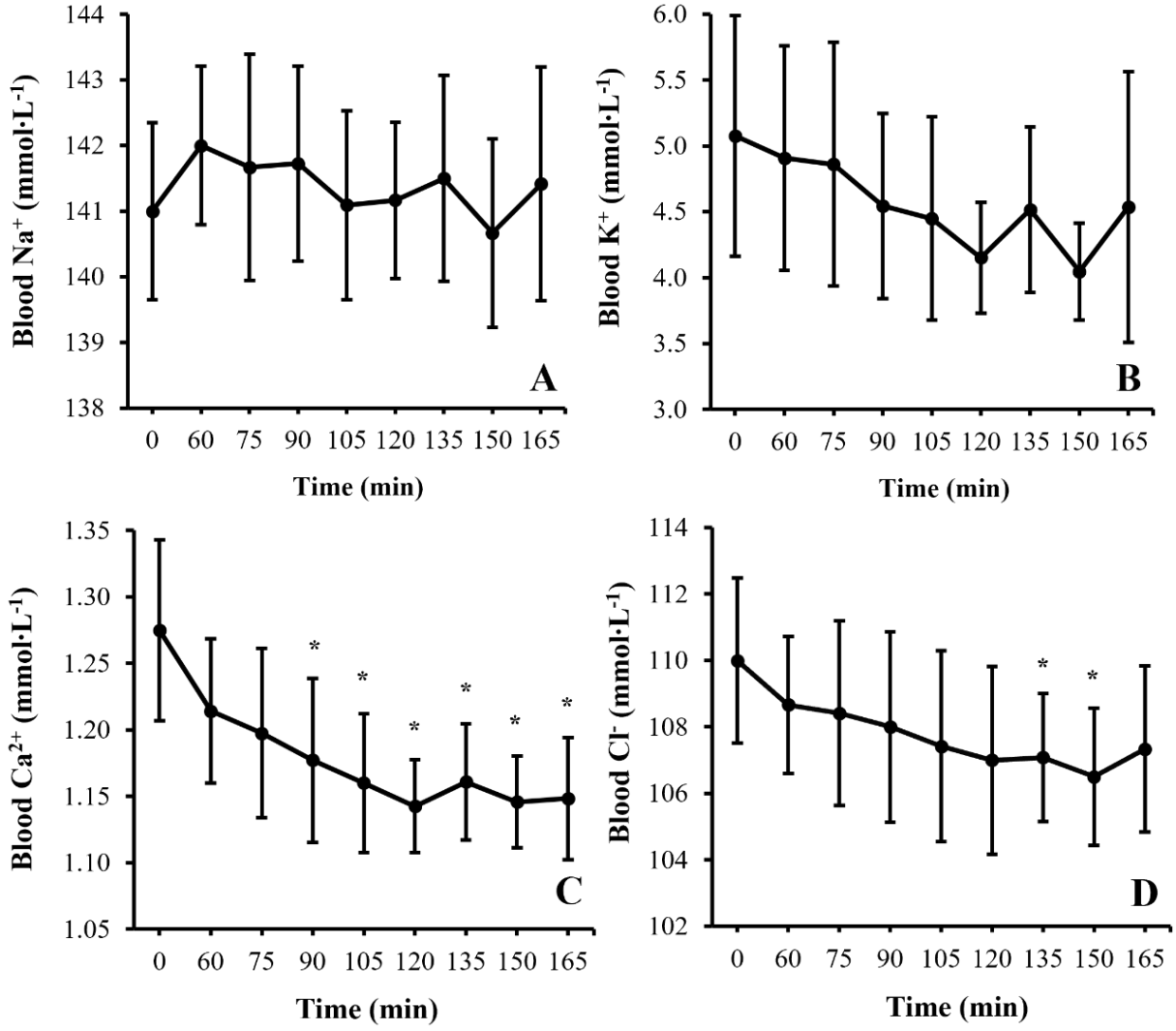

Figure 7a.4. Group mean changes observed in blood concentrations of A) Na^+, B) K^+, C) Ca^{2+} and D) Cl^- observed over the sampling timeframe. * = increased compared to baseline concentration (p <0.05).

7a.3.2 Effects of Diet

The energy and macronutrient composition of the meal ingested 1–3 hours before $NaHCO_3$ ingestion did not affect the absolute increases in blood HCO_3^-, pH, or the SID (Table 7a.4). However, the macronutrient consumption of the meal may have delayed the blood HCO_3^- time course since protein

(r_s = –0.581) and fat composition (r_s = –0.594) both displayed moderate, negative correlations with time to peak blood HCO_3^-. Conversely, protein intake may have accelerated time to peak SID, with a strong, positive correlation (r_s = 0.711) being observed. The total energy content of the meal also had a moderate, positive correlation with time to peak SID, although this did not reach statistical significance (r_s = 0.555, p = 0.061). Fat intake was associated with an increased baseline blood HCO_3^- (r_s = 0.609) and SID (r_s = 0.639) concentration, with both displaying strong, positive correlations. The amount of Na^+ consumed 1–3 hours before $NaHCO_3$ ingestion also had a strong, positive correlation with baseline HCO_3^- (r_s = 0.644, p = 0.024), but not with pH (r_s = –0.315, p = 0.318) or the SID (r_s = 0.171, p = 0.596). No other correlations were found between Na^+, K^+, Cl^-, or Ca^{2+} ingestion and time course changes in blood acid-base balance.

Table 7a.4. The associations between the dietary composition of a meal ingested 1–3 hours before $NaHCO_3$ and time course changes in HCO_3^-, pH, and the SID.

Absolute Dietary Variables	**Blood Acid-Base Variable**		
	HCO_3^-	**pH**	**SID**
	Correlations with time to peak		
Energy (kcal)	p = 0.202, r_s = -0.397	p = 0.785, r_s = -0.088	p = 0.061, r_s = 0.555
Carbohydrate (g)	p = 0.506, r_s = -0.213	p = 0.784, r_s = -0.088	p = 0.194, r_s = 0.403
Protein (g)	***p* = 0.048, r_s = -0.581***	p = 0.870, r_s = -0.053	***p* = 0.010, r_s = 0.711***
Fat (g)	***p* = 0.042, r_s = -0.594***	p = 0.411, r_s = -0.262	p = 0.539, r_s = 0.197
	Correlations with absolute change		
Energy (kcal)	p = 0.430, r_s = 0.252	p = 0.084, r_s = 0.519	p = 0.827, r_s = 0.071
Carbohydrate (g)	p = 0.372, r_s = 0.284	p = 0.127, r_s = 0.466	p = 0.814, r_s = 0.076
Protein (g)	p = 0.476, r_s = 0.228	p = 0.054, r_s = 0.569	p = 0.221, r_s = 0.381
Fat (g)	p = 0.846, r_s = 0.063	p = 0.316, r_s = 0.316	p = 0.259, r_s = –0.354
	Correlations with baseline concentrations		
Energy (kcal)	p = 0.285, r_s = 0.336	p = 0.645, r_s = -0.149	p = 0.569, r_s = 0.171
Carbohydrate (g)	p = 0.652, r_s = 0.146	p = 0.801, r_s = -0.082	p = 0.920, r_s = 0.033
Protein (g)	p = 0.724, r_s = 0.114	p = 0.114, r_s = -0.480	p = 0.826, r_s = 0.071
Fat (g)	***p* = 0.036, r_s = 0.609***	p = 1.000, r_s = -0.001	***p* = 0.025, r_s = 0.639***

* = indicates a significant correlation between dietary intake and acid-base variable (p <0.05)

7a.3.3 Gastrointestinal Discomfort

All swimmers reported at least one gastrointestinal side-effect, though the severity of these instances were rated below five out of 10 arbitrary units on in 94% (29 of 31) of occurrences (Table 7a.5). Of the reported side-effects, 71% (22 of 31) peaked in severity at 60 and 75 min post-ingestion. The most common symptoms were belching (reported by 58% of swimmers), followed by stomach bloating and nausea (reported by 50% of swimmers).

Table 7a.5. The three most severe gastrointestinal side-effects reported by individual swimmers following the ingestion of 0.3 g·kg BM^{-1} $NaHCO_3$.

Swimmer (Body mass)	Caps	Symptom 1	Severity (*n*/10)	Peak (mins)	Symptom 2	Severity (*n*/10)	Peak (mins)	Symptom 3	Severity (*n*/10)	Peak (mins)	Aggregated score
1 (90.7 kg)	28	Belching	4.9	60	Stomach bloating	4.9	60	Nausea	2.3	60	17.7
2 (69.5 kg)	21	Belching	2.7	60	Stomach bloating	1.7	135	Stomach cramp	1.1	60	6.6
3 (55.8 kg)	17	Nausea	4.1	75	Stomach bloating	1.4	60	None	0.0	N/A	5.5
4 (62.2 kg)	19	Belching	3.9	60	Stomach bloating	2.4	60	Nausea	0.7	75	6.9
5 (72.1 kg)	22	Belching	1.7	75	None	0.0	N/A	None	0.0	N/A	1.7
6 (64.6 kg)	20	Stomach ache	4.0	165	None	0.0	N/A	None	0.0	N/A	4.0
7 (60.6 kg)	19	Nausea	1.4	60	None	0.0	N/A	None	0.0	N/A	1.4
8 (54.3 kg)	17	Belching	4.9	60	Flatulence	3.9	165	Stomach ache	1.5	135	11.0
9 (57.7 kg)	18	Nausea	2.6	60	None	0.0	N/A	None	0.0	N/A	2.6
10 (65.0 kg)	20	Belching	5.0	60	None	0.0	N/A	None	0.0	N/A	5.0
11 (67.9 kg)	21	Flatulence	2.6	150	Stomach bloating	2.1	60	Bowel urgency	1.5	165	6.1
12 (63.7 kg)	20	Vomiting	10.0	105	Nausea	10.0	105	Stomach ache	1.5	90	22.3

Aggregated score = sum of the most severe incidence of all nine symptoms (*n*/90). Caps = total number of $NaHCO_3$ capsules ingested.

7a.4 Discussion

This was the first study to compare the time course changes of three acid-base variables in adolescent swimmers following the ingestion of 0.3 g·kg BM^{-1} $NaHCO_3$ alongside a pre-exercise meal. Similar to previous research in adults, large absolute increases in blood HCO_3^- and pH concentrations were observed (Gough et al., 2017; Jones et al., 2016). Of the three acid-base variables that were measured, blood HCO_3^- and pH appeared to peak at a similar time (120 and 130 min post-ingestion, respectively). There was, however, a 34 min difference separating peaks in blood HCO_3^- and the apparent SID (96 min post-ingestion), which may be of practical significance given that strong ion shifts could be the primary ergogenic mechanism of $NaHCO_3$ (Siegler et al., 2016; Westerblad, 2016). In addition to these findings, this study provides justification for the use of individualised $NaHCO_3$ ingestion strategies in highly trained adolescent swimmers, given the high inter-individual variation in blood HCO_3^- time course changes. This therefore provides the basis for further research to investigate whether individualised $NaHCO_3$ ingestion strategies, or strategies based on the SID, could be more effective for highly trained adolescent swimmers than the currently recommended standardised approaches (Maughan et al., 2018).

Following the ingestion of 0.3 g·kg BM^{-1} $NaHCO_3$ in capsule form, highly trained adolescent swimmers displayed peak blood pH and HCO_3^- concentrations at a similar time (~120–130 min post-ingestion), supporting the strong relationship between these measures (de Oliveira et al., 2020; Jones et al., 2016). The remainder of this thesis will therefore focus on the blood HCO_3^- time course since this measure is considered to be more reliable than pH (Gough et al., 2017; Boegman et al., 2020). Interestingly, when time course changes in blood HCO_3^- were compared to those of the SID, there appeared to be a mean 34 min difference (g = 0.94) between peak concentrations. This could have important implications in practice given the contested $NaHCO_3$ mechanisms, whereby it is unclear whether an enhanced H^+ buffering capacity (i.e., time to peak HCO_3^-) or intramuscular strong ion uptake (i.e., time to peak SID) is responsible for the ergogenic effects (Siegler et al., 2016). Why there

was a potential time difference in these measures could not be elucidated, though the consumption of a meal 1–3 hours before $NaHCO_3$ ingestion may have been a contributing factor. Indeed, correlations indicated that higher protein and fat intakes accelerated time to peak HCO_3^-, possibly to assist with the clearance of waste metabolites (e.g., ammonia, NH_4) produced during digestion (Remer, 2001). In contrast, greater energy and protein intakes may have slowed the absorption of strong ions (Abuhelwa et al., 2017), subsequently delaying time to peak SID. However, as these are based on correlations and not mechanistic data, this cannot be confirmed. Nonetheless, as peak HCO_3^- and SID concentrations could occur at different times in practice, further research is required to identify whether individualised $NaHCO_3$ strategies based on these timings can be more effective for performance than a standardised approach.

The majority of adolescent swimmers in this study demonstrated peak blood HCO_3^- concentrations above the proposed ergogenic threshold (+5–6 $mmol \cdot L^{-1}$; Heibel et al., 2018), contrasting previous research in trained adolescents (+3.4 $mmol \cdot L^{-1}$, Guimarães et al., 2020; Zajac et al., 2009). A speculative explanation for this difference could have been that the current cohort had an early maturation onset (Baxter-Jones & Helms, 1996), perhaps assisting their selection to the high-performance swimming club where they were recruited. This is supported since both male (72 ± 11 kg) and female (60 ± 5 kg) swimmers in the current cohort had considerably greater body mass than the 'well-trained' male swimmers (56 ± 1 kg) recruited by Zajac et al. (2009), despite being the same age. If this was the case, then the current swimmers could have benefited from maturity-related differences in gut physiology (e.g., caecal pH, distal microbiota; Agans et al., 2011; Bai et al., 2016) and/or muscle and blood buffering capabilities (e.g., monocarboxylate transporter density, Na^+/HCO_3^- co-transport; Juel, 2008), both of which could have enabled greater blood HCO_3^- increases to occur. However, this requires further research considering maturity status was not measured in this study, nor its predecessors. Based on the results of this study, a more realistic explanation for the low blood HCO_3^- concentrations observed by Zajac et al. (2009) and Guimarães et al. (2020) was because they both administered $NaHCO_3$ at standardised time points, thus measuring blood HCO_3^- concentration

before individual peaks were achieved. This therefore adds further support for the use of individualised $NaHCO_3$ ingestion strategies in highly trained adolescents where possible, though additional research is required to determine whether this translates into a performance benefit.

An increase in the apparent SID was also achieved by highly trained adolescent swimmers following $NaHCO_3$ ingestion, supporting previous work in trained adults (Gough et al., 2019a; 2019b). However, these previous investigations both demonstrated greater group mean increases in the SID (+6–10 $mEq \cdot L^{-1}$) compared to the present study (+4 $mEq \cdot L^{-1}$), despite not purposely seeking to identify a peak concentration. Furthermore, the current study also observed lower baseline (33 vs. 36–38 $mEq \cdot L^{-1}$) and absolute peak SID concentrations (37 vs. 42–46 $mEq \cdot L^{-1}$), inferring that adolescents might have less capacity for strong ions movements (e.g., reduced Na^+/K^+ pump activity; Juel, 2008). Alternatively, these differences may be explained since Gough et al. (2019a, 2019b) required participants to ingest $NaHCO_3$ at least four hours post-prandial, therefore removing the potential delay and/or depression of strong ion absorption caused by a pre-exercise meal (Abuhelwa et al., 2017). Additionally, an *ad libitum* intake of water in this study could have increased plasma volume, possibly masking the absolute strong ion shifts that may have taken place (Brown et al., 1971). An example of this might have been observed in blood Na^+ concentrations, where increases across the study timeframe were largely mitigated (peak: +1 $mmol \cdot L^{-1}$) compared to previous observations under fasted conditions (+3 $mmol \cdot L^{-1}$) (Gough et al., 2017; 2019b; Jones et al., 2016). Despite this, large effect sizes were calculated for reductions in blood K^+, Ca^{2+}, and Cl^- between 120–150 min post-ingestion, suggesting that adolescent swimmers experienced an intramuscular uptake of strong ions at this time (Lühker et al., 2017; Sostaric et al., 2006). Though considering this study did not measure intramuscular SID or exercise performance, it is currently unclear how these $NaHCO_3$-induced changes in the apparent SID currently benefit the performances of highly trained adolescent swimmers.

Although research agrees that absolute peaks in blood HCO_3^- concentrations are highly individual following $NaHCO_3$ ingestion (Boegman et al., 2020; Gough et al., 2017; Jones et al., 2016), the process of identifying such a specific time point has been criticised. This is because ingesting 0.3 g·kg BM^{-1} $NaHCO_3$ in capsules often produces +5 mmol·L^{-1} increases in blood HCO_3^- for prolonged periods (>100 min; Boegman et al., 2020; de Oliveira et al., 2020; Jones et al., 2016), suggesting that a long-lasting ergogenic window might exist with this dosing strategy (Heibel et al., 2018). However, the current data contrasts this suggestion, identifying that prolonged (>90 min) blood HCO_3^- increases above +5 mmol·L^{-1} only occurred in half of the cohort, with others achieving the +5 mmol·L^{-1} threshold at completely different time points (e.g., swimmers 6 and 10 in Figure 7a.1). Based on these erratic time course changes, it appears that not all individuals will experience a long-lasting 'ergogenic window'. Therefore, while standardised ingestion timeframes might be appropriate for some adolescent swimmers, this would not be known without first undergoing the time to peak determination process. A caveat is that this procedure is expensive and currently possesses little research to suggest a performance benefit versus standardised $NaHCO_3$ timings; thus, supporting the need for further research comparing dosing strategies.

There were minimal incidents of severe gastrointestinal side-effects when highly trained adolescents ingested $NaHCO_3$ capsules 1–3 hours after a self-selected meal. While each swimmer reported at least one side-effect, the severity of these symptoms was scored below five out of 10 on most occurrences (94%). This low level of gastrointestinal distress supports previous research by Carr et al. (2011b), where the co-ingestion of $NaHCO_3$ capsules with a meal provided the best mitigation of side-effects (versus $NaHCO_3$ solution and/or fasted conditions). This may be because capsules and food co-ingestion are suggested to slow the reduction of $NaHCO_3$ to Na^+ and carbonic acid (H_2CO_3), subsequently reducing the rate of acid-base disturbances in the stomach (e.g., increases in carbon dioxide and water) (Heigenhauser, 1991; Turnberg et al., 1970). Alternatively, the age of the swimmers might have contributed to the lack of gastrointestinal symptoms, aligning with previous work that has also found minimal $NaHCO_3$ side-effects in adolescent athletes (Guimarães et al., 2020;

Zajac et al., 2009). While there is currently no clear explanation why side-effects might be lower in adolescents, one suggestion is that they possess less acidity in the gastrointestinal fluids compared to adults; potentially meditating acid-base disturbances occurring in the stomach when alkaline substances are ingested (Merchant et al., 2016). Another general observation is that severe gastrointestinal side-effects often occur in athletes of higher body mass (≥75 kg; Cameron et al., 2010; Kahle et al., 2013), possibly through consuming higher absolute $NaHCO_3$ doses. Therefore, since adolescents are typically smaller in size and mass than their adult counterparts, they may experience lesser side-effect because of the lower absolute $NaHCO_3$ doses required. However, this study did observe vomiting in one participant, which indicates that the severity gastrointestinal side-effects should be assessed on an individual basis.

The study methods were applied based on logistical (e.g., removing highly trained swimmers from training) and ethical considerations (e.g., repeated blood analysis of adolescents). This limited the current study from including a PLA experiment or repeatability measures that could have altered the interpretation of results. Nonetheless, previous work found no changes in the time course behaviours of blood HCO_3^-, pH, or Na^+ with PLA treatments (de Oliveira et al., 2020; Gough et al., 2017); therefore, it was assumed that similar results would have been observed. On the other hand, the repeatability of blood HCO_3^- measures are controversial when 0.3 g·kg BM^{-1} $NaHCO_3$ capsules are ingested in a fed state. Indeed, Boegman et al. (2020) reported an 'excellent' repeatability of measures (ICC: r = 0.77) in world-class rowers following $NaHCO_3$ ingestion with a standardised snack (energy: 682 kcal; protein: 20 g; carbohydrate: 140 g), whereas de Oliveira et al. (2020) found repeatability to be 'poor' (ICC: r = 0.34) when recreational adults ingested $NaHCO_3$ an hour after a standardised breakfast (energy: 563 kcal; protein: 9 g; carbohydrate: 90 g). Since both studies differed in meal composition, participant training status, time post-prandial, and blood analysis methods (capillary vs. venous samples), this leaves the repeatability of the current data unclear. However, the main purpose of this research was to identify the time course changes in three alternate blood acid-base balance variables following $NaHCO_3$ ingestion in a highly trained adolescent cohort. Since this was the first

study to suggest that a difference in time to peak HCO_3^- and SID may exist in practice, future studies should therefore aim to determine the repeatability of these two measures under competition scenarios (e.g., pre-competition meal, after warm-up).

7a.5 Conclusion

This study found that highly trained adolescent male and female swimmers were capable of achieving significant increases in blood HCO_3^-, pH, and SID following the ingestion of 0.3 g·kg BM^{-1} $NaHCO_3$ in capsule form. Importantly, individual peaks in blood HCO_3^- and SID appeared to be separated by >30 min, which may be of practical significance given that strong ion shifts could be a key $NaHCO_3$ ergogenic mechanism. Future research should therefore explore whether a $NaHCO_3$ ingestion strategy based on time to peak SID could be an efficacious approach to supplementation, ideally versus time to peak HCO_3^- and standardised methods. This study also suggests that highly trained adolescent swimmers might not possess a long-lasting ergogenic window following the ingestion of $NaHCO_3$ capsules, supporting the practice of individualising $NaHCO_3$ ingestion where logistically and financially possible.

Chapter 7b – The Effects of Individualised and Standardised Sodium Bicarbonate Ingestion on High-Intensity Repeated Swimming and a Subsequent Time-Trial Performance

7b.1 Introduction

Highly trained adolescent swimmers typically engage in 8–10 training sessions·week^{-1} (see Chapter 3), many of which will contain at least one high-intensity exercise set (e.g., anaerobic threshold/tolerance, intermittent exercise at supramaximal intensities) (Pollock et al., 2019; Shaw et al., 2014). Such training sessions are designed to stress the ATP-PCr and glycolytic energy systems, resulting in the muscular accumulation of metabolites such as La^-, H^+, and inorganic phosphate; that each have associations with skeletal muscle fatigue (Barnett, 2006; Cairns, 2006). Indeed, during sustained periods of intense exercise, the production of H^+ overwhelms the natural buffering mechanism (i.e., blood HCO_3^-), resulting in a decline in blood and muscle pH (Fitts, 2016). Though this acidic intramuscular environment may not be the cause of fatigue per se (Westerblad, 2016), it is under these conditions that other plausible fatiguing mechanisms also occur, including impairments to CHO utilisation (i.e., inhibition of key glycolytic enzymes; Hollidge-Horvat et al., 1999), excitation-contraction coupling (i.e., increased muscle K^+ efflux; Sostaric et al., 2006), and sarcoplasmic reticulum function (reduced Ca^{2+} sensitivity and handling; Allen et al., 2008). Supporting extracellular blood buffering capacity with the ingestion of $NaHCO_3$ could therefore offset fatigue during key training sets, potentially enabling highly trained swimmers to make greater adaptions over time.

To date, research has reported mixed performance outcomes when $NaHCO_3$ was ingested before repeated, high-intensity swimming exercise. Both Gao et al. (1988) and Gough et al. (2023) showed $NaHCO_3$ to benefit swimming performance in the latter stages of 5 x 100 yard (vs. PLA, bout 4: -0.7 s, bout 5: -0.9 s) and 8 x 50 m freestyle tests (bouts 5–8: -0.5 to -1.3 s, g = 0.26–0.79), respectively; albeit in regional/collegiate adult swimmers, and not in highly trained adolescents competitive at the national level. On the other hand, Zajac et al. (2009) found $NaHCO_3$ to produce an overall 1.3% faster time to complete 4 x 50 m freestyle sprints in highly trained adolescents; however, this improvement was only noticeable in the first swimming bout (-0.5 s, g = 0.50). Finally, Campos et al. (2012) observed no $NaHCO_3$ benefits towards 6 x 100 m freestyle time-trials (-0.1 s, g = 0.07) in

international-level swimmers, though this study used a suboptimal dosing timeframe for $NaHCO_3$ capsules (60 min pre-exercise; Carr et al., 2011b). Indeed, a potential reason for these differences was the use of varying ingestion strategies, which all involved ingesting $NaHCO_3$ at standardised pre-exercise time points. Such approaches may be flawed in practice given that peak buffering capacity can occur anywhere between 40-240 min post-ingestion between athletes (de Oliveira et al., 2021; Gough et al., 2017), potentially warranting the use of individualised dosing strategies. To date, only Boegman et al. (2020) have directly compared individualised and standardised $NaHCO_3$ ingestion strategies on exercise performance, finding an enhanced 2000 m rowing performance (-2.0 s, g = 0.19) in world-class competitors. Although, the efficacy of this approach remains unclear since performances were not compared to control/PLA conditions, nor does it give any indication of a performance effect for swimming exercise.

There is also a potential ability of $NaHCO_3$ to accelerate the recovery of acid-base balance after fatiguing exercise, achieving a full recovery after 20–40 min (Gough et al., 2019a). This may have important practical implications since swimming competitions often demand consecutive races to be performed with only short rest periods (<40 min). Pierce et al. (1992) and Pruscino et al. (2008) have previously investigated $NaHCO_3$ as a nutritional aid to enhance recovery between two time-trial swimming performances (2 x 200 yards with 20 min recovery and 2 x 200 m with 30 min recovery, respectively), although the latter found a small benefit compared to a PLA supplement (-1.6 s, g = 0.34). Similarly, both studies also employed standardised $NaHCO_3$ ingestion strategies (0.2 g·kg BM^{-1} solution, 60 min pre-exercise and 0.3 g·kg BM^{-1} capsules, 7 doses over 90 min pre-exercise, respectively), which could have mitigated the ergogenic potential in some swimmers. Therefore, the aim of this study was two-fold: (a) to compare the effectiveness of an individualised $NaHCO_3$ ingestion strategy versus a standardised approach and a PLA on repeated swimming exercise; and (b) to assess acid-base recovery following these ingestion methods to establish whether they can enhance a subsequent 200 m freestyle time-trial performance.

7b.2 Methods

7b.2.1 Participants

Twelve national swimmers were recruited for this study, who were all aged ≥16 years and classified as 'highly trained' (see Chapter 2, section 2.1.2). Each swimmer underwent pre-experimental testing to determine the time course of blood acid base variables (i.e., peak HCO_3^- and SID) as per Chapter 7a. However, during the experimental period, five males withdrew from the study (attrition) and could not be replaced due to time and financial restraints (Lakens, 2022). Therefore, a total of seven highly trained young swimmers participated in this study (one male, sex females, age: 19 ± 2 years, height: 1.74 ± 0.09 m, body mass: 69.0 ± 8.2 kg, WA points for 200 m freestyle event: 678 ± 75). At the time of the study, all swimmers were in preparation for national championships and were completing a swimming volume of 51.3 ± 6.3 km·week^{-1}. Written informed consent was obtained from all swimmers (and parents/guardians where appropriate) prior to the start of the study. Ethical approval was granted by the BCU ethics committee (Newbury/7595/R(B)/2020/Aug/HELS FAEC) in accordance with the Declaration of Helsinki.

7b.2.2 Pre-Experimental Procedures

This study had five research trials: one pre-determination of peak blood HCO_3^- concentration; one familiarisation trial, and three experimental trials that were conducted in a single-blind, randomised, and crossover design. All trials took place the host swimming club's training facilities (25 m pool), where swimmers were asked to arrive having prepared as per the pre-experimental controls in Chapter 2 (section 2.1.4). This included an instruction for swimmers to eat as they normally would prior to a key training session, which was given for two reasons: (a) to increase external validity; and (b) to limit the occurrence of gastrointestinal side-effects (see Chapter 7a, section 7a.3.3). Co-ingestion of creatine (n = 5) and beta-alanine (n = 3) was reported by swimmers, though these supplements had been ingested consistently for over 24 weeks prior to the study. These supplements were therefore not

expected to produce large changes in performance (Chung et al., 2012; Peyrebrune et al., 2005) or blood buffering capacity (see Chapter 7a, section 7a.3.1).

7b.2.3 Supplement Timings

Individualised (IND) $NaHCO_3$ ingestion timings were determined in accordance with the previously described methods in Chapter 7a (see section 7a.2.3). Individual peaks in blood HCO_3^- occurred between 105–195 min post-ingestion, with swimmers (but not the researcher) blinded from results. The standardised (STND) $NaHCO_3$ ingestion strategy was based on a peak in group mean blood HCO_3^- observed within this cohort (Chapter 7a, section 7a.3.1). This timing was 150 min pre-exercise, which did not coincide with any of the swimmer's IND ingestion timings. Both experimental strategies consisted of 0.3 g·kg BM^{-1} $NaHCO_3$ that were administered in hydroxypropyl methylcellulose capsules (772 ± 30 mg·capsule^{-1}, size 00, Bulk, Colchester, UK). A PLA supplement was to be ingested 90 min pre-exercise to blind swimmers from their IND timings. The PLA consisted of an equimolar Na^+ dose (sodium chloride: 0.21 g·kg BM^{-1}, ASDA, Leeds, UK) to offset any possible ergogenic effects of Na^+ ingestion (Mora-Rodriguez & Hamouti, 2012). Additional cornflour (ASDA, Leeds, UK) was also added to PLA capsules to replicate appearance and fullness. Despite the recommendation in Chapter 7a, an ingestion timing based on peak SID was not logistically possible as this coincided with either IND or STND in four participants.

7b.2.4 Experimental Procedures

Swimmers were requested to arrive at their training facility 10–15 min before their pre-exercise $NaHCO_3$ timings. Upon arrival, swimmers engaged in five min of seated rest before giving a 70 μL sample of capillary blood from the fingertip for the assessment of baseline (BASE) blood variables (i.e., HCO_3^-, K^+, Ca^{2+}, Na^+, Cl^- and La^-), which was analysed via a blood gas analyser (see Chapter 2, section 2.2.5). Using these values, the apparent SID was calculated using the following formula: K^+ +

Na^+ + Ca^{2+} - Cl^- - La^- (Lloyd, 2004). Gastrointestinal side-effects (nausea, flatulence, stomach cramp, belching, stomach ache, bowel urgency, diarrhoea, vomiting, stomach bloating) and perceived readiness to exercise (PRE) were also monitored at BASE, using ten different VAS (see Chapter 2, section 2.3.2 for interpretation). Repeat blood, gastrointestinal, and perceived readiness to exercise measures were taken on five further occasions: before warming up (45 min pre-exercise: 45-PRE); after warming up (immediately pre-exercise: 0-PRE); after 6 x 75 m maximal swimming sprints (immediately post-exercise: 0-POST); after 30 min active recovery (30-POST); and after a follow-up 200 m freestyle time-trial (immediately post-exercise: POST-TT). At the end of each trial, the greatest score for each of the nine gastrointestinal side-effects were combined to give an aggregated gastrointestinal disturbance score for the experimental conditions.

7b.2.5 Swimming Exercise Tests

Swimmers began a self-selected 30–40 min warm-up prior to the first swimming test (see Chapter 2, section 2.4.1). In short, swimmers started with ~10 min of self-selected, land-based exercise, before entering a 25 m pool for a progressive intensity 1000 m warm-up prepared by the head swimming coach (~20–30 min). Following the warm-up, swimmers were organised into swimming lanes ready to complete 6 x 75 m maximal effort sprints in their specialist swimming stroke (five freestyle, one butterfly, one breaststroke). Each swimming bout was competed at 150 s intervals, which typically resulted in 40–60 s exercise and 90–110 s passive rest. This was a commonly used swimming test within this cohort, who demonstrated a high test-retest reliability for average 75 m swimming time (CV: 0.2–2.3%) and an ‘excellent’ reproducibility over four attempts (ICC: r = 0.997, p <0.001) (Atkinson & Nevill, 1998; Koo & Li, 2016). Two experienced swimming coaches manually timed each swimming bout, with the mean of the two times used as the performance measure. Average 75 m swimming time, the aggregated time-to-complete all swimming bouts, and individual 75 m bouts were all analysed for performance effects.

A 30 min active recovery period then ensued where swimmers completed 600–1000 m of low intensity swimming (~20 min), before engaging in foam rolling (~0–5 min) and/or passive rest (~5–10 min). Swimmers then completed a maximal effort 200 m freestyle time-trial from a dive start, which was timed in accordance with the 6 x 75 m test. Based on the familiarisation trial, the swimmers were performing at 90–98% of their personal best times at the time of the study. Swimmers completed both exercise tests in their own swimming lanes, with a maximum of two swimmers completing the protocol at any one time. All warm-ups, swimming lanes, and recovery strategies were recorded and kept consistent for each trial. Swimmers were asked for their RPE after each swimming test, which was collected using a CR10 Borg scale (Borg, 1998).

7b.2.6 Statistical Analysis

All statistical tests were carried out in accordance with Chapter 2 (section 2.5.2). Repeated measures ANOVA tests were used to compare swimming performance (mean 75 m time, 200 m time-trial), RPE, aggregated gastrointestinal side-effects, and pre-exercise dietary intakes (energy, CHO, protein, fat, fluid) between the three experimental conditions (IND vs. STND vs. PLA). Additional 3 (condition) x 6 repeated measures ANOVAs were conducted to compare performance differences between individual swimming bouts (6 x 75 m), as well as possible changes in blood responses (HCO_3^-, SID, Na^+, K^+, Ca^{2+}, Cl^-, La^-) and readiness to exercise across the study timeframe (BASE, 45-PRE, 0-PRE, 0-POST, 30-POST, POST-TT). Effect sizes are reported as $P\eta^2$ for all ANOVA tests, whereas *g* was calculated and reported for all pairwise comparisons (for interpretations, see Chapter 2, section 2.5.2). Smallest worthwhile changes (SWC) of 1.1 s (6 x 75 m) and 1.6 s (200 m TT) were identified using 0.2 x SD of this cohort's previous performance data (Bernards et al., 2017). Test-retest reliability for performance tests were calculated using CV, whereas reproducibility was analysed via ICC (Chapter 2, section 2.5.3). All data are reported as mean ± SD. Statistical significance was set at $p < 0.05$.

7b.3 Results

7b.3.1 Blood Metabolites

Initial time to peak testing found all swimmers to achieve an absolute increase in blood HCO_3^- concentration that exceeded +5 mmol·L^{-1} (mean: +7.7 ± 1.0 mmol·L^{-1}, CV = 13%), albeit at variable post-ingestion time points (129 ± 32 min, CV = 25%). However, while $NaHCO_3$ did increase blood HCO_3^- during the experimental trials (F = 6.2, p <0.001, $P\eta^2$ = 0.51), pre-exercise increases above the +5 mmol·L^{-1} threshold only occurred in four swimmers with IND (range: +0.2 to 7.2 mmol·L^{-1}) and three swimmers with STND (range: +1.8 to 7.4 mmol·L^{-1}). This resulted in little group blood HCO_3^- differences being observed between IND and STND at 45-PRE (mean difference = -1.3 mmol·L^{-1}, p = 0.159, g = 0.49), 0-PRE (+0.8 mmol·L^{-1}, p = 1.000, g = 0.32), or any other time point during the study (all p >0.005; Figure 7b.1). Both $NaHCO_3$ conditions produced large increases in blood HCO_3^- compared to PLA at all pre-exercise time points (all p <0.005, g >0.80), except for immediately after exercise (i.e., 0-POST and POST-TT). At 30-POST, blood HCO_3^- concentrations had returned to 96% and 98% of the values observed at 0-PRE for IND and STD, respectively.

No differences occurred in the SID between all three ingestion strategies (F = 0.6, p = 0.777, $P\eta^2$ = 0.10; Figure 7b.2). Furthermore, all effect size calculations across the study were either trivial or small (g <0.50) when comparing IND versus STND, and IND versus PLA. When comparing STND versus PLA, however, large effect sizes were observed for the difference in the SID at 45-PRE (+3.6 mEq·L^{-1}, g = 0.92) and 0-PRE (+4.0 mEq·L^{-1}, g = 0.94).

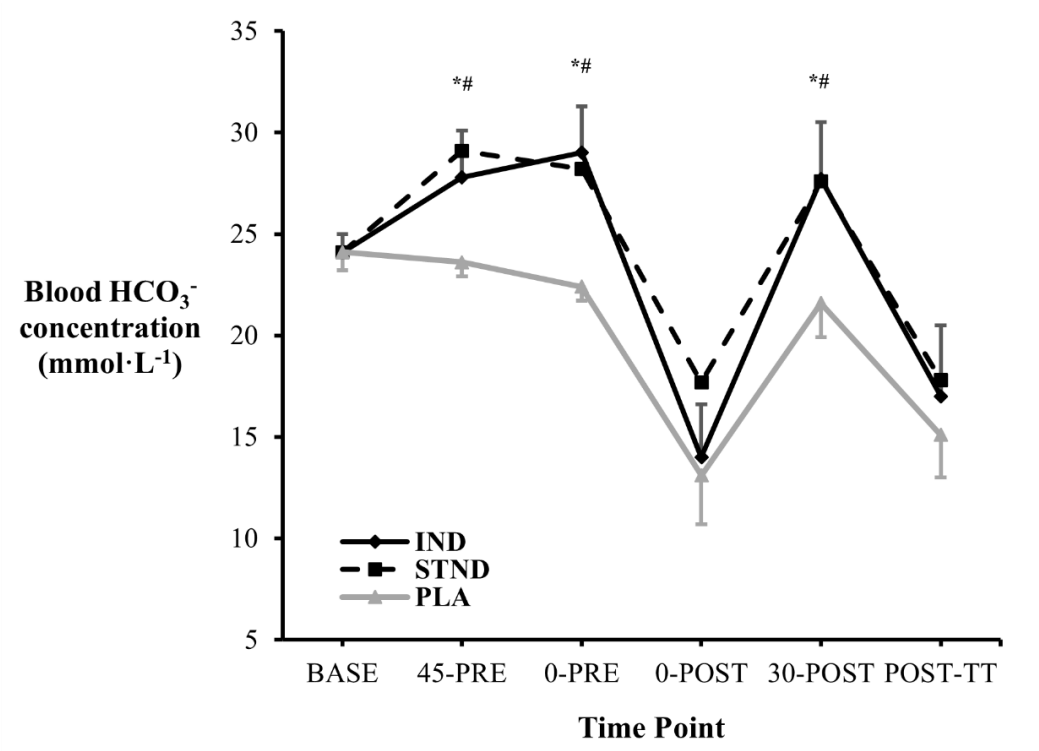

Figure 7b.1. Changes in blood HCO_3^- concentration observed across the study timeframe. * = IND different to PLA (p <0.05). # = STND different to PLA (p <0.05).

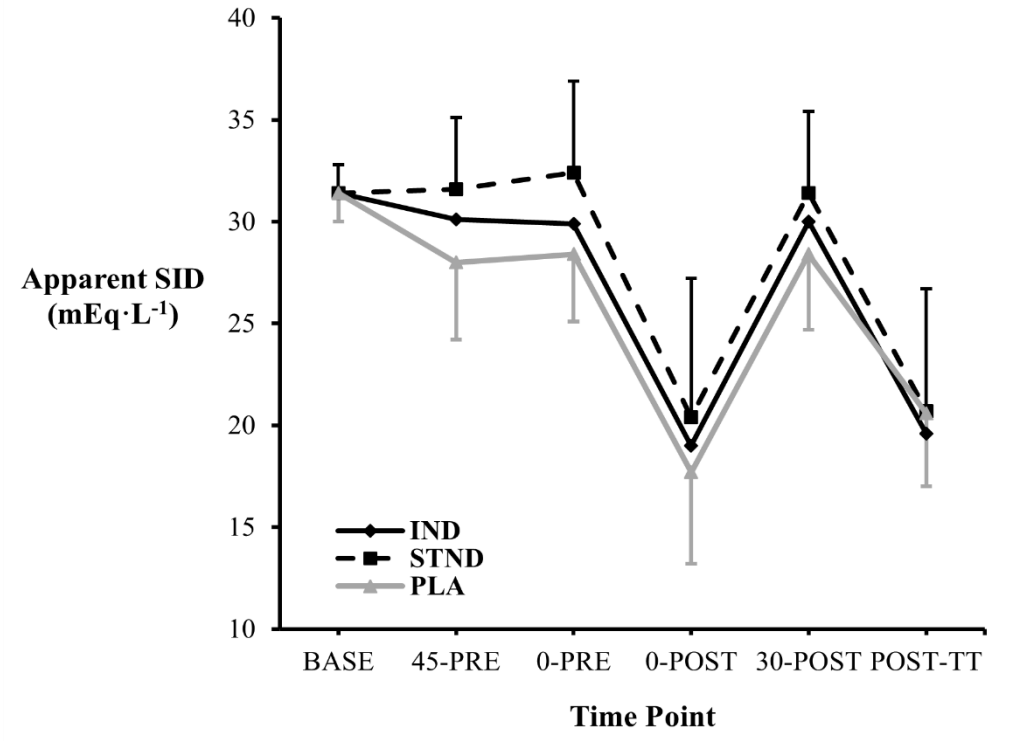

Figure 7b.2 – Changes in the apparent SID observed across the study timeframe.

Though no differences in the SID occurred between conditions, supplemental effects were observed for the isolated movements of Cl^- ($F = 3.7$, $p = 0.048$, $P\eta^2 = 0.38$) and Ca^{+2+} ($F = 2.7$, $p = 0.032$, $P\eta^2 = 0.31$) (Figure 7b.3). Chloride levels were increased with PLA ingestion, reaching statistical significance versus IND at 45-PRE (+3.1 $mmol \cdot L^{-1}$, $p = 0.036$, $g = 1.14$) and STND at 0-PRE (+4.1 $mmol \cdot L^{-1}$, $p = 0.005$, $g = 1.85$). These levels remained elevated versus both $NaHCO_3$ conditions after the first exercise test (0-POST and 30-POST, mean differences >4 $mmol \cdot L^{-1}$, all $p < 0.05$, $g > 0.80$). Decreases in Ca^{2+} were observed with both $NaHCO_3$ ingestion timings versus PLA, reaching statistical significance at 0-PRE (IND = -0.11 $mmol \cdot L^{-1}$, $p < 0.001$, $g = 1.86$; STND = -0.09 $mmol \cdot L^{-1}$, $p = 0.007$, $g = 1.87$) and 30-POST (IND = -0.12 $mmol \cdot L^{-1}$, $p < 0.001$, $g = 2.79$; STND = -0.09 $mmol \cdot L^{-1}$, $p = 0.007$, $g = 2.09$). The changes that occurred in K^+ ($F = 1.4$, $p = 0.293$, $P\eta^2 = 0.18$) and Na^+ concentrations ($F = 1.3$, $p = 0.244$, $P\eta^2 = 0.18$) did not reach statistical significance between all three groups. Blood La^- concentrations were also similar between all three groups throughout the investigation period ($F = 2.1$, $p = 0.157$, $P\eta^2 = 0.26$), including at both post-exercise time points (Figure 7b.4). At the POST-TT time point, however, moderate effect sizes were calculated for the mean difference in blood La^- observed in both $NaHCO_3$ groups versus PLA (IND = +3.9 $mmol \cdot L^{-1}$, $g = 0.76$; STND = +2.7 $mmol \cdot L^{-1}$, $g = 0.64$).

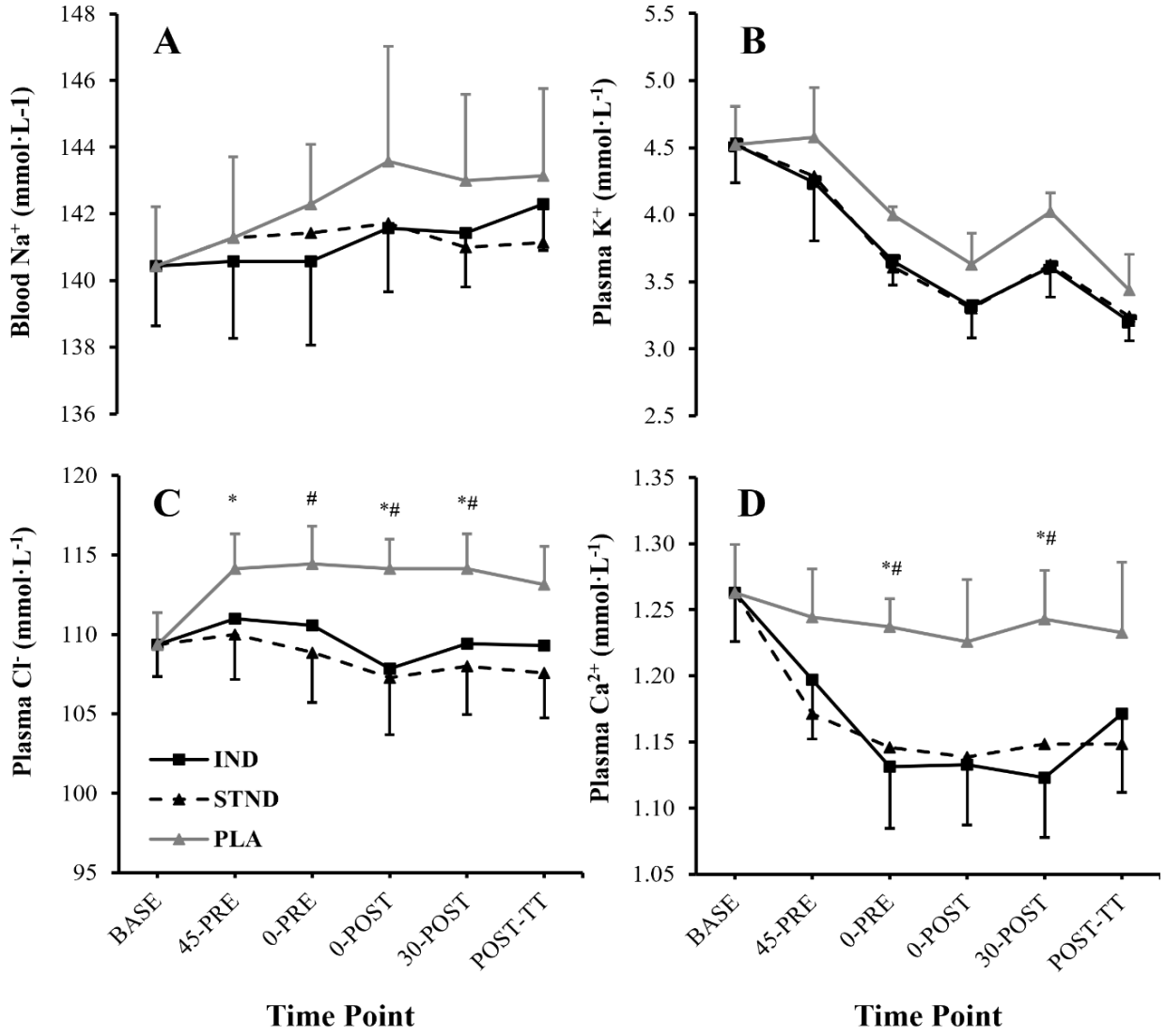

Figure 7b.3. Changes in blood concentrations of A) Na^+, B) K^+, C) Cl^-, and D) Ca^{2+} across the study timeframe. * = IND different compared to PLA (p <0.05). # = STND different to PLA (p <0.05).

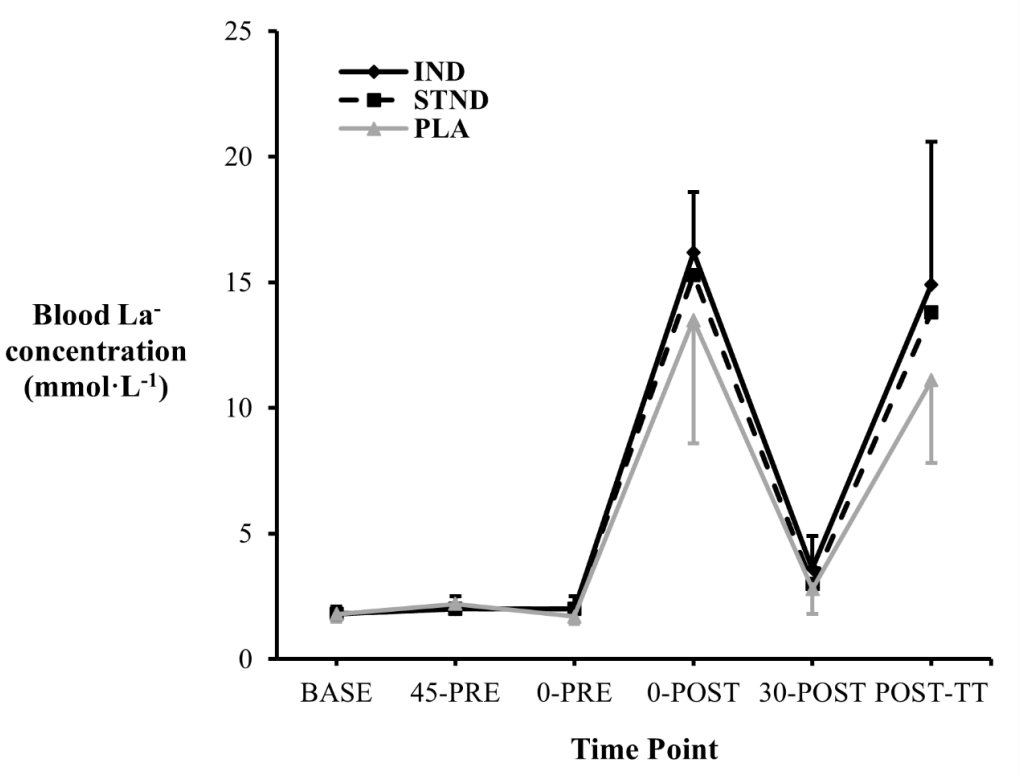

Figure 7b.4. Changes in blood La^- concentration observed across the study timeframe.

7b.3.2 Swimming Performance

No differences were observed in mean 75 m swimming time (F = 1.2, p = 0.326, $P\eta^2$ = 0.17) or any individual swimming bout (F = 1.2, p = 0.316, $P\eta^2$ = 0.17) during the 6 x 75 m test (Table 7b.1). This included five of seven swimmers producing highly repeatable swimming times across the experimental trials (mean 75 m time: ±0.1–0.7 s, CV = 0.1–0.9%). The remaining two swimmers both recorded performances above the SWC (1.1 s). These swimmers were swimmer five (IND: 57.1 s and PLA: 57.2 s vs. STND: 59.1 s) and swimmer six (IND: 50.3 s and STND: 51.3 s vs. PLA: 53.9 s). Effect sizes for each 75 m swimming bout, mean 75 m swim time, and aggregated time-to-complete the 6 x 75 m swimming test were all trivial (g <0.20) between supplemental conditions.

Table 7b.1. Mean and aggregated performance times in the 6 x 75 m swimming test.

Performance Variable	Ingestion Strategy		
	IND	**STND**	**PLA**
Bout 1 (s)	47.6 ± 5.0	47.7 ± 5.9	47.9 ± 5.4
Bout 2 (s)	47.1 ± 4.7	47.5 ± 6.1	47.8 ± 5.7
Bout 3 (s)	47.3 ± 5.1	47.7 ± 6.1	47.9 ±5.8
Bout 4 (s)	47.0 ± 5.1	47.6 ± 6.0	47.9 ± 5.5
Bout 5 (s)	47.3 ± 5.0	48.2 ± 6.0	48.2 ± 5.4
Bout 6 (s)	47.2 ± 5.4	48.3 ± 6.0	48.1 ± 5.6
Mean 75 m (s)	47.2 ± 4.7	47.8 ± 5.6	48.0 ± 5.2
Mean aggregated (min:s)	4:43.5 ± 30.3	4:47.0 ± 35.8	4:47.8 ± 33.3

Mean ± SD.

Neither group could also be differentiated based on 200 m freestyle time-trial performance (F = 0.3, p = 0.642, $P\eta^2$ = 0.05), with similar swimming times recorded in all three conditions (IND: 131.0 ± 8.2 s, STND: 131.5 ± 7.1 s, PLA: 131.1 ± 7.1 s; all g <0.20). Similarly, repeatable performances were observed in five of the seven swimmers (±0.4–1.6 s, CV = 0.2–0.6%). The two remaining swimmers both recorded swimming times that exceeded the SWC (1.6 s), which were swimmer one (IND: 115.6 s vs. STND: 118.8 s and PLA: 117.9 s) and swimmer five (PLA: 136.9 s and STND: 137.9 s vs. IND: 140.7 s).

7b.3.3 Perceptual Measures

There were no differences in RPE reported between supplement groups following the 6 x 75 m swimming test (F = 1.4, p = 0.274, $P\eta^2$ = 0.19) or the 200 m freestyle time-trial (F = 0.2, p = 0.804, $P\eta^2$ = 0.04). Ratings of perceived exertion scores were 9.4 ± 0.6 units (IND), 9.3 ± 0.8 units (STND) and 8.8 ± 1.5 units (PLA) immediately after the 6 x 75 m test (all g <0.20); and 8.9 ± 1.1 units (IND), 9.1 ± 0.9 units (STND), and 9.1 ± 1.2 (PLA) immediately after the 200 m freestyle time-trial (all g <0.20). Perceived readiness to exercise was also no different between all three experimental conditions across the study timeframe (F = 0.7. p = 0.725, $P\eta^2$ = 0.10), which peaked before the 6 x 75 m swimming test in all three conditions (0-PRE scores, IND: 7.0 ± 1.8 units, STND: 7.3 ± 1.3 units,

PLA: 6.8 ± 1.5 units, all g <0.50). Perceived readiness to exercise scores before the 200 m freestyle time-trial were 6.2 ± 2.2 units (IND), 5.0 ± 3.8 units (STND), and 5.4 ± 2.4 units (PLA), with the +1 mean difference between IND and the other conditions considered to be small (g = 0.36 vs. STND, g = 0.32 vs. PLA).

7b.3.4 Gastrointestinal Side-Effects

Aggregated scores for gastrointestinal side-effects did not differ between supplemental conditions (F = 1.8, p = 0.206, $P\eta^2$ = 0.21), with mean scores being 30.0 ± 22.6 units (IND), 17.0 ± 10.2 units (STND), and 20.9 ± 16.8 units (PLA). Despite no statistical significance between groups, the mean difference between IND and the other two conditions did produce moderate (g = 0.69 vs. STND) and small (g = 0.43 vs. PLA) effect size calculations, respectfully. These scores were highly variable, however, with large ranges in aggregated scores reported for IND (3–69 units, CV = 75%), STND (4–34 units, CV = 60%), and PLA (6–47 units, CV = 81%). The most severe gastrointestinal side-effects reported by individuals in each experimental condition are presented in Table 7b.2.

Table 7b.2. Most severe gastrointestinal side-effects reported by swimmers in each trial.

Swimmer	Ingestion Strategy		
	IND	**STND**	**PLA**
1	Stomach Bloating 9.8/10 (45-PRE)	Nausea 7.1/10 (45-PRE)	Stomach Bloating 3.4/10 (45-PRE)
2	Stomach Ache 4.9/10 (0-POST)	Stomach Bloating 5/10 (30-POST)	Nausea 3.5/10 (0-PRE)
3	Stomach Ache 4.1/10 (0-PRE)	Nausea 3.2/10 (45-PRE)	Vomiting 10/10 (45-PRE)
4	Nausea 6.2/10 (0-POST)	Bowel Urgency 1.7/10 (0-POST)	Bowel Urgency 1.5/10 (POST-TT)
5	Stomach Ache 0.6/10 (45-PRE)	Stomach Ache 2.4/10 (BASE)	Nausea 8.2/10 (45-PRE)
6	Nausea 8.9/10 (0-PRE)	Nausea 7/10 (45-PRE)	Nausea 8.7/10 (45-PRE)
7	Nausea 10/10 (POST-TT)	Nausea 6.6/10 (30-POST)	Nausea 6/10 (0-PRE)

7b.3.5 Dietary Controls

Participants successfully replicated their pre-exercise meal composition prior to each trial, reporting similar energy (F = 0.9, p = 0.438, $P\eta^2$ = 0.13), CHO (F = 0.9, p = 0.429, $P\eta^2$ = 0.13), protein (F = 0.8, p = 0.481, $P\eta^2$ = 0.12), fat (F = 1.9, p = 0.197, $P\eta^2$ = 0.24), and fluid intakes (F <0.1, p = 1.000, $P\eta^2$ <0.01). The mean pre-exercise meal during this study consisted of 1.4 ± 0.7 g·kg BM^{-1} of CHO; 0.6 ± 0.3 g·kg BM^{-1} of protein; 0.5 ± 0.3 g·kg BM^{-1} of fat; and 1.4 ± 0.4 L of fluid.

7b.3.6 Order Effects and Supplement Predictions

No order effects were identified between trials for mean 75 m swimming time (F = 0.3, p = 0.767, $P\eta^2$ = 0.04) or 200 m freestyle time-trial performances (F = 1.5, p = 0.265, $P\eta^2$ = 0.20). Moreover, swimmers were successfully blinded in this study, only correctly predicting whether they consumed either $NaHCO_3$ (IND or STND) or PLA on 33% of occasions.

7b.4 Discussion

The primary purpose of this investigation was to assess the effects of an individualised versus a standardised $NaHCO_3$ ingestion strategy on repeated, high-intensity swimming performance. Despite both $NaHCO_3$ strategies enhancing blood HCO_3^- concentrations prior to exercise, neither provided any additive ergogenic benefits compared to a Na^+-matched PLA. The secondary purpose was to observe acid-base recovery and whether this could improve performance in a follow-up 200 m freestyle time-trial. After a 30 min active recovery window, both $NaHCO_3$ strategies restored blood HCO_3^- concentration to elevated levels prior to exercise, though this again failed to produce any ergogenic benefits. These results infer that $NaHCO_3$, regardless of dosing strategy, may not be an effective strategy for highly trained young swimmers to improve sprint swimming performances in training, or enhance recovery for subsequent swimming time-trial bouts in competition.

Individualising the timing of $NaHCO_3$ ingestion did not produce greater pre-exercise blood HCO_3^- concentrations compared a standardised approach (+0.8 mmol·L^{-1}, g = 0.32), supporting previous research in world-class rowers (+0.5 mmol·L^{-1}, g = 0.29) (Boegman et al., 2020). However, the previous study did observe pre-exercise blood HCO_3^- increases of +6 mmol·L^{-1} (individualised) and +5.5 mmol·L^{-1} (standardised) with both $NaHCO_3$ strategies (Boegman et al., 2020), which were associated with 'almost certain' and 'possible' ergogenic benefits, respectively (Heibel et al., 2018). In contrast, blood HCO_3^- increases in the present study did not exceed the proposed ergogenic threshold of +5 mmol·L^{-1} (Heibel et al., 2018), despite all swimmers reaching this threshold in the initial time to peak testing. An explanation for this might be due to this study's dietary controls, which encouraged swimmers to consume a meal 1–3 hours before exercise to align with practical guidelines (Shaw et al., 2014). This resulted in some swimmers either ingesting $NaHCO_3$ with their pre-exercise meal (i.e., 120–150 min pre-exercise), or consuming their meal after $NaHCO_3$ ingestion (i.e., 150–195 min pre-exercise); both of which differed from the initial time to peak testing and likely affected $NaHCO_3$ absorption characteristics (Abuhelwa et al., 2017; Remer & Manz, 1995). Conversely, Boegman et al. (2020) utilised a standardised meal strategy that involved the ingestion of a snack three hours before $NaHCO_3$ ingestion (i.e., 4–6 hours pre-exercise). Though, while this elicited greater blood HCO_3^- responses, this meal strategy is unlikely to be replicated in practice, and therefore was not considered for this study. As such, these results highlight the logistical challenges when attempting to individualise $NaHCO_3$ outside of laboratory conditions, potentially requiring further investigation of blood HCO_3^- time courses with different meal intakes and timings, and during a variety of applied scenarios, to truly individualise $NaHCO_3$ ingestion for athletes.

Alternatively, he importance of achieving a +5 mmol·L^{-1} increase in blood HCO_3^- is questionable. Previous studies in swimmers have demonstrated ergogenic benefits of $NaHCO_3$ when pre-exercise increases in blood HCO_3^- were only +3.5–4.4 mmol·L^{-1} above baseline values (Gao et al., 1988; Kumstát et al., 2018; Zajac et al., 2009), which were in accordance with the observations in this study (IND: +4.9 mmol·L^{-1}, STND: +4.1 mmol·L^{-1}). This adds to the premise that an increased blood

buffering capacity might not be the primary ergogenic mechanism following $NaHCO_3$ ingestion (Westerblad, 2016), and instead the altered SID could delay muscle depolarisation and maintain excitation-contraction coupling during high-intensity exercise (Siegler et al., 2016). In this study, pre-exercise declines in blood Cl^- and Ca^{2+} occurred prior to exercise, potentially signalling their intramuscular uptake (Lühker et al., 2017; Sostaric et al., 2006). However, no differences in K^+, Na^+, nor the collective SID were observed between $NaHCO_3$ and PLA conditions, which contrasted previous research (Gough et al., 2018a, 2019a, 2019b). This finding might have occurred due to the use of a since Na^+-matched PLA condition, which potentially induced a similar activity of the skeletal muscle pumps and exchangers (e.g., Na^+-K^+ or Na^+-H^+), and/or Na^+-K^+ ATPase, as the $NaHCO_3$ conditions (Siegler & Gleadall-Siddall, 2010). Though speculative, this could suggest that Na^+ is more important than HCO_3^- to secure an ergogenic benefit of $NaHCO_3$ ingestion, thus adding further support for future use of a time to peak SID approach (as per Chapter 7a). On the other hand, the Na^+-matched PLA contributed towards similar gastrointestinal symptoms as $NaHCO_3$ ingestion, perhaps due to acute mucosal irritation and fluid shifts in the stomach (Metheny & Krieger, 2020). This could also suggest that the side-effects from $NaHCO_3$ and PLA were equally ergogenic or ergolytic for performance, warranting the use of non-supplemental control conditions in future to elucidate any possible effects of $NaHCO_3$ on swimming performance.

Another reason why $NaHCO_3$ may have been ineffective in this study was due to the exercise protocols. The first swimming exercise involved 6 x 75 m maximal effort bouts with short rest periods, which was selected based on its familiarity and repeatability in this cohort. Equally, this test also induced large acid-base perturbations, which was evidenced through declines in blood HCO_3^- (-9–15 $mmol \cdot L^{-1}$), SID (-11–15 $mEq \cdot L^{-1}$), and pH (-0.19–0.21 units; data not presented) immediately after exercise. However, because such large perturbations were produced over a short timeframe (<60 s), the rapid rates of change in pH (and thus intramuscular H^+ accumulation) were likely to outweigh the possible ergogenic mechanisms expected from $NaHCO_3$ supplementation (de Araujo Dias, 2015; Higgins et al., 2013; McNaughton et al., 1992b). The second exercise protocol was an all-out

swimming distance (200 m) that a recent meta-analysis suggested was likely to be enhanced with $NaHCO_3$ ingestion (Grgic & Mikulic, 2022). Similarly, no performance benefits were observed following either $NaHCO_3$ ingestion strategy, despite both conditions recovering and increasing blood HCO_3^- concentrations in the 30 min recovery window (both +3.5 $mmol \cdot L^{-1}$ vs. baseline; +6 $mmol \cdot L^{-1}$ vs. PLA). Though while these blood values represent an elevated blood buffering capacity prior to the time-trial exercise, this may not have contributed to an ergogenic effect since: (a) there were little differences in SID between $NaHCO_3$ and PLA conditions; and/or (b) the initial repeated sprint exercise impeded exercise by producing muscle damage and fatigue at the neuromuscular level (Girard et al., 2011; Heubert et al., 2005). This is problematic when attempting to translate these results to competition performances, since competitions only feature time-trial swimming and not repeated sprint exercise. Yet, as $NaHCO_3$ successfully recovered and increased blood HCO_3^- concentrations 30 min after a maximal performance, future $NaHCO_3$ research involving repeated time-trial swimming exercise is warranted.

This study is not without its limitations. Due to the financial and time burdens of this study, it was not possible to replace the five male participants who withdrew after time to peak HCO_3^- determination. Unfortunately, this left study sample consisting mostly of female swimmers, in which menstrual cycle stage was not accounted for. However, there is currently no information to suggest that menstrual cycle phases alter the physiological and exercise responses to $NaHCO_3$ supplementation (Saunders et al., 2022). Additionally, the one male swimmer in the study was highly competitive at the national level, contributing to large SDs in performance data that could have masked the small, yet critical improvements in exercise performance. To overcome this, data was presented at the individual level using a SWC, in which no trends for a $NaHCO_3$ benefit could be established. Moreover, it should be noted that this study utilised a highly trained sample size similar to previous $NaHCO_3$ research investigating repeated swimming intervals (n = 8–10; Campos et al., 2012; Gao et al., 1988; Zajac et al., 2009) and 200 m time-trial efforts (n = 6–9; de Salles Painelli et al., 2013; Joyce et al., 2012; Lindh et al., 2008; Pierce et al., 1992; Pruscino et al., 2008); though this may indicate that the

majority of sport science research requires greater sample sizes to increase its statistical power (Jones et al., 2003). Despite this, this was the first study to compare individualised and standardised $NaHCO_3$ ingestion strategies in an applied swimming scenario, and thus the outcomes from this research have important implication for both practice and future research.

7b.5 Conclusion

In summary, ingesting $NaHCO_3$ capsules at either individualised or a standardised (150 min) pre-exercise time points provided no ergogenic benefit towards repeated swimming sprints, or a follow-up 200 m time-trial in highly trained adolescent swimmers. The prolonged ingestion timeframes when using capsules caused logistical problems when aligning practical meal guidelines (i.e., 1–3 hours pre-exercise), resulting in some swimmers ingesting $NaHCO_3$ with meals, or consuming meals after $NaHCO_3$ ingestion, both of which differed from how individualised ingestion strategies were pre-determined (i.e., meal 1–3 hours before $NaHCO_3$ ingestion). Nonetheless, increases in blood HCO_3^- were observed in accordance with previous research, which might alternatively suggest that the exercise tests involved were too intensive to benefit from the proposed $NaHCO_3$ mechanisms. Based on the practical issues highlighted by this study, additional work is required in order to optimise $NaHCO_3$ ingestion protocols for swimmers in applied practice. Furthermore, it is speculated that more consistent ergogenic benefits might occur in middle-to-long distance swimming exercise (400–800 m), though with scant evidence, this cannot be confirmed at present.

Chapter 8 – The Effect of Citrulline Malate on Aerobic Swimming Performance in Highly Trained Adolescent Swimmers

8.1 Introduction

Citrulline malate (CM) has recently been touted as a possible ergogenic aid for sports performance (Gough et al., 2021), although the best use of this supplement is currently unclear. The primary ingredient, L-citrulline, is a known precursor to NO production, and is therefore thought to have multiple physiological benefits that enhance muscle blood flow and O_2 uptake kinetics (see Chapter 1, section 1.5.3). Furthermore, L-citrulline also has roles in the urea cycle, which could enhance the clearance rate of waste metabolites (e.g., ammonia) during exercise (Breuillard et al. 2015); possibly delaying La^- production and enabling a greater oxidative metabolism of pyruvate (thus increasing ATP supply; Hargreaves & Spriet, 2020). Moreover, the co-ingestion of malate could have synergistic benefits that promote the rate of oxidative ATP production via its roles in the TCA cycle (Gough et al., 2021). One such pathway involves malate in anaplerotic reactions, where its dehydrogenation into oxalacetate is critical for continued aerobic ATP production and resynthesis (Gibala et al., 2000). Equally, malate is also involved in ancillary reactions that alter the concentrations of TCA intermediates, possibly assisting ATP production during prolonged exercise (Bendahan et al., 2002). Based on these suggested mechanisms, it is intuitive to suggest that CM would be of most ergogenic benefit to whole-body exercise with a large aerobic component (Gough et al., 2021), such as swimming training or middle- and long-distance swimming events (Rodríguez & Mader, 2011).

Though the CM mechanisms appear to be aligned with prolonged aerobic exercise, there has been little research in this mode of exercise. Indeed, most early work with CM supplementation has focused on resistance exercise, which appears to have followed on from a landmark study by Pérez-Guisado and Jakeman (2010). This was one of the first investigations to utilise CM as an ergogenic aid, finding 8 g CM (60 min pre-exercise) to enhance bench press repetitions to failure both before (+18%) and after (+53%) a chest-based workout. Research has since aimed to replicate these positive results, though the outcomes have been equivocal (Aguiar & Casonatto, 2022; Vårvik et al., 2021). To date, only two studies have measured performance in exercise that is considered to be aerobic, both of

which failed to show CM to have any effect on T_{LIM} cycling (≥90% $\dot{V}O_{2peak}$, Cunniffe et al., 2016; Gills et al., 2021). However, these studies had confounding factors that should be considered. First, Gills et al. (2021) administered an 8 g CM dose that has been associated with mixed performance outcomes (Gough et al., 2021), therefore higher doses of 12–15 g may be necessary to elicit more consistent increases in plasma L-citrulline and NO (Moinard et al., 2008); especially in trained participants (Jones et al., 2018). Second, Cunniffe et al. (2016) measured performance following 10 x 15 m maximal cycling sprints, which could have: (a) hindered aerobic work capacity by causing local muscle fatigue (Heubert et al., 2005); or (b) allowed the window for ergogenic potential (~60 min post-ingestion) to pass before the aerobic work had started (Gough et al., 2021). As a result, there is a need for further research investigating the effects of 12–15 g CM on full-body, aerobic exercise.

Swimmers are one such population that could benefit from the purported CM benefits, given their sport demands a large muscular recruitment from the upper and lower body, while also stressing both the aerobic and anaerobic energy systems (Pyne & Sharp, 2014). Enhancing physiological functions such as blood flow, ammonia/blood La^- clearance, and ATP production could all therefore be expected to enhance middle-distance swimming performances (200–400 m), particularly if these distances are repeated across multiple training sets (Rodríguez & Mader, 2011). Thus, the purpose of this study was to investigate whether a high CM (15 g) dose could be ergogenic to the aerobic performances of highly trained swimmers in a typically used training set (6 x 300 m).

8.2 Methods

8.2.1 Participants

An a priori power calculation (input parameters: repeated measures ANOVA test for within-between interactions, two groups, six measures, α = 0.05; ß = 0.80; correspondence = 0.78, based on repeatability data presented in section 8.2.4) determined that a sample of size of 14 swimmers was

required to identify a small effect size (0.20) in mean 300 m swimming performance with a power of 84% (G*Power, v.3.1.9.4, Universität Düsseldorf, Germany). Seventeen highly trained national and age-group swimmers (see Chapter 2, section 2.1.2) from a high-performance swimming club were therefore recruited for this study (aged ≥16 years, training for competitive distances ≥200 m). However, six swimmers withdrew from the study before data collection was complete (four attrition, one injury, one withdrew consent), resulting in a final study sample of 11 highly trained young swimmers (six male, five female, age: 17 ± 3 years, height: 1.71 ± 0.05 m, body mass: 60.6 ± 8.3 kg, WA points for 200 m freestyle: 650 ± 99). Though this sample size was below the recommendation, this was justified based on the time and resource constraints of conducting the experiment in a highly trained cohort (Lakens, 2022). At the time of the study, all swimmers were engaged in an aerobic training phase that consisted of 6–8 pool (mean swimming volume: 52.1 ± 7.7 km·week^{-1}) and 2–3 land-based training sessions (~60 min) each week. Written informed consent was provided prior to participation in this study by all swimmers and their parents/guardians if aged under 18 years. Ethical approval was granted by BCU, which was in accordance with the Declaration of Helsinki (Newbury/#10146/sub2/R(B)/2022/Mar/HELS FAEC).

8.2.2 Preliminary Procedures

All pre-experimental controls were in accordance with Chapter 2 (section 2.1.4). These included swimmers being instructed to follow their habitual nutrition practices prior to training, except for limiting NO_3^--rich foods in the seven days before each experimental trial (Gough et al., 2021). Both swimmers and their parents/guardians received a list of NO_3^--rich foods to facilitate adherence to this request. Two swimmers reported the use of chronic ergogenic aids (i.e., beta-alanine, creatine), which was permitted as these had consistently been ingested for over 24 weeks, thus the largest physiological adaptations with these supplements would have already occurred (Chung et al., 2012; Peyrebrune et al., 2005). Adherence to the dietary controls was checked via a verbal recall with each swimmer, as per previous research (Cunniffe et al., 2016; Gills et al., 2021).

8.2.3 Experimental Procedures

This study involved three trials: one familiarisation, and two experimental trials that were conducted in a double-blind, randomised, and crossover design. Immediately on arrival at the training venue, swimmers completed five min seated rest before giving baseline (BASE) blood La^- and blood pressure (SBP and DBP) measures, which were carried out as per Chapter 2 (sections 2.2.5 and 2.2.6, respectively). Following BASE measures, all swimmers were given an opaque sports bottle containing either CM or PLA. The experimental solution consisted of 15 g CM (Myprotein, Manchester UK), 100 mL orange cordial (Sainsburys, Leeds, UK) and 300 mL water. The PLA consisted of 400 mL orange cordial (Sainsburys, Leeds, UK) in accordance with Cunniffe et al. (2016). Both solutions were ingested within a five min window, 60 min before the start of exercise. The CM dose and timings used in this study were thought to produce peak plasma L-citrulline and NO concentrations compared to other dosing strategies (Moinard et al., 2008). None of the swimmers had prior experience of ingesting CM and all solutions were created and randomised by a sport and exercise technician.

In the 60 min ingestion window, swimmers prepared for exercise by following the warm-up routines previously outlined in Chapter 2 (section 2.4.1). This included ~10–15 min of land preparation, before entering a 25 m pool for a ~30 min progressive swimming warm-up prepared by the head coach. The remaining 15 min was spent in passive rest while swimming lanes were organised for the aerobic swimming test. In this time, pre-exercise (PRE-EX) measures of blood La^- and blood pressure were taken. In addition, RPE was collected using a CR10 Borg scale (Borg, 1998) to rate the perceived intensity of the warm-up. Each measurement (blood La^- SBP, DBP, RPE) was collected once more immediately at the cessation of the aerobic swimming test (POST-EX). All warm-ups, swimming lanes, and timings were kept consistent for both experimental trials. At the end of each experimental trial, swimmers were asked to predict their supplement ingestion in accordance with the processes in Chapter 2 (section 2.4.5).

8.2.4 Aerobic Swimming Test

A 6 x 300 m maximal freestyle swimming test was used to measure aerobic swimming performance, which was recommended by the head coach based on prior use in this cohort. The test required a maximal 300 m freestyle time-trial to be completed every 4.5 min for six bouts, with the time between 300 m completion and the following bout (~60 s) serving as passive rest. In the three months prior to the study, four swimmers had completed the 6 x 300 m test on a more frequent basis (3–6 attempts), demonstrating a high test-retest reliability for mean 300 m completion time (CV: 1.1–2.9%), as well an 'excellent' reproducibility of results over their first three attempts (ICC: r = 0.782, p = 0.005) (Atkinson & Nevill, 1998; Koo & Li, 2016). This exercise protocol was therefore considered as a suitable measure of aerobic performance in highly trained adolescent swimmers. Performance times were measured by two experienced swimming coaches, with the mean of their times recorded for data analysis. Swimmers performed the 6 x 300 m test with a maximum of two per lane, which was kept consistent for all trials. Aggregated time-to-complete all 300 m time-trials, mean 300 m time, and individual 300 m time-trial bouts were all analysed for possible CM versus PLA differences.

8.2.5 Statistical Analysis

All statistical tests were carried out in accordance with Chapter 2 (section 2.5.2). Paired samples t-tests were used to compare mean performance outcomes (aggregated time-to-complete 6 x 300 m, mean 300 m time) following CM and PLA ingestion, whereas a one-way ANOVA was also used to explore potential sex differences. A 2 (supplement) x 3 (BASE, PRE-EX, POST-EX) repeated measures ANOVA was used to compare blood La^-, SBP, DBP, and RPE between supplement conditions, with these measures also assessed for sex-based differences with a three-way ANOVA (supplement x time x sex). Effect sizes are reported as $P\eta^2$ for all ANOVA tests, whereas g was calculated and reported for all pairwise comparisons (for interpretations, Chapter 2, section 2.5.2). Test-retest reliability for the 6 x 300 m swimming test was presented using based on past data from four swimmers using CV and ICC calculations (see Chapter 2, section 2.5.3). A SWC was calculated

for mean 300 m time (±1.9 s) by multiplying the SD of a control group of swimmers by 0.2 (Bernards et al. 2017).

8.3 Results

8.3.1 Aerobic Swimming Performance

There were no differences in the aggregated time-to-complete 6 x 300 m (p = 0.679, g = 0.08), mean 300 m time (p = 0.683, g = 0.09), or any individual 300 m swimming bout (F = 1.2, p = 0.679, $P\eta^2$ = 0.02) between CM and PLA conditions (Table 8.1). Inspection of individual data found nine swimmers exceeded the SWC for mean 300 m time, though this was highly variable with five swimmers performing better with CM (mean change: -6.5 ± 2.5 s) and four performing better with PLA (-5.4 ± 1.2 s) (Figure 8.1A). Sub-group analysis did not identify any sex differences at the group mean level (F = 2.5, p = 0.093, η^2 = 0.29), with similar mean 300 m swimming times for both males (CM: 3:27.1 ± 8.9 s vs. PLA: 3:29.6 ± 5.9 s, g = 0.31) and females (CM: 3:37.9 ± 7.5 s vs. PLA: 3:36.5 ± 8.7 s, g = 0.16) (Figure 8.1B). At the individual level, however, a greater proportion of males exceeded the SWC with CM (three improved, two maintained, one worsened; mean change: -2.5 + 5.8 s), whereas performance changes were more variable in females (two improved, three worsened; mean change: +1.4 ± 6.0 s).

Table 8.1. Mean swimming times per bout during the 6 x 300 m freestyle test.

300 m bout	Mean 300 m time (min:s)		Effect Size (g)
	CM	PLA	
1	3:30.4 ± 9.8	3:32.2 ± 8.3	0.19
2	3:31.8 ± 9.0	3:32.5 ± 7.1	0.08
3	3:31.6 ± 9.4	3:33.1 ± 8.1	0.16
4	3:33.4 ± 10.1	3:33.0 ± 7.2	0.04
5	3:33.0 ± 10.0	3:33.6 ± 8.2	0.06
6	3:31.8 ± 10.5	3:32.2 ± 9.4	0.03
Mean	3:32.0 ± 9.6	3:32.8 ± 7.7	0.09
Aggregated	21:12.0 ± 57.8	21:16.6 ± 46.6	0.08

Mean ± SD.

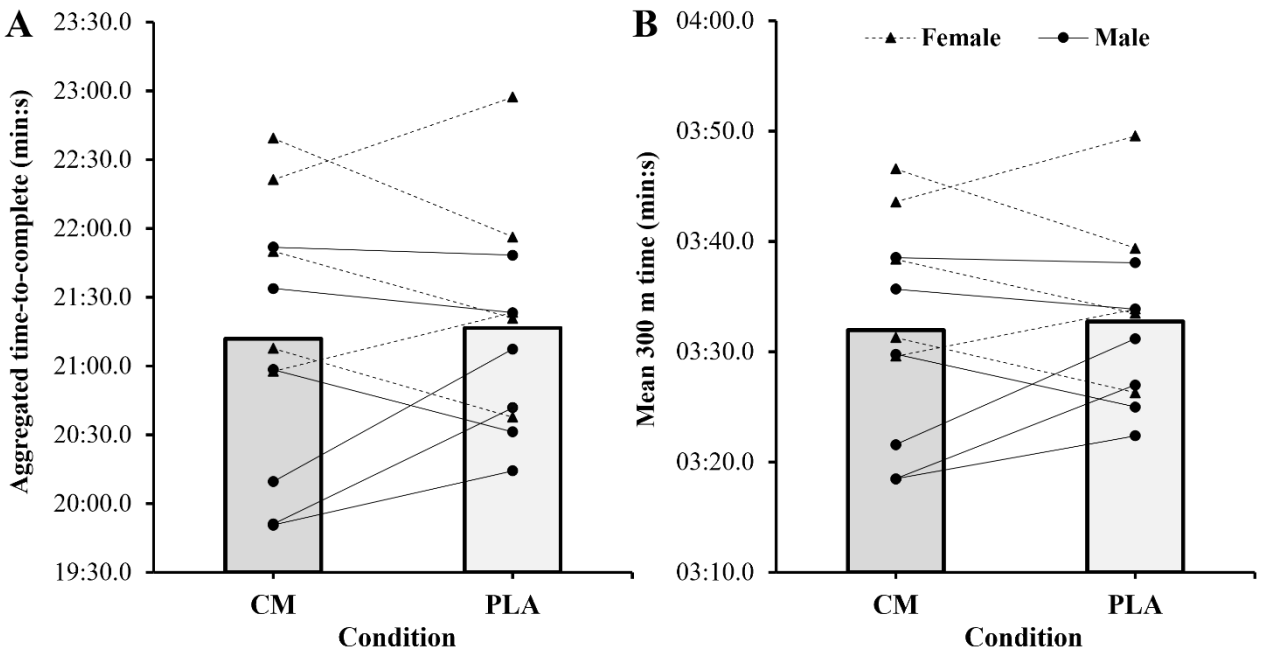

Figure 8.1. Mean and individual (A) aggregated time-to-complete, and (B) mean 300 m swimming time during the 6 x 300 m freestyle test.

8.3.2 Physiological Variables

Blood La^- concentrations were similar between supplements across the study timeframe (F = 2.3, p = 0.126, $P\eta^2$ = 0.19; Figure 8.2), with no significant effects of sex being observed (F = 1.7, p = 0.224, $P\eta^2$ = 0.16). There was, however, a small effect size calculated at the POST-EX time point (CM: 6.6 ± 2.9 mmol·L^{-1} vs. PLA: 5.2 ± 3.0 mmol·L^{-1}, g = 0.46), which was more noticeable in male (CM: 7.9 ± 2.7 mmol·L^{-1} vs. PLA: 5.2 ± 3.6 mmol·L^{-1}, g = 0.78) than female swimmers (CM: 5.1 ± 2.5 mmol·L^{-1} vs. PLA: 5.2 ± 2.7 mmol·L^{-1}, g = 0.03).

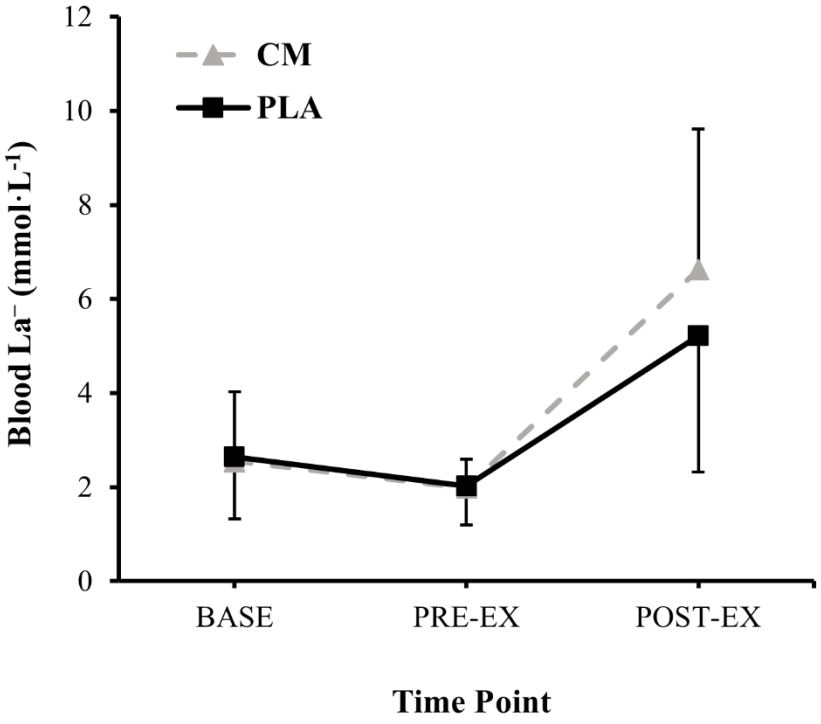

Figure 8.2. Mean changes in blood La^- across the study timeframe.

Similarly, there were no effects of CM on SBP (F = 1.4, p = 0.267, $P\eta^2$ = 0.12) or DBP (F = 1.2, p = 0.311, $P\eta^2$ = 0.11) across the study timeframe (Figure 8.3), including no effects of sex (SBP: F = 2.7, p = 0.097, $P\eta^2$ = 0.23; DBP: F = 1.8, p = 0.202, $P\eta^2$ = 0.16). Despite this, a moderate effect size was calculated at the POST-EX time point between conditions for SBP (CM: 149 ± 18 mmHg vs. PLA: 138 ± 16 mmHg, g = 0.64), which occurred in both male (CM: 153 ± 14 mmHg vs. PLA: 142 ± 19 mmHg, g = 0.60) and female swimmers (CM: 145 ± 22 mmHg vs. PLA: 134 ± 13 mmHg, g = 0.58).

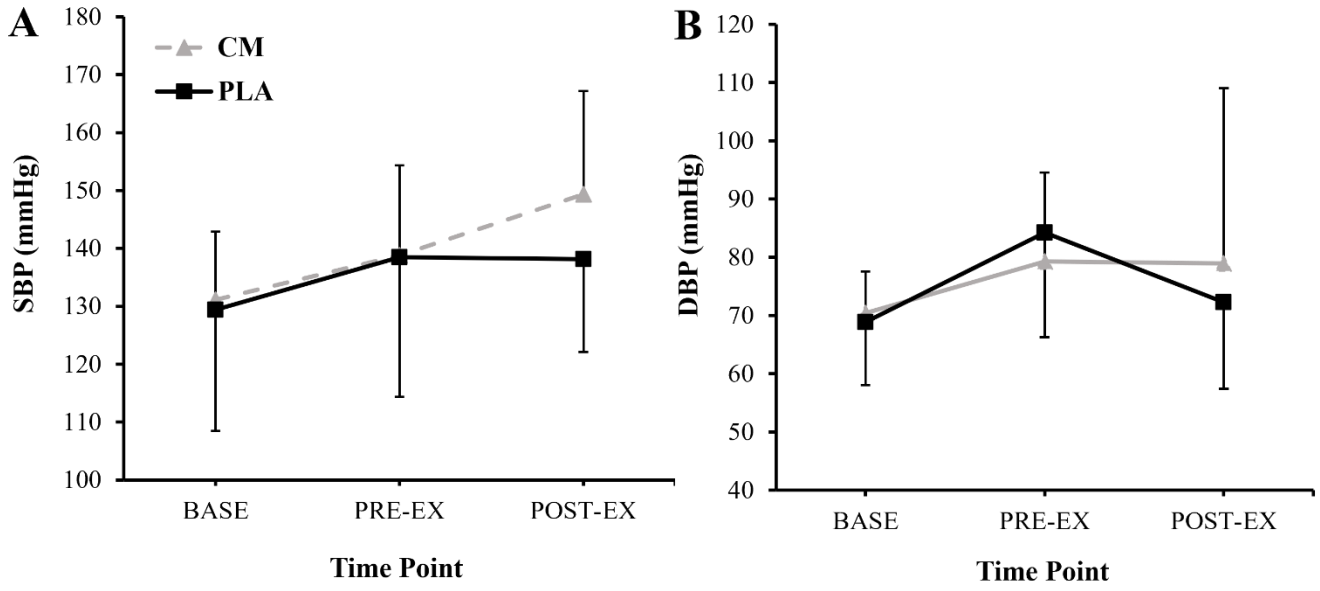

Figure 8.3. Mean changes in (A) SBP and (B) DBP over the study timeframe.

8.3.3 Ratings of Perceived Exertion

All swimmers reported similar RPE scores regardless of supplement (F = 0.8, p = 0.397, $P\eta^2$ = 0.07) or sex (F = 0.1, p = 0.941, $P\eta^2$ <0.01). However, a small effect size was calculated following the 6 x 300 m test (CM: 9.0 ± 0.8 units vs. PLA: 8.6 ± 1.1 units, g = 0.40), which appeared to be more evident in male (CM: 9.2 ± 0.8 units vs. PLA: 8.5 ± 1.0 units, g = 0.71) than female swimmers (CM: 8.8 ± 0.8 units vs. PLA: 8.8 ± 1.3 units, g <0.01). Warm-up RPE was consistent for both trials (CM: 5.5 ± 0.8 units vs. PLA: 5.5 ± 0.7 units, g <0.01).

8.3.4 Order Effects and Supplement Predictions

There were no differences in the mean 300 m swimming times between the familiarisation and the two experimental trials (F = 0.9, p = 0.434, $P\eta^2$ = 0.08). Swimmers predicted their supplement ingestion on 50% (11 of 22) occasions.

8.4 Discussion

The aim of this study was to investigate the effects of 15 g CM on the aerobic swimming performances of highly trained male and female swimmers. At the group mean level, CM did not have any influence during a 6 x 300 m freestyle swimming test, with variable performance outcomes being observed (five improved, four worsened, two maintained). Moreover, there was little evidence to suggest that CM influenced blood pressure, blood La^- production, or RPE across the study timeframe; indirectly suggesting that the purported CM mechanisms were not active in this study. Possible CM effects were observed when taking sex into account, such that males seemingly had a more consistent performance effect (three improved, two maintained, one worsened) than females (two improved, three worsened). However, as this was based on a small sub-group of swimmers, further research with a larger participant sample is required. Resultantly, the use of CM as an ergogenic aid for aerobic swimming cannot be recommended at present, particularly in highly trained adolescent cohorts.

Overall, this study found variable performance outcomes when highly trained adolescent swimmers ingested 15 g CM an hour before an aerobic swimming test (6 x 300 m). The reasons for such variability were unclear, although the lack of performance effect with CM benefit does align with past research. Indeed, neither Cunniffe et al. (2016) nor Gills et al. (2021) reported an ergogenic effect when male cyclists ingested 8–12 g CM prior to T_{LIM} cycling (≥90% $\dot{V}O_{2peak}$). One consistency between all three studies was the use of trained participants, which could negate the CM effects on NO production since these systems may already be upregulated through training adaptations (McConell et al. 2007; Totzeck et al 2012). This theory might also support why males in this study seemingly had a more consistent supplement effect than females, since post-hoc observations found the male sub-group to have less WA points than females (605 ± 118 vs. 704 ± 21 points); suggesting they were of a lower training status in middle-distance swimming events (World Aquatics, 2023). However, these observations should be interpreted with caution as they were made in a small sub-group of the participant cohort, whereas neither this study nor its predecessors directly measured NO

bioavailability (Cunniffe et al. 2016; Gills et al. 2021). Nonetheless, since possible aerobic benefits might have been observed in trained male swimmers, further investigation with a larger sample size is warranted.

No clear differences in physiological or perceptual measures were observed following CM or PLA ingestion, which was unexpected given that a large CM dose was used. In contrast, an observation of effect sizes indicated that SBP may have been increased during exercise with CM ingestion (+11 mmHg), supporting previous suggestions that blood flow regulation might not be a primary acting mechanism (Trexler et al., 2019). This cannot be confirmed, however, since blood pressure measurements are not directly associated to blood flow/vasodilation in healthy, young swimmers (Barkhidarian et al., 2019). Moreover, past research has also identified an ergogenic effect with CM when no blood pressure changes were observed (Wax et al., 2015, 2016). Potential increases in SBP might therefore be related to the sensitivity of the sphygmomanometer, with noise (e.g., public swimming environment), postural changes (e.g., prone swimming to seated position), and/or machine accuracy all factors that could have affected results (Sharman & LaGerche, 2015). Moderate effect sizes in sub-group analyses also indicated that male swimmers might have experienced greater blood La^- accumulation (+1.7 $mmol \cdot L^{-1}$) and RPE (+0.7 units) during exercise with CM, which contradicts the proposed benefits associated with urea function and ATP replenishment (Bendahan et al., 2002). However, since variable blood La^- and RPE results are frequently reported in CM and L-citrulline research (Gough et al. 2021; Rhim et al. 2020), these results should also be interpreted curiously since they were only found via effect sizes in an underpowered study sample. Combined, these results highlight the need for more direct measures of ammonia, blood flow, and ATP concentrations in future research to elucidate the acting CM mechanisms. Although, incorporating such measures can be invasive and produce logistical challenges that may not be appropriate in highly trained swimming cohorts.

The application of 6 x 300 m maximal freestyle bouts was based on reliable and repeatable results in four swimmers, though these swimmers primarily specialised in long-distance freestyle events (400–1500 m). This produced a potential limitation as recruitment as this study included swimmers specialising in middle distances (200–400 m), who may have found the test more physically and mentally challenging than their peers (Piras et al., 2019; Pyne & Sharp, 2014). Resultantly, a reduced exercise motivation could have been the key driver behind the variable performance outcomes, as opposed to differences caused by training status and/or sex. However, since no subjective measures of pre-exercise motivation were recorded, possible CM effects cannot be ruled out at present. Another possible limitation was that swimmers seemed to be able to detect their supplemental condition having already tasted the PLA supplement, stating that 15 g CM gave a more 'sour' and 'spicy' taste. This enabled the swimmers to correctly predict their supplement condition on 50% of occasions, though based on their variable performances with CM, it was unlikely that an expectancy effect occurred. Nonetheless, to counter this issue, future PLA treatments could be better taste-matched, whereas subjective measures of ergogenic expectancy are also recommended to identify participant attitudes before and after supplement ingestion.

8.5 Conclusion

Consuming 15 g CM an hour before an aerobic swimming test (6 x 300 m) did not produce any ergogenic benefits for highly trained adolescent swimmers. Moreover, no clear differences between CM and a PLA occurred in measures of blood La^-, blood pressure, or RPE. There was, however, some evidence to suggest that SBP was raised after exercise with CM ingestion, though it was unclear whether this was a supplement effect or through the accuracy of measurement. Future research involving more direct physiological measurements of ammonia, NO production, and ATP are therefore required where logistically possible to elucidate the CM mechanisms of action. Given that CM had no clear benefits towards swimming performance, this supplement cannot currently be recommended as an ergogenic aid for highly trained adolescent swimmers.

Chapter 9 – General Discussion

9.1 Key Outcomes and Future Directions

9.1.1 Dietary Observations

Chapter 3 of this thesis observed the habitual dietary intakes of UK-based, highly trained adolescent swimmers at three different training phases: during a regular training cycle; during a period of no formal training (COVID-19 lockdown); and during a period of reduced training volume (post-COVID-19 lockdown). At the conception of this thesis, only two studies had investigated the nutritional intakes of adolescent swimmers at multiple time points, showing that nutrition intakes remained unchanged across the season regardless of the training demands (Alméras et al., 1997; Kabasakalis et al., 2007). In contrast to this previous work, current adolescent swimmers appear to manipulate their dietary energy and macronutrient intakes to reflect a change in training demands. Moreover, most swimmers also reported consuming the minimally recommended macronutrient intakes at all time points (i.e., CHO: ≥3–5 g·kg BM^{-1}·day^{-1}, protein: ≥1.5 g·kg BM^{-1}·day^{-1}; Shaw et al., 2014), suggesting that this cohort had a high level of nutritional competence. A caveat to this finding, however, was the swimmers in this study were all receiving sport nutrition support prior to and during the observation period. Therefore, while these findings suggest that adolescent swimmers are consuming appropriate diets to support health, performance, recovery, and growth (Desbrow, 2021; Hannon et al., 2020b); this outcome can only be generalised to swimmers who directly engage with sport nutrition support. As this may not be the case at many high-performance swimming clubs (Jovanov et al., 2019; Moreno et al., 2022), more accessible sport nutrition support may be needed across the swimming landscape.

During periods of formal training, highly trained adolescent swimmers also reported dietary intakes that achieved the UK RNI for most micronutrients. This outcome corroborated previous research in adolescent swimmers (Hassapidou et al., 2002; Kabasakalis et al., 2007; Martínez et al., 2011; Simič & Mohorko, 2018), likely because this cohort consumes a naturally high vitamin and mineral intake through their heightened DEI requirements (Shaw et al., 2014; Thomas et al., 2016). One concern was

that 75% of female swimmers reported an inadequate iron consumption at both in-season time points (~13–14 mg·day^{-1}); however, these mean intakes were only just below the UK RNI (<14.8 mg·day^{-1}). Such intakes may have therefore been a reporting error and were not expected to pose a risk to health and/or performance (Lukaski et al., 1996; Vallieres et al., 1989); though this should be considered on a case-by-case basis. Conversely, the lockdown period coincided with a decline in most micronutrient intakes, resulting in many swimmers failing to achieve the UK RNI for calcium, iron, magnesium, and potassium. This could be problematic in times of DEI restriction, such as in future pandemics; recovery from serious injuries/illnesses; or when purposefully targeting a reduction in body fat percentage; all times where inadequate micronutrient intakes are critical to maintain health status (Huskisson et al., 2007). Nonetheless, based on these outcomes, it does not appear that micronutrient intakes are a key concern in highly trained adolescent swimmers when they are consuming a large DEI to meet in-season training demands. Thus, in future periods of energy restriction, swimmers should seek individualised sport nutrition support and consider the use of vitamin and mineral supplements (Close et al., 2022).

It was unclear from this thesis whether the nutritional behaviours of highly trained adolescent swimmers were altered by the COVID-19 pandemic. Indeed, dietary intakes before and after the COVID-19 lockdown suggested that swimmers maintained a similar nutritional profile, albeit with increased inter-individual variations within each intake variable. This indicates that a greater proportion of swimmers began to over- or under-consume some nutrients after COVID-19, possibly because: (a) not all swimmers readjusted their intakes following the return to sport (Alméras et al., 1997; Montenegro et al., 2017); (b) diet quality had declined (Pillay et al., 2020); and/or (c) swimmers reported their intakes less accurately due to a reduced motivation/increased anxiety as lockdown conditions extended beyond five weeks (Fitzgerald et al., 2021; Magkos & Yannakoulia, 2003; Pillay et al., 2020). The latter point was supported since the original timeline for food diary collections included a July time point (four months into lockdown), although poor submissions at this time meant that this time point could not be analysed. However, these possible COVID-19 effects remain

speculative, given this thesis did not seek to capture the swimmers' thoughts and perceptions before, during, or after the lockdown period. Practitioners should therefore continue to monitor the dietary intakes of highly trained adolescent swimmers, as support and interventions may be required on an individual basis following the return to sport.

Throughout Chapters 6–8 of this thesis, swimmers were encouraged to consume their habitual pre-exercise nutritional intakes to replicate how supplements would be ingested in training and competitions. Further analyses found that typical pre-exercise meals were ingested 1–3 hours before swimming, and included the following the intakes that aligned with the recommendations for swimmers (Shaw et al., 2014; Stellingwerff et al., 2011): energy = 10.5 kcal·kg BM^{-1} (696 ± 308 kcal); CHO = 1.1 ± 0.7 g·kg BM^{-1} (72 ± 42 g); protein = 0.6 ± 0.2 g·kg BM^{-1} (37 ± 17 g); and fat = 0.4 ± 0.3 g·kg BM^{-1} (26 ± 16 g). It should be noted, however, that these intakes were assessed through a variety of collection methods within chapters, such that photographed food diaries were used for familiarisation trials, followed by either verbal recall or written food logs to monitor adherence. Thus, the accuracy of these combined intakes is questionable. Nevertheless, it appeared as though highly trained adolescent swimmers could appropriately time energy and macronutrients to support their swimming performance, which in addition to consuming adequate daily intakes, appears to justify the use of ergogenic aids as an advanced nutritional strategy (Garthe & Maughan, 2018).

A concern throughout this thesis was that many adolescent swimmers either chose not to engage with sport nutrition support or did not develop the skills to apply knowledge to practice. For example, retrospective analysis of food diaries was only possible in 13 of 26 available swimmers in Chapter 3, due to swimmers either failing to provide a food diary for three full days; providing a written food diary with unclear information; or not providing a food diary at all. Resultantly, this chapter may have only accounted for the nutrition intakes of swimmers who had a high nutrition proficiency and/or genuine interest in their own nutrition. This could therefore give an inaccurate portrayal of the nutrition intakes taking place across the whole swimming club. Further evidence of this was found in

Chapter 5, since only 35% of swimmers adhered to supplement recommendations (2000–5000 IU·day^{-1} vitamin D_3) after receiving education and resources. Indeed, this chapter did not exclude the non-adherent swimmers from data analysis, subsequently showing that most developed an insufficient or deficient vitamin D status after not engaging with nutrition advice. Combined, these outcomes highlight a potential flaw in current sport nutrition provisions, despite the presently used methods (i.e., classroom-based) improving sport nutrition knowledge in adolescent swimmers (Foo et al., 2021). Potential solutions to better transfer knowledge into practice could be to co-educate swimmers with key stakeholders (i.e., parents/guardians, coaches), as this could reinforce nutrition principles and support long-term adherence (Dorsch et al., 2019); or by using non-financial incentives to increase engagement, such as gamification methods which could appeal to this cohort's competitive nature (Tam et al., 2019). Although, both of these alternative education methods require further research as it is currently unclear whether they are more effective than a classroom approach.

9.1.2 Supplement Intakes

Comparable to previous research in competitive swimmers (Moreno et al., 2022; Shaw et al., 2016a), Chapter 5 of this thesis showed that 98% of swimmers from a UK-based, high performance swimming club regularly engaged in supplement use. What was novel about this research, however, was that it investigated three distinctive phases in the swimming talent pathway: national-level (aged ≥16 years); age-group (aged 13–17 years); and development (aged 11–14 years) swimmers. Since this thesis showed widespread supplement use at all three of these stages, the following discussion will focus on practical applications for each training phase.

In the youngest of the age categories, development swimmers typically used four different supplements, most of which were sports supplements at competitions, with multivitamins also frequently used on a more regular occurrence. Other novel findings were that swimmers at this training age: (a) utilised parents/guardians as the primary source of supplement information (74%);

(b) mostly obtained supplements from grocery stores (78%); (c) consumed supplements primarily for 'performance' (37%); and (d) were unsure why they consumed 18% of all supplements. Together, this information suggests that parents/guardians of young swimmers purchase and supply their children with accessible supplements, often without a rationale for their use. This could be a problem given that a surprisingly high proportion (12–58%) of nutritional supplements contain banned substances (Martínez-Sanz et al., 2017); though this is mostly associated with 'performance-enhancing', 'stimulant', or 'proprietary blend' supplements purchased via the internet, rather than commercially available sports foods and drinks (Attipoe et al., 2017; Geyer et al., 2004; Kamber et al., 2001; Parr et al., 2007). Nonetheless, because development swimmers stated 'performance' as their main reason for using nutritional supplements, this thesis supports targeting sport nutrition and doping education (e.g., clean sport programme) towards swimmers and their parents/guardians early in their swimming careers, which could support the safe uptake of supplements at later training stages (Hurst et al., 2020). Moreover, these outcomes also highlight a potential need for swimming clubs to integrate greater support to develop swimmers' (and their parents/guardians) practical nutrition skills and food literacy, in order to shift the focus away from 'performance' and towards more developmental goals that are important at this early training age (Shaw et al., 2014).

Elite swimmers are recognised for their widespread use of nutritional ergogenic aids (Moreno et al., 2022; Shaw et al., 2016a), yet prior to this thesis, it was unclear at what age their ingestion becomes commonplace. Chapter 4 showed this time point occurred between the ages of 13–17 years, where age-group swimmers started utilising CAF (23%), creatine (8%), and beta-alanine (8%). Additionally, a lower proportion of swimmers consumed sports foods and drinks at competitions, yet an increased number of swimmers reported ingesting pill and powder sports supplements on a more regular basis (e.g., protein powder: 54%, electrolytes: 38%). Experienced national swimmers reported consuming a similar number of ergogenic aids as international swimmers (~2 per swimmer; Moreno et al., 2022; Shaw et al., 2016a), including widespread use of CAF (82%), creatine (55%), beta-alanine (45%), and $NaHCO_3$ (36%). A potential explanation for these high supplement intakes may be related to

swimmers displaying high rates of attrition at ~16–20 years of age, particularly if continuous performance improvements or competitive success are not being achieved (Monteiro et al., 2017). It is therefore intuitive to suggest that supplement intakes at the age-group and national levels should be managed, rather than discouraged by performance nutritionists. This may be best achieved by introducing progressive nutrition strategies as swimmers progress in training age; firstly, focussing on achieving the basic nutrition principles with practical skills (e.g., food literacy, cooking skills, shopping); then building sport nutrition knowledge and awareness of nutritional supplements with possible health and performance benefits; and finally, individualising ergogenic supplement intakes based on specific performance and/or body composition requirements (Garthe & Maughan, 2018).

A progressive nutrition strategy was observed in the investigated swimming club throughout this thesis, as demonstrated in Chapter 2 (section 2.1.4). In brief, electronic resources (e.g., recipe books, macronutrient sources, basic sport nutrition) were directed at parents/guardians at the development level; structured group education and practical workshops (e.g., cooking, shopping, meal planning) were introduced at the age-group level; and individualised support was available to experienced national swimmers (e.g., consultations, body composition periodisation, supplement strategies). Subsequently, both age-group and national swimmers cited a performance nutritionist as their primary supplement advisor, though only for ~50% of all reported supplements. Furthermore, limitations in the data collection process meant that supplement doses and timings were not reported, nor was it asked whether supplements were sourced from batch-tested suppliers; both important pieces of information needed to assess whether safe supplement practices were being followed (Burke, 2019). The interview method also removed the anonymity of the swimmer; therefore, it was plausible that not all supplements were declared due to fears that the nutritionist/researcher might not be supportive of their decisions (Kasper et al., 2020). Resultantly, it was not possible to determine whether the progressive sport nutrition strategy used within the investigated high-performance swimming club supported the safe and effective uptake of nutritional supplement, warranting further research with more in-depth questioning regarding adolescent supplement ingestion. Nonetheless, the aim of

Chapter 4 was to investigate the supplement intakes at different training phases and observe possible trends between performance levels, in which novel research outcomes were achieved.

9.1.3 Observations in Vitamin D Status

All swimmers throughout this thesis spent the autumn and winter months training in the UK (latitude = 52° N), spent a large quantity of time completing indoor training (15–20 hours·week^{-1}, see Chapters 3–4), and consistently consumed inadequate vitamin D intakes (<10 µg.day^{-1}; see Chapter 3); all of which are risk factors for vitamin D deficiency (Farrokhyar et al., 2015; Thomas et al., 2016). Theoretically, the provision of group education and supplement guidance to adolescent swimmers and their parents/guardians would have increased swimmers' awareness of the importance of vitamin D (Hollabaugh et al., 2022; Leitch et al., 2021), potentially negating the seasonal declines in 25(OH)D observed in previous research (Dubnov-Raz et al., 2015; Geiker et al., 2017; Rockwell et al., 2020a). However, the present thesis showed that this was not the case, with 60% of swimmers experiencing declines in vitamin D status, including 70% of the cohort entering a mid-winter training period with an insufficient 25(OH)D (25% deficient). This outcome suggests that education alone is not an adequate strategy to offset vitamin D declines or influence the uptake of vitamin D_3 supplements. Indeed, evidence from Chapter 4 showed that only 38% and 20% of age-group and development swimmers declared the use of vitamin D_3 supplements, respectively. In comparison, this percentage was higher (73%) within national swimmers, who each received individualised sport nutrition support and supplement guidance. This suggest that a more personalised approach centred around behaviour change techniques might be required to influence vitamin D intakes in future (Michie & Johnston, 2012). Though as not all swimmers will have direct access to performance nutritionists who can utilise such techniques, further research is needed to identify alternative strategies to incentivise vitamin D_3 supplement uptake in adolescent swimmers at the group level.

While this thesis and other research showed that 2000–5000 IU·day^{-1} vitamin D_3 is an effective strategy to offset seasonal declines in vitamin D status (Dubnov-Raz et al., 2015a; Lewis et al., 2013b; Rockwell et al., 2020a), it remains unclear how this translates into health and/or performance benefits for swimmers. For instance, Dubnov-Raz et al. (2015a, 2015b) found no differences in swimming performance, strength, or illness severity between swimmers who increased their 25(OH)D with 2000 IU·day^{-1} vitamin D_3, versus non-supplementing swimmers who experienced large seasonal declines. Lewis et al. (2013b) on the other hand, found that 77% of muscle injuries occurred following large reductions in serum 25(OH)D (>25 nmol·L^{-1}). However, this was found in swimmers who all maintained a sufficient vitamin D status year-round (>100 nmol·L^{-1}), potentially inferring that negative effects might be related to the overall decline in 25(OH)D as opposed to having an insufficient or deficient status. Alternatively, Rockwell et al. (2020a) showed that swimmers who supplemented with 5000 IU·day^{-1} vitamin D_3 maintained their serum 25(OH)D (131 ± 29 nmol·L^{-1}), while also displaying increases in circulating testosterone and lower body power output (deadlift, squat, vertical jump). Interestingly, this effect was not observed in swimmers who did not use vitamin D_3 supplements, who experienced large 25(OH)D declines (~30 nmol·L^{-1}) but also maintained a sufficient status (81 ± 16 nmol·L^{-1}). Thus, while preventing seasonal declines in serum 25(OH)D appears to be beneficial, further research is needed to determine whether: (a) developing insufficient vitamin D actually causes health or performance decrements; (b) if an optimal vitamin D status exists for highly trained adolescent swimmers; and (c) whether particular supplement protocols (i.e., 5000 IU·day^{-1}) carry ergogenic potential.

9.1.4 The Effectiveness of Ergogenic Aids

The second part of this thesis sought to identify the effectiveness of three acute ergogenic aids (CAF, $NaHCO_3$, CM) in applied swimming scenarios. Considering that highly trained adolescent swimmers appeared to be capable of consuming adequate daily nutrition intakes under the guidance of a performance nutritionist, it was thought that the addition of ergogenic supplements would optimise

swimming performance (Garthe & Maughan, 2018). However, neither of the investigated supplements showed any performance benefits versus PLA conditions (Table 9.1). These outcomes add further ambiguity over whether highly trained adolescent swimmers should be engaging in widespread ergogenic supplement use, given that risk-benefit analyses often do not seem to be worthwhile (Desbrow et al., 2014). However, the outcomes of this thesis only add to the scant research currently available in highly trained swimmers, warranting further research in different applied scenarios, and with alternative dosing strategies, before the beneficial effects of ergogenic aids can be dismissed. As a result, the practical applications and future directions from each experimental chapter shall be discussed, and how these may relate to future practice.

Table 9.1. Performance outcomes following highly trained adolescent swimmers' ingestion of acute nutritional ergogenic aids.

Supplement	Ingestion Protocol	Exercise Protocol	Effect Size vs. PLA (*g*)	Swimmers Achieving the SWC vs. PLA
CAF	Evening ingestion: 3 mg·kg BM^{-1} 60 min before exercise	100 m TT (specialist stroke)	0.07	1 of 8
	Next morning	100 m TT (specialist stroke)	0.06	0 of 8
$NaHCO_3$ (IND)	0.3 g·kg BM^{-1} 105–195 min before exercise	6 x 75 m (specialist stroke)	0.15	2 of 7
	0.3 g·kg BM^{-1} 150–240 min before exercise	200 m TT (freestyle)	0.01	1 of 7
$NaHCO_3$ (STND)	0.3 g·kg BM^{-1} 150 min before exercise	6 x 75 m (specialist stroke)	0.03	1 of 7
	0.3 g·kg BM^{-1} 195 min before exercise	200 m TT (freestyle)	-0.05	0 of 7
CM	15 g 60 min pre-exercise	6 x 300 m (freestyle)	0.09	5 of 11*

CAF = caffeine (Chapter 6); $NaHCO_3$ = sodium bicarbonate (Chapter 7b); CM = citrulline malate (Chapter 8); * = note that 5 of 11 also performed slower than PLA.

Chapter 4 found CAF to be the most popular ergogenic aid used by highly trained adolescent swimmers; however, the efficacy of this supplement was challenged given its failure to enhance swimming performance (Chapter 6). This lack of effect occurred with a 3 mg·kg BM^{-1} CAF dose, which was expected to be ergogenic given this cohort's negligible habitual CAF intakes (<50 mg·day^{-1}; Chapters 3 and 6) (Spriet, 2014). However, basing doses on habitual intakes overlooked this cohort's prior CAF experiences at competitions, where a variety of dosing strategies were reported (~1–6 mg·kg BM^{-1}). It is therefore speculated that these past experiences negated the possible performance effects, either because: (a) swimmers relied on side-effects for competition benefits, which were not experienced with a 3 mg·kg BM^{-1} dose (McClung & Collins, 2013); or (b) occasional CAF use at competitions increased tolerance to the central effects, potentially requiring larger doses to stimulate both central and peripheral mechanisms (Pickering & Kiely, 2019b). Additionally, CAF was administered to swimmers in a single capsule, which may have 'looked' less ergogenic compared to the swimmers' usual CAF source (e.g., vs. six tablets), and lead swimmers to believe that a performance effect would not occur (Shabir et al., 2018). This may be overcome in future practice with larger standardised CAF doses (4–6 mg·kg BM^{-1}) as per previous research (Collomp et al., 1992; Pruscino et al., 2008), or potentially the use of personalised CAF strategies (i.e., dose, timing, source); though, further research is needed to ensure these alternate strategies are well tolerated and safe in adolescent swimming cohorts.

On the contrary, CAF might have been ineffective in this thesis due to the short duration of the exercise task (≤60 s). Indeed, while CAF is suggested to have ergogenic potential in sprinting tasks, the evidence is equivocal (Guest et al., 2021). The reason Chapter 6 utilised a 100 m swimming time-trial was based on CAF enhancing the performance of adolescent swimmers across this distance in previous research (Collomp et al., 1992); however, the prior study investigated the effects on swimmers of a lower training status ('trained'/regional-level vs. 'highly trained'/national level; McKay et al., 2021), and with a larger CAF dose (4 vs. 3 mg·kg BM^{-1}). Hence, it is possible that 3 mg·kg BM^{-1} CAF might be more reliable in both lesser trained adolescent swimmers and/or longer

duration swimming races that cause greater metabolic perturbations, such as middle- and long-distance time-trials (200–1500 m; Grgic, 2022). At present, only Azizimasouleh et al. (2014) have investigated a 3 mg·kg BM^{-1} CAF dose on a 400 m distance in adolescent swimmers, although no effects were found due to this study utilising a suboptimal dosing timeframe (30 min pre-exercise). Therefore, while this thesis failed to find an ergogenic benefit of CAF to 100 m swimming distances, further research is needed with alternate doses and longer swimming distances.

The key outcome from Chapter 7a was that ingesting 0.3 g·kg BM^{-1} $NaHCO_3$ produced large increases in the blood buffering capacity of highly trained adolescent swimmers, similar to those observed in adults (Boegman et al., 2020; Gough et al., 2017). This included increases in blood HCO_3^- concentrations that exceeded the 'ergogenic threshold' (≥5 mmol·L^{-1}; Heibel et al., 2018), while also enhancing the apparent SID via the extracellular movements of K^+, Ca^{2+}, and Cl^- (Siegler et al., 2016). Moreover, adolescent swimmers each had their own individual $NaHCO_3$ absorption characteristics, suggesting that individualised strategies based on time to peak blood HCO_3^- might be the most efficacious approach to supplementation. However, when individualised $NaHCO_3$ was used in practice (Chapter 7b), this strategy produced no further increases in blood buffering capacity compared to a standardised approach, nor did any of the $NaHCO_3$ strategies provide ergogenic benefits versus a PLA condition. It was unclear why no ergogenic effects were observed, though it is speculated that the highly trained cohort could perform the swimming tests (6 x 75 m, 200 m freestyle time-trial) at supramaximal intensities; thus, inducing a high rate of pH change that overwhelmed blood buffering capabilities regardless of $NaHCO_3$ ingestion (de Araujo et al., 2015; Higgins et al., 2014; McNaughton, 1992b). Therefore, further research is required in longer swimming durations ,such as middle- and long-distance time-trials (400–800 m); especially given these distances have a similar duration (~4–9 min) to 4 km cycling (Gough et al., 2018; 2019; 2021) and 2000 m rowing (Boegman et al., 2020), where individualised $NaHCO_3$ has showed ergogenic potential.

Why an individualised $NaHCO_3$ strategy did not produce any further increases in blood HCO_3^-, pH, or the apparent SID compared to a standardised approach was unclear, but these results were comparable to similar research (Boegman et al., 2020). In contrast to the present thesis, however, Boegman et al. (2020) did identify an ergogenic effect with their individualised approach. A possible reason for these differing performance outcomes were the standardised ingestion timings, such that Boegman et al. (2020) utilised a timeframe that was potentially too short when using $NaHCO_3$ capsules (60 min pre-exercise), whereas the current thesis based standardised ingestion on group mean blood HCO_3^- responses (i.e., 150 min pre-exercise) (Carr et al., 2011b; Jones et al., 2016; Chapter 7a, section 7a.3.1). Alternatively, peak strong ion declines were also observed in the bloodstream approximately 120–150 min post-$NaHCO_3$ ingestion (see Chapter 7a, section 7a.3.1 and Chapter 7b, section 7b.3.1). Therefore, the individualised $NaHCO_3$ strategy used by Boegman et al. (2020) may have inadvertently showed the ergogenic potential of the SID, given that no differences in blood HCO_3^- were observed. Although, this cannot be confirmed as Boegman et al. (2020) did not measure strong ions, nor did they compare performance versus a PLA condition; leaving it unclear whether their individualised $NaHCO_3$ strategy was ergogenic at all. Combined, this thesis questions the practice of individualising $NaHCO_3$ ingestion based on time to peak blood HCO_3^-. This gives premise to future research investigating the effectiveness of $NaHCO_3$ based on a time to peak SID approach as recommended in Chapter 7a, since strong ion movements could yet prove to be the primary acting $NaHCO_3$ mechanism.

This thesis also identified key limitations regarding the use of individualised $NaHCO_3$ strategies in practice. In Chapters 7a and 7b, adolescent swimmers underwent the currently accepted method for pre-determining time to peak blood HCO_3^-, which involved ingesting $NaHCO_3$ in a post-prandial state and remaining quietly seated until a peak was observed (de Oliveira et al., 2020; Gough et al., 2017; Jones et al., 2016). However, this method does not account for the various other activities that swimmers engage in as part of their pre-exercise preparation. Firstly, when swimmers followed their typical pre-exercise nutrition schedules (i.e., high CHO meal 1–3 hours pre-exercise), this resulted in

swimmers consuming their meals either after $NaHCO_3$ ingestion, or at the same time as $NaHCO_3$ ingestion; both of which could have delayed $NaHCO_3$ absorption and dampened the increases in blood HCO_3^- concentration (Abuhelwa et al., 2017). Secondly, swimmers engaged in both pool and land-based warm-ups in the 45 min prior to exercise, which because of their intermittent intensity, utilised some of the circulating HCO_3^- and potentially mitigated the subsequent performance (Gurton et al., 2021). Finally, neither the pre-determination process or simulated competitions in training account for the pre-race anxiety that would be experienced at major competitions, which might also affect the $NaHCO_3$ absorption characteristics via increases in heart rate/blood flow (Fortes et al., 2017) or gut dynamics (Wilson et al., 2021). Therefore, at present, the expensive and time-consuming task of pre-determining a time to peak blood alkalosis (HCO_3^- or SID) may not be worthwhile outside of the laboratory setting. This warrants further work to be completed with athletes at real-world competitions, who are in full nutritional and physical preparation; though this does carry logistical and ethical challenges.

Citrulline malate was the final acute nutritional ergogenic aid investigated in this thesis, which has mechanisms seemingly aligned to whole-body, aerobic exercise (Gough et al., 2021). However, when highly trained adolescent swimmers ingested 15 g CM prior to a typical aerobic swimming test (6 x 300 m), a variety of performance outcomes were observed (five faster, five slower, one unchanged). It was therefore unclear whether these variable outcomes were individual responses to CM, or whether they were caused by variability in the swimming test. Indeed, while prior results in this cohort showed the 6 x 300 m test to be valid and reliable, this was only monitored in long-distance swimmers (400–1500 m), and not in middle-distance swimmers (200–400 m) who may have found the test more physically and mentally challenging (Piras et al., 2019). The physiological effects of CM were also unclear, since no differences in blood pressure, blood La^-, or RPE were observed compared to PLA; although, these measures often remain unchanged even when ergogenic effects are reported (Rhim et al., 2020; Wax et al., 2015, 2016). Future work is therefore needed with CM that measures more precise physiological measures of ammonia, NO production, ATP synthesis, and blood flow; all of

which could help elucidate the underpinning ergogenic mechanisms (Gough et al., 2021). Moreover, owing to CM showing promise in resistance exercise (Vårvik et al., 2020), further research in shorter (≤60 s), more anaerobic swimming protocols may be of greater ergogenic potential. Though as this work is yet to be completed, CM cannot be recommended as an ergogenic aid for highly trained adolescent swimmers at present.

9.1.5 General Observations with Ergogenic Aid Use

To maximise external validity to real-world training and competition practices, each experimental chapter encouraged highly trained adolescent swimmers to follow their usual pre-exercise nutrition, as opposed to standardised or fasted nutrition strategies in most research. As presented in earlier in this discussion (section 9.2.1), adolescent swimmers mostly consumed pre-exercise nutritional intakes in accordance with the recommended guidelines (i.e, 1–4 g·kg BM^{-1} CHO, ≥0.3 g·kg BM^{-1} protein; Shaw et al., 2014; Stellingwerff et al., 2011). However, there were large inter-individual variances within these intakes, including the timing of meals (i.e., 1–4 hours pre-exercise) and the dietary composition (CHO range: 0.5–3 g·kg BM^{-1}; protein range: 0.2–1 g·kg BM^{-1}; fat range: 0.1–0.8 g·kg BM^{-1}). Moreover, some swimmers also reported the long-term (≥6 months) ingestion of beta-alanine and creatine, although these were not expected to have interfered with the acute erogenicity of the investigated supplements (de Salles Painelli et al., 2013; Elosegui et al., 2022). Nonetheless, it is speculated that the lack of combined nutrition and supplement controls throughout this thesis may have negated the ergogenic responses in experimental chapters, either by: (a) already bringing swimmers closer to their peak performance, thus leaving only a small window for the supplement to have an ergogenic effect; and/or (b) interfering with the supplement absorption characteristics (Abuhelwa et al., 2017; Chapter 7a), making the use of ‘optimal’ doses and timings obsolete at the individual level. Future research is therefore needed with athletes using ergogenic aids while in full competition nutrition preparation (i.e., meal composition, meal timing, co-ingested supplements) to identify the ‘true’ performance impact of these supplements in the real world. This might also require

the comparison of ‘optimal’, personalised, and control supplements in future research, in order to elucidate the most effective ingestion strategies for individual athletes.

A second general observation was that CAF, $NaHCO_3$, and CM were mostly well tolerated by adolescent swimmers. With CAF, this included no group level differences in any subjective physiological (i.e., tachycardia, jitters, headache, stomach upset), psychological (i.e., anxiety, mood, alertness, tiredness, readiness to exercise), or sleep effects (e.g., sleep latency, sleep quality) compared to PLA (see Chapter 6, sections 6.3.2–6.3.4). However, one swimmer did report severe (≥9/10 rating) stomach upset after exercise and overnight following CAF ingestion, whereas another had a prolonged sleep latency (+3 hours) that made them miss the following days performance; suggesting these effects should be considered on an individual basis. Similarly, $NaHCO_3$ only induced minor (≤5/10 rating) gastrointestinal side-effects for most swimmers (see Chapter 7a, section 7a.3.3 and Chapter 7b, section 7b.3.4), despite ingesting a 0.3 g·kg BM^{-1} dose that is often associated with debilitating symptoms (Cameron et al., 2010; Kahle et al., 2013). Similarly, some swimmers did report severe cases of bloating, nausea, and vomiting following $NaHCO_3$ on an individual basis, though these did not appear to be consistent, nor did the symptoms appear to have any ergolytic effects (compared to PLA). Finally, while side-effects were not directly measured with CM ingestion, none of the swimmers reported any anecdotal symptoms when asked by the researcher. Together, this evidence suggests that ergogenic aids are well tolerated by most adolescent swimmers in practice and are unlikely harm performance during training and competitions. Nonetheless, the presence of individual responses does require further attention, supporting the use of personalised ingestion strategies where possible to maximise performance, while minimising the adverse effects.

9.2 General Limitations of the Thesis

A limitation of this thesis was that it was mostly conducted within one high-performance swimming club who part-funded the research, therefore the desire was to: (a) seek performance solutions within

the swimming club; and (b) limit the sharing of knowledge/interventions with direct competitors. Firstly, this led to the previously discussed limitation (see section 9.1.1), as to whether the observations made in dietary intakes (Chapter 3) and supplement practices (Chapter 4) could be generalised to the wider swimming population. Second, only utilising one swimming club limited the potential study sample sizes. This was further by logistical constraints, such as: (a) trials having to be structured into the swimmers' periodised training schedules; (b) trials unable to be rearranged due to limited pool access; (c) participants having low availability because of school commitments or lack of transport; and/or (d) high attrition rates that seemingly occurred after COVID-19 (i.e., Chapters 3, 7b, and 8). These factors undoubtedly reduced statistical power in some experimental chapters (Cohen, 1988), though was potentially overcome by the rarity of the cohort, their repeatable performances, and by paying greater attention to the individual outcomes rather than group mean results (Sands et al., 2005). Moreover, the sample sizes used in this thesis were in line with previous investigations of highly trained swimmers (e.g., n = 6–11; Goods et al., 2017; Kumstát et al., 2018; Pruscino et al., 2008; Zajac et al., 2009). The sample sizes within this thesis were therefore justified (Lakens, 2022), though attempts to include larger sample sizes are required in future research.

Conducting research within a highly trained cohorts also has its limitations since training outcomes and competition performances take precedent over the research results. All exercise trials therefore had to be agreed with the head coach prior to their implementation, and as such, a trade-off between what the coach was willing to incorporate into the training schedule, and what was an appropriate protocol to answer the research question(s) had to be considered. This was notable in Chapter 7b, whereby a repeated time-trial approach (i.e., Pierce et al., 1992; Pruscino et al., 2008) would have been most valid for assessing $NaHCO_3$ effects in real-world competitions. However, dedicating four mid-cycle training weeks (i.e., familiarisation, IND, STND, PLA) to two time-trials was not deemed acceptable, hence the inclusion of a speed/threshold test (6 x 75 m). Another consideration was relating the exercise trials to the swimmers' key events, which meant allowing swimmers to utilise their preferred strokes in Chapter 6 (simulated competition in the specific preparation phase) and

Chapter 7b (speed/threshold test in the specific preparation phase), whereas Chapter 8 enforced the freestyle stroke (aerobic test in the general preparation phase). Chapter 7b also enforced the freestyle stroke for the 200 m time-trial, which was because of the large time differences that occur between strokes across this distance (i.e., freestyle vs. breaststroke = ~40–50 s), and due to all recruited swimmers being competent in this event. It is recognised that changes of stroke, exercise distance, and in-season timings between chapters may have all influenced performance outcomes; though all methodology was conceptualised from prior research and aimed towards the specific ergogenic mechanisms of each supplement, therefore the outcomes reflected applied practice.

Additionally, this thesis avoided the use of highly invasive physiological measures. Indeed, the use of less invasive physiological measures (i.e., capillary bloods, sphygmomanometer, subjective ratings) were thought to be safer than venepuncture or cannula methods in the pool environment, making them a more ethical choice for adolescent cohorts (Fryer et al., 2014). Moreover, these methods were also selected to reduce participant stress (Fryer et al., 2014), thus increasing their willingness to take part in experimental trials. However, such measures limited the collection of plasma levels of CAF, L-citrulline, NO, and ammonia; whereas changes in body position (seated assessment vs. prone swimming) made it difficult to accurately monitor blood pressure and vasodilation; all of which were required for mechanistic explanations following CAF (Guest et al., 2021) and CM ingestion (Gough et al., 2021). In addition, Chapters 7a and 7b assessed blood changes in strong ion status, and although declines in blood K^+, Cl^-, and Ca^{2+} appeared to indicate movements between the extracellular and intracellular fluids (Lückher et al., 2017), this could not be confirmed without directly monitoring intramuscular concentrations. Nonetheless, all supplement doses, timings, and sources were based on current best practices (Gough et al., 2021; Maughan et al., 2018), therefore all of the respective supplement's mechanisms could be assumed.

A final limitation was that neither menstrual cycle phase and/or contraceptive use was monitored within this thesis. This was based on current research suggesting that menstrual cycle phase does not

have significant influence over exercise performances (Collenso-Semple et al., 2023; McNulty et al., 2020), nutritional behaviours (Langan-Evans et al., 2023), or supplement responses (CAF: Lara et al., 2020a; 2020b; $NaHCO_3^-$: Saunders et al., 2022) in highly trained females. Moreover, given the time restraints, it would not have been possible to arrange exercise trials to coincide menstrual cycle phases between swimmers, which is reflective of real-world practice. Nonetheless, it is recognised that current assumptions of the menstrual cycle are based on limited research (McNulty et al., 2020), and is not specific to either the adolescent athlete population, or swimmers. Indeed, there appeared to be some evidence that females experienced a more variable response to CM supplementation compared to males in Chapter 8. Additionally, it is possible that hydration (which can be affected by Na^+ ingestion; Giersch et al., 2019) and gastrointestinal symptoms (Moore et al., 1998) can be influenced by the menstrual cycle phase, potentially impairing the ergogenic response to $NaHCO_3^-$ supplementation in Chapter 7b. Thus, in order to build the evidence base, future studies should aim to document information such as menstrual cycle phase (tracking or ovulation kits) and contraceptive use (Smith et al., 2022; Elliot-Sale et al., 2021). Though this would not have affected the outcomes of this thesis, this information could have contributed towards future meta-analyses to give a greater insight into the menstrual cycle/conceptive effects on adolescent female athletes.

9.3 Conclusions and Practical Recommendations

The results of this thesis support that highly trained adolescent swimmers in the UK could consume an appropriate nutrition intake to support their health, recovery, growth, and performance; and can alter these intakes dependant on training loads. This was, however, only identified in a sample of swimmers who were actively engaging with sport nutrition support, therefore whether the outcomes can be generalised to the wider UK swimming population was less clear. Nonetheless, considering this population's training status and aspirations to be competitive at the international level, it is prudent to suggest that all swimmers and/or their high-performance swimming clubs should be accessing sport nutrition support if optimal performance is the goal. Since the cohort in this thesis

showed they could support their daily training needs through nutrition, the use of supplements to further enhance health and performance appears to be justified.

Supplement use is highly prevalent in adolescent swimmers, beginning with the use of sports foods and drinks at the development level, before transitioning into widespread use of ergogenic aids and health supplements at the national level. ‘Performance’ was the key reason for nutritional supplement use from an early age, which was advocated by parents/guardians who purchased and provided supplements to their children. Together, this combined information suggests that sport nutrition support and education should be accessible to all levels of competitive swimming, which might best delivered through a step-like process as swimmers progress in training age; starting with basic nutrition education, practical skills, and anti-doping messages for swimmers and their parent/guardians; before developing into more specific nutrient timing practices, and introducing ergogenic aids under the guidance of a performance nutritionist. However, even though nutritional ergogenic aids were highly popular within highly trained adolescent swimmers, this thesis did not provide conclusive evidence that their intake is worthwhile. This questions their suitability in the real-world, although further research using a variety supplemental doses, timings, and sources is still required to elucidate optimal strategies for training and competition.

Chapter 10 – References

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