The Effects of Carbohydrate Mouth-Rinsing on External and Internal Loads in Hydrated Male Ice Hockey Players During On-Ice Scrimmages

by

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ABSTRACT

THE EFFECTS OF CARBOHYDRATE MOUTH-RINSING ON EXTERNAL AND INTERNAL LOADS IN HYDRATED MALE ICE HOCKEY PLAYERS DURING ON-ICE SCRIMMAGES

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This research examined the potential beneficial effects of mouth-rinsing (MR) a carbohydrate (CHO) versus placebo (PLA) solution on external and internal loads in hydrated male ice hockey players during three 20-min regulation periods and one 12-min overtime of 3-on-3 on-ice scrimmages. Skaters repeated 2 min shift and rest intervals, with MR every ~10 min. A local positioning system measured external load, and heart rate and ratings of perceived exertion measured internal load. During regulation play, there was similar fatigue between conditions. In overtime, high-intensity distance (224 ± 77 vs. 185 ± 66 m, $p = 0.042$), peak speed (24.6 ± 1.6 vs. 23.7 ± 1.3 $km \cdot h^{-1}$, $p = 0.02$) and sprint number (1.9 ± 1.2 vs. 1.2 ± 0.9, $p = 0.01$) were significantly higher with CHO versus PLA MR, with no differences in internal load. Overall, players generated greater external loads with CHO MR late in on-ice hockey scrimmages.

DEDICATION

This thesis is dedicated to my late Opa and Oma, Bill and Dien Nyman. Thank you for teaching me the value of hard work, perseverance and family. *Ik hou van jou.*

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LIST OF ABBREVIATIONS

3v3- 3-on-3

5v5- 5-on-5

ATP- Adenosine Triphosphate

AU- Arbitrary Unit

BM- Body Mass

CAF- Caffeine

CES- Carbohydrate electrolyte solution

CHO- Carbohydrate

Cl^-- Chloride

DEH- Dehydrated

DW- Dry Weight

ECG- Electrocardiogram

FFA-Free Fatty Acids

GI- Gastrointestinal

GPS- Global Positioning System

HIIT- High-Intensity Interval Training

HR- Heart Rate

IHI- Intermittent High-Intensity

K^+- Potassium

LIST- Loughborough Intermittent Shuttle Test

LPS- Local Positioning System

MR- Mouth Rinsing

Na+- Sodium

NF- No Fluid

NHL- National Hockey League

OT- Overtime

PCr- Phosphocreatine

PK- Penalty Kill

PLA- Placebo

PP- Power Play

RPE- Rating of Perceived Exertion

RSA- Repeated Sprint Ability Test

RSS- Repeated Skate Sprint Test

SR72- 72 m Shuttle Run

SS- Steady State

T_c- Core Temperature

TMA- Time-Motion Analysis

TOI- Time On Ice

TRIMP- Training Impulse

TS- Thirst Sensation

TT- Time Trial

USG- Urine Specific Gravity

UWB- Ultra Wide Band

VO_2max- Maximal Oxygen Uptake

Yo-Yo IRT-1- Yo-Yo Intermittent Recovery Test Level-1

CHAPTER 1: REVIEW OF THE LITERATURE

The objectives of this literature review are to: i) examine the physical and physiological requirements of ice hockey, ii) understand the mechanisms of energy expenditure and the use of fuel sources in ice hockey performance, iii) assess the available carbohydrate mouth-rinsing research for potential avenues to improve mental and physical performance in intermittent high-intensity sport, and iv) explore current methods of athlete monitoring to quantify external and internal loads of hockey players on-ice.

1.1 THE GAME OF ICE HOCKEY

1.1.1 Game Structure and Positional Roles

Ice hockey is an intermittent high-intensity (IHI) team sport with an activity pattern that consists of short bouts of high-intensity and high-power exercise, interspersed with longer periods of low-intensity exercise and rest (Green *et al.* 1976; Burr *et al.* 2008; Jackson *et al.* 2016, 2017; Douglas and Kennedy 2020). High-intensity activities include repeated sprint skating, quick changes in direction, body contact, grappling, and rapid accelerations and decelerations. Low-intensity activities consist of low-speed skating and gliding. Exercise intervals are interspersed with rest on the bench that can be passive (seated) or lightly active (standing, pacing on the spot) (Burr *et al.* 2015). Thus, to achieve optimal performance in training and competition, hockey players require multifaceted physical and physiological capabilities, including explosive power, speed, and muscular strength, as well superior anaerobic and aerobic capacities. Additionally, the fast pace of ice hockey necessitates enhanced mental awareness for rapid decision making and execution of complex tactical skills, such as shooting, passing, and puck handling (Linseman *et al.* 2014).

Ice hockey is played on a large ice rink surrounded by boards (~26-31 x 61 m). All players wear full body protective equipment and move around the surface by skating. Hockey sticks are used to maneuver, pass and shoot the puck on the opposition net in attempts to score goals. The object of the game is to score more goals than the opposing team within the given time frame. Standard competitions are 60-min in length, broken into three 20-min periods, separated by ~15-20 min intermissions (Jackson *et al.* 2016, 2017). However, it is common for games to extend past regulation time should an overtime (OT) period be required to determine the winner of a tied game (Rosenberg *et al.* 2021). Typically, teams dress 20-player rosters (12 forwards, 6 defence, 2 goaltenders) to allow for rotation of multiple lines. Players complete multiple short shifts per period and substitutions are often made on the fly (Lignell *et al.* 2018). During regulation game play, there are 5 skaters and 1 goaltender per side on the playing surface (5v5). In the event of special-teams circumstances, such as powerplays (PP) and penalty kills (PK), match-ups can be 5v4, 5v3, 4v4 and even 4v3 (Douglas and Kennedy 2020). In addition, multiple professional and amateur organizations have adopted 3-on-3 (3v3) structure for short-period OT (5-min).

Skaters are classified into two positional groups: forwards (centre, left wing, right wing) and defence (left defence, right defence) (Jackson *et el.* 2017). The primary role of the forwards is to advance the puck through means of skating, stickhandling and passing, with the eventual goal of shooting the puck into the opposition's net to score. The primary role of the defence is to tactically interfere with the opposition to strip them of the puck and prevent scoring. Given the small playing area and fast pace of competition though, all skater positions take part in the generation of offense and protective strategies of defence throughout the game.

The goaltender position is substantially different from skater positions in multiple aspects, as they are confined to a smaller area, wear larger protective equipment, and have the primary role of stopping or blocking the puck from entering the net (McCarthy *et al*. 2020). This produces a unique set of physiological requirements that, when combined with the low sample size per team (n = 2), limits statistical power and relevance in the majority of existing ice hockey research. For these reasons, the majority of research examined throughout this review focuses on skaters only. The existing body of literature predominantly focuses on males, though there will be inclusion of female data in this review where relevant.

1.1.2 Physical and Physiological Demands

Research attempting to quantify the physical and physiological demands of ice hockey dates back to the 1970's, though there has since been substantial progression in player development and competition, as well as the technologies available to measure athlete performance (Green *et al.* 1976; Green 1978; Jackson *et al*. 2017; Douglas and Kennedy 2020). In the last few decades male hockey players have become larger, leaner, stronger, and more aerobically fit than before, likely due to significant advancements in training and nutrition strategies (Montgomery 2006; Burr *et al.* 2008; Quinney *et al*. 2008; Sigmund *et al.* 2016). These trends tend to be most exaggerated at the professional level, where there is elevated quality and quantity of competition, although, they have also been observed in other elite cohorts, including male collegiate and junior teams (Sigmund *et al*. 2016; Jackson *et al*. 2017; Triplett *et al*. 2018).

Off-ice tests of strength, power and cardiovascular fitness are well established, but there are few protocols (squat jump, resisted linear sprint) that demonstrate the ability to effectively predict on-ice performance (Burr *et al.* 2007; Thompson *et al.* 2020). Comparisons between off-ice to on-ice performance are typically limited by the prevalence of different surfaces (i.e. floor vs. ice), as well as the difficulty of replicating the unique biomechanics facilitated by skating (Burr *et al.* 2008; Stetter *et al*. 2019; Vigh-Larsen *et al*. 2019; Thompson *et al*. 2020). On-ice tests demonstrate greater validity, but are still restricted in their ability to reproduce the spontaneous movement patterns and unique skills that are characteristic to game play.

Researchers have employed on-ice athlete monitoring methods to accurately characterize and quantify the demands of individual hockey players in both 'real-world' training and competition scenarios (Brocherie *et al.* 2018; Lignell *et al.* 2018; Douglas and Kennedy 2020; Vigh-Larsen *et al*. 2020). Although early studies effectively described the intermittent activity pattern in ice hockey, findings were limited by low sample sizes and obsolete observation techniques (Dillman *et al.* 1984; Bracko *et al.* 1998). Consequently, it was incorrectly reported that hockey players spent the majority of their time on-ice performing low-to-moderate intensity activities, which failed to accurately describe the high physical and physiological demands experienced by these athletes (Lignell *et al*. 2018).

The high-intensity nature of ice hockey is best exemplified by the short duration of shifts, which typically last 30-80s for elite males, and are followed by 2-3 min of passive or lightly active rest on the bench (Burr *et al.* 2015; Brocherie *et al*. 2018; Lignell *et al*. 2018; Douglas and Kennedy 2020; Vigh-Larsen *et al*. 2020). At the professional level, male athletes perform an average of 7.4 ± 1.8 shifts per period and 22.3 ± 4.9 shifts per game, which slightly exceeds collegiate demands (Jackson *et al*. 2017; Brocherie *et al.* 2018). In competition, this activity pattern accumulates 15-25 min of time on ice (TOI), which is dramatically lower than playing time in other team sports (Brocherie *et al.* 2018; Lignell *et al.* 2018). It should be noted that several factors can influence TOI, including individual position, team role, coaching strategies, penalties/advantages, and game score (Jackson *et al.* 2016; Lignell *et al.* 2018).

Indeed, several groups have reported marked differences in positional exercise volumes, intensities and loads. In terms of volume, both Lignell *et al.* (2018) and Douglas and Kennedy (2020) have observed that elite male defence experience longer shifts than forwards, accumulating significantly more TOI and greater total distance per game. Across the body of ice hockey literature, however, average total distances during competition range from ~3500-6000 m for all male skaters (Brocherie *et al.* 2018; Lignell *et al.* 2018; Douglas and Kennedy 2020; Vigh-Larsen *et al.* 2020).

Regarding exercise intensity, in world-class U20 men's international hockey games defence cover significantly more distance at very slow (1.0-10.9 $km \cdot h^{-1}$), slow (11.0-13.9 $km \cdot h^{-1}$) and moderate speeds (14.0-16.9 $km \cdot h^{-1}$) relative to forwards (Douglas and Kennedy 2020). Meanwhile, forwards cover significantly greater distance at very fast (21.0-24.0 $km \cdot h^{-1}$) and sprint speeds (>24 $km \cdot h^{-1}$). Findings from the National Hockey League (NHL) are similar, and forwards have been observed to perform 54% more high-intensity skating (≥17.0 $km \cdot h^{-1}$) per min than defence. However, these statistics should not undermine the efforts of defence, as it has been reported in several male studies that all skaters cover at least half of their total distance at high-intensity speeds (Lignell *et al*. 2018; Douglas and Kennedy 2020; Vigh-Larsen *et al*. 2020). Moreover, there are several intense actions that are difficult to objectively quantify since they occur at slow/static speeds and involve minimal change in on-ice position, such as grappling, battling and using body contact to gain puck possession (Jackson *et al.* 2016, 2017).

Further consequences of positional skating patterns have been observed in athlete load. PlayerLoad is an external performance variable developed by Catapult Sports (Melbourne, Australia) that expresses gross mechanical load as a modified vector magnitude and can effectively capture high-fatiguing movements across three axes (anterior-posterior, mediolateral, and longitudinal) (Boyd *et al.* 2011). In addition to PlayerLoad, on-ice load can also be measured by the frequency and volume of explosive efforts, which include high-intensity movements such as accelerations, decelerations and changes in direction, as well as high-intensity skating and shots made by players (Douglas *et al.* 2019*a,b*). In world class women, forwards exhibit greater PlayerLoad and number of explosive efforts relative to defence in both training and competition (Douglas *et al.* 2019*a,b*). In competition relative to training, both skater positions demonstrated significant exacerbation of these load variables.

Unsurprisingly, on-ice competition can be physically fatiguing, which is apparent from decrements in player ability to maintain high-intensity activities over time (Brocherie *et al*. 2018; Lignell *et al.* 2018; Douglas and Kennedy 2020; Vigh-Larsen *et al*. 2020). In international U20 men's hockey, this arises as reduced sprint skating distance from the first (171.7 ± 62.5 m) to third periods (122.1 ± 9.1 m), paired with simultaneous decrements in repeated sprint performance (Douglas and Kennedy 2020; Vigh-Larsen *et al*. 2020). Interestingly, this decline was not observed in NHL players, which implies that increased experience and/or fitness capacity possibly enhances athlete resistance to fatigue (Lignell *et al.* 2018). However, it could be argued that quality of sprints at the professional level is reduced with time, as sprint skating speed was significantly lower in period 3 (24.2 ± 0.1 $km \cdot h^{-1}$) and OT (24.5 ± 0.1 $km \cdot h^{-1}$), compared to periods 1 (26.2 ± 01 $km \cdot h^{-1}$) and 2 (25.8 ± 0.1 $km \cdot h^{-1}$). Evidence of player fatigue has also been reflected by decrements in load across time in international women's hockey (Douglas *et al.* 2019*a*). From the first to third periods, forwards displayed significantly reduced peak accelerations, while defence exhibited decreased PlayerLoad. Additionally, both positions experienced significant decrements in total explosive efforts across all periods.

Despite the emphasis on external performance outcomes in much of the literature, measures of internal load are also important as they aid in understanding the link between physical activity, physiological load and fatigue (Ulmer *et al*. 2019; Gamble *et al*. 2019). The most common measures of internal load in ice hockey are heart rate (HR), core temperature (T_c) and rating of perceived exertion (RPE).

The substantial cardiac demands of elite ice hockey have been characterized in men and women, and numerous studies have confirmed that HR quickly accelerates to near maximum when players engage in high-intensity activity during in-game shifts, and remains elevated above normal resting levels between shifts (Green *et al.* 1976; Montgomery 1988; Jackson *et al.* 2016, 2017; Vigh-Larsen *et al.* 2020). In varsity hockey, mean shift HRs of players corresponded to 92% of max in women, and 96% and 92% of max in men for forwards and defence, respectively (Jackson *et al.* 2016, 2017). Similar values have been reported in international competition, with elite males displaying average HRs of 82-87% max during shifts, and a mean peak HR of 97% max (Vigh-Larsen *et al*. 2020). In professional male ice hockey players, HR load (% HRmax) has demonstrated a positive relationship with skating performance (Lignell *et al*. 2018). Significant inverse correlations have been established between HR load in an on-ice physical capacity test (Yo-Yo Intermittent Recovery Ice-Hockey test, level 1 submaximal) and very fast skating distance (r = -0.50), total high-intensity skating distance (r = -0.47), and number of high-intensity skating bouts (r = -0.55) during competition. Considering the high HRs experienced on-ice, it is appropriate that elite male hockey players habitually exhibit relative maximal oxygen uptakes (VO_2max) in the range of 55-60 ml·kg^{-1}·min^{-1} (Montgomery 2006; Quinney *et al.* 2008; Peterson *et al.* 2015; Lignell *et al.* 2018; Triplett *et al.* 2018).

Since heat is a biproduct of muscle metabolism, it is understandable that hockey players regularly struggle with impaired thermoregulation during intense practices and games (Logan-Sprenger *et al.* 2011; Gamble *et al*. 2019). Consequently, mean T_c in the range of 38.4–38.9 ^oC have been recorded during prolonged hockey activity in collegiate and recreational level men (Batchelder *et al.* 2010; Linseman *et al.* 2014; Palmer *et al.* 2017b; McCarthy *et al.* 2020) and women (Boville *et al*. 2015; Driscoll *et al.* 2020). This promotes fluid loss through sweating as a means to cool the athlete (Gamble *et al.* 2019). Despite the fact that hockey arenas are colder environments (typically <10^{o}C), protective equipment impairs athletes' ability to effectively dissipate heat, and thus fluid loss is exacerbated (Noonan *et al.* 2007; Logan-Sprenger *et al.* 2011). In men, average sweat rates are highest at the professional (2.02 ± 0.74 L·hr^{-1}) and semi-professional levels (2.03 ± 0.62 L·hr^{-1}), which are significantly greater than rates in junior hockey (1.63 ± 0.58 L·hr^{-1}) (Gamble *et al.* 2019). Women exhibit moderately lower sweat rates, with Olympians presenting significantly higher rates (0.99 ± 0.08 L·hr^{-1}) compared to university (0.67 ± 0.05 L·hr^{-1}) and recreational women (0.42 ±0.03 L·hr^{-1}) (Bigg *et al.* 2019). An additional consequence of sweating is major loss of electrolytes such as sodium, which plays a key role in fluid retention and skeletal muscle contractility (Logan-Sprenger *et al.* 2011).

Moreover, high sweat rates increase the risk of mild dehydration, which is net fluid loss equivalent to ~1.5-2% body mass (BM) (Gamble *et al.* 2019). This condition is highly unfavourable as it can lead to increased cardiovascular and thermoregulatory strain, as well as intensify perceptions of fatigue (Logan-Sprenger *et al.* 2011; Palmer *et al.* 2017*a,b*; Gamble *et al*. 2019; Driscoll *et al.* 2020). In hockey specifically, mildly dehydrated (DEH) players exhibit decrements in late game exercise performance and execution of sport-specific skills compared to individuals who replaced fluid lost with through sweat with carbohydrate electrolyte solutions (CES) (Linseman *et al.* 2014; Palmer *et al.* 2017*b*; Driscoll *et al.* 2020; McCarthy *et al.* 2020). It was concluded that these effects were a consequence of fatigue, as significantly increased RPEs were observed in DEH conditions.

1.1.3 Summary

Activity patterns in ice hockey are highly intermittent, and players typically accumulate 15-25 min of TOI per 60-min game. Though shifts are short, they contain several brief high-intensity actions, and players routinely reach near maximum HRs. Forwards and defence display slight differences in exercise volume, intensity and load in training and competition, which are likely influenced by distinct positional roles and strategic game play. Nonetheless, the rigorous effort of physical performance induces substantial physiological demand in all skaters, resulting in considerable cardiovascular and thermoregulatory strain with prolonged playing time. This puts athletes at risk of mild dehydration and increases individual perceptions of effort, as well as renders decrements in physical performance and execution of sport-specific skills due to fatigue. Overall, it is important to understand the physical and physiological demands of ice hockey, as this information can be used to design targeted training and recovery strategies to help prepare athletes to achieve optimal performance in competition. However, there are several potential factors outside of external and internal loads that contribute to fatigue, such as energy requirements and fuel availability.

1.2 ENERGY AND FUEL REQUIREMENTS FOR ICE HOCKEY

There are several obstacles in obtaining accurate bioenergetic measurements for intermittent-intensity sport, as it is difficult to replicate the sporadic and rapid changes of direction and speed in a laboratory environment, and controlled tests often fail to incorporate sport-specific skills (Williams and Rollo 2015). There are even further challenges when it comes to measuring energy expenditure in ice hockey, as off-ice testing protocols cannot replicate the biomechanics and 360º movements of skating, while on-ice evaluation of respiratory kinetics is largely impractical (Peterson *et al.* 2015). Consequently, the available bioenergetic research literature in ice hockey remains rather limited, and thus, a variety of exercise protocols will be examined herein. Additionally, this section will explore fuel requirements for ice hockey with an emphasis on carbohydrate (CHO) metabolism and its subsequent effects on performance.

1.2.1 Anaerobic and Aerobic Metabolism

Though there is difficulty in assessing on-field energy expenditure in ice hockey, the fundamental energetic processes are largely analogous to metabolism in IHI exercise. Energy for skeletal muscle contraction is simultaneously derived from both the anaerobic and aerobic energy systems in the form of adenosine triphosphate (ATP) (Hargreaves and Spriet 2020). However, relative contributions from each system are heavily influenced by the duration and intensity of exercise. The anaerobic system has a higher rate of ATP production and can increase flux within milliseconds of muscle contraction, whereas the aerobic system has a higher capacity to produce ATP, but depends on the function of the respiratory and cardiovascular systems (Hargreaves and Spriet 2020).

Hence, the anaerobic system is dominant in situations where energy demands exceed what the aerobic system can support, or there is a rapid need for energy provision, such as the onset of exercise or transitions to higher power outputs (Hargreaves and Spriet 2020). Also, anaerobic pathways can function with no oxygen supply. For these reasons, the anaerobic system is the primary producer of energy in ice hockey, as typical shifts involve several intermittent bouts of activity (5-7) that are of short duration (2-3.5 s), but are very high-intensity (>100% VO_2max) (Brocherie *et al.* 2018).

Anaerobic production of ATP occurs through substrate level phosphorylation, which is enabled by the degradation of phosphocreatine (PCr) and muscle glycogen. In the first of several all-out sprints, energy requirements for the initial 6 s of exercise are predominantly fulfilled by PCr hydrolysis (~50%) and anaerobic glycolysis (~44%) (Gaitanos *et al.* 1993; Parolin *et al.* 1999). However, these reactions cannot be sustained indefinitely. At very high intensities, PCr exhibits rapid degradation (10-15 s), while anaerobic glycolysis produces a build-up of lactate, leading to eventual metabolic disruption (increased muscular acidity) (Hargreaves and Spriet 2020). The occurrence of these events is rapid in ice hockey. After a 1-min shift in an elite male hockey scrimmage, muscle lactate (70 $mmol \cdot kg^{-1} \cdot$dry weight (d.w)) and PCr (35 $mmol \cdot kg^{-1} \cdot$d.w) levels are dramatically changed from baseline values (6.9 ± 2.7 $mmol \cdot kg^{-1} \cdot$d.w and 79.1 ± 6.7 $mmol \cdot kg^{-1} \cdot$d.w, respectively) (Vigh-Larsen *et al.* 2020). These values are reflective of those obtained at exhaustion from high-intensity running in soccer players (Krustrup *et al.* 2006*b*). Reduced capacity of anaerobic pathways can lead to fatigue and have negative consequences on performance, thus recovery is extremely important.

In addition to producing ATP throughout IHI exercise, the aerobic system facilitates the resynthesis of PCr and clearance of anaerobic metabolites during periods of lower-intensity exercise and rest (Hargreaves and Spriet 2020). This occurs through oxidative phosphorylation, which has the capacity to produce 12 x more ATP from glycogen than anaerobic pathways (Williams and Rollo 2015). Complete restoration of PCr takes ~60-120s, whereas recovery from sustained high-glycolytic flux can take several minutes (Hargreaves and Spriet 2020). The short frequency between ice hockey shifts combined with intermittent activity patterns on-ice means that complete recovery of glycolytic flux may not be feasible during rest intervals. Hence, there is increased reliance on PCr and aerobic metabolism with repeated sprints and prolonged time in stop-and-go sports (Gaitanos *et al.* 1993; Hargreaves and Spriet 2020).

In a historical analysis by Green (1979), it was estimated that over the course of an ice-hockey game, 69% of energy production was derived from anaerobic pathways, while the remaining 31% was from aerobic pathways. The primary fuel for anaerobic glycolysis is CHO from muscle glycogen. In aerobic metabolism both CHO and free fatty acids (FFAs) are used as fuel, but there are reciprocal shifts in oxidation influenced by exercise intensity, as well as fuel availability (Williams and Rollo 2015). For example, reliance on CHO is increased when exercise intensity reaches levels ≥ ~80% VO_2max or CHO is more readily available in the muscle or the blood. Given that both male and female hockey players routinely approach maximal HRs during training and competition, it is evident that the aerobic system regularly experiences demands that exceed the ~80% VO_2max threshold (Jackson *et al*. 2016; 2017; Vigh-Larsen *et al*. 2020).

Since hockey players engage in repeated patterns of IHI skating and explosive efforts over prolonged periods of time, successful performance and mitigation of fatigue requires both anaerobic production of power and aerobic facilitation of recovery (Montgomery 1988; Cox *et al.* 1995; Stanula *et al*. 2014). Given the immense physical effort of ice hockey, both systems depend on glycogen or its derivatives to produce ATP to meet energy requirements. Therefore, CHO is the dominant fuel in ice hockey.

1.2.2 Glycogen Depletion and Fatigue

In early research, it was observed that intermittent bouts of skating (10 x 1 min @ ~120% VO_2max) significantly exacerbated glycogen depletion by two-fold compared to continuous steady state (SS) skating (60 min @ ~55% VO_2max) (Green 1978). Between the two separate protocols, glycogen depletion was greatest in type II and type I fibres, respectively. Thus, it was reasonable to hypothesize that significant depletion of type II fibres would occur in game-like scenarios. However, the evidence presented in later investigations was conflicting, as type I fibres were reported to have the greatest glycogen depletion in on-ice competition over type II fibres (Green *et al*. 1978; Monpetit *et al*. 1979). There have been few analyses of the effects of on-ice competition on player muscle glycogen content in the decades since, but there has been a consensus that significant depletion (~50%) occurs from pre- to post-game (Simard *et al.* 1988; Akermark *et al.* 1996). Specific fibre-type utilization of glycogen in ice hockey was not re-examined until very recently.

In 2020, Vigh-Larsen and colleagues completed a novel study that measured muscle glycogen content and fatigue in elite men during a controlled hockey game. Three-periods of 5v5 on-ice scrimmage were played between two teams, each rotating three lines of players (n=15/team). Periods were adjusted in length so that each player performed eight 1-min shifts separated by 2-min of passive recovery, accumulating 24 min TOI across the entire game. Repeated skate sprint (RSS) tests (3 x 33.25 m maximal sprints; 25 s recovery) were also performed pre- and post-game, and during the 18-min intermissions between periods. The greatest advancements in this study were the use of wearable microtechnology (*section 1.4*) and the frequency and quantity of muscle sample collection. Unlike the historical research that only collected pre- and post-game samples, Vigh-Larsen's group were able to successfully perform biopsies (vastus lateralis) within ~30 s of the end of shifts, allowing for sample collection to occur across each period. Thus, glycogen depletion with respect to playing time could be examined with much greater precision.

Through biochemical analysis it was revealed that there was continual depletion of muscle glycogen with time, and that significant depletion from baseline (400 ± 22 mmol·kg^{-1}·d.w) occurred within the first period (302 ± 81 mmol·kg^{-1}·d.w). Further significant depletion from the first period was measured in the third period (207 ± 71 mmol·kg^{-1}·d.w) and post-game samples (188 ± 43 mmol·kg^{-1}·d.w). These final values were similar to those reported in men after a soccer game, but notably, were achieved with 4-5-fold less playing time (Krustrup *et al*. 2006*a*). Furthermore, from pre- to post-game, histochemical analysis revealed that the number of muscle fibres categorized as full or partly full of glycogen dropped from 58% to 6% in fast-twitch fibres (type II), and 51% to 5% in slow-twitch fibres (type I). This resulted in 60% and 68% of fast- and slow-twitch fibres being categorized as empty post-game, with the majority of remaining fibres being partially empty. The results of this study demonstrated that glycogen is heavily depleted from both fibre types simultaneously during repeated bouts of IHI exercise in ice hockey. These findings are in contrast with earlier hockey research (Green 1978; Green *et al*. 1978; Monpetit *et al*. 1979) but are in-line with historical sprinting data that reported similar declines of muscle glycogen between fibre types following a 30 s maximal treadmill sprint (Greenhaff *et al.*1994).

Beyond identifying specific fibre-type glycogen depletion, another prominent finding from Vigh-Larsen *et al.*'s 2020 study was confirmation of the association between low muscle glycogen levels and athlete fatigue in ice hockey competition. From the athlete monitoring data it was established that as TOI increased, athletes performed fewer accelerations and decelerations, and traveled at slower speeds. These findings closely reflected the fatigue development observed in other recent hockey studies (Lignell *et al*. 2018; Brocherie *et al*. 2018; Douglas and Kennedy 2020). However, in the Vigh-Larsen *et al.* study (2020) there was proven glycogen depletion and it was concluded that low energetic states in skeletal muscle produced intolerance to repeated high-intensity exercise bouts in ice hockey. Additionally, it was speculated that low muscle glycogen may weaken muscular force production, possibly due to negative effects on glycolytic rate, sarcoplasmic reticulum calcium release, and muscle excitability (Ørtenblad *et al*. 2011; Vigh-Larsen *et al*. 2020). This could have detrimental effects on muscular power production, which would impair acceleratory and sprint skating actions (Cox *et al*. 1995).

1.2.3 Carbohydrate and Exercise Performance

It is well established that consumption of CHO before and during exercise can enhance performance. In prolonged SS exercise (>1 hr), ingestion of exogenous CHO improved endurance capacity by helping maintain CHO oxidation rates, and possibly by sparing liver and muscle glycogen (Coyle *et al.* 1986; Jeukendrup 2004; Jentjens *et al*. 2004). Several studies have also reported that ingestion of exogenous CHO solutions (6.0-7.0%) enhanced performance in IHI exercise compared to a PLA condition (Nicholas *et al*. 1995; Welsh *et al*. 2002; Foskett *et al*. 2008; Phillips *et al.* 2010). The exercise models implemented in these studies included multiple (4-6) 15-min periods of intermittent-shuttle running using the Loughborough Intermittent Shuttle Test (LIST) or a similar adapted protocol. The LIST was designed to replicate the movement patterns and exercise intensities observed in stop-and-go sport competition, such as soccer, rugby and field hockey games (Nicholas *et al.* 2000). Each 15-min cycle of the LIST involved 11 repetitions of the following: 3 x 20 m walk, 1 x 20 m max sprint, 3 x 20 m cruise (~95% VO_2max), 3 x 20 m jog (~55% VO_2max). Welsh and colleagues (2002) added vertical jumps to this protocol to replicate a basketball game. Following the cessation of the last period of LIST running in these studies, participants repeated intermittent shuttle-running (1:1 20 m jog and cruise intervals) to voluntary exhaustion. Compared to ingestion of PLA solution, CHO ingestion was observed to significantly improve final period (45-60 min) sprint time (Welsh *et al.* 2002), as well as time to exhaustion in both adolescent and adult male and female IHI team sport athletes (Nicholas *et al*. 1995; Foskett *et al*. 2008; Phillips *et al.* 2010). However, the mechanisms responsible for these benefits have been debated, as there was evidence of muscle glycogen sparing with CHO vs. PLA ingestion in one study (Nicholas *et al.* 1999), but no difference in these levels between conditions in another (Foskett *et al.* 2008). Moreover, performance improvements were observed at varying time points (< 60 min, > 60 min, > 90 min). Increased blood insulin levels and muscle glucose uptake, as well as maintenance of central nervous system function and blood glucose levels were proposed as other potential mechanisms (Welsh *et al.* 2002; Foskett *et al.* 2008).

Performance improvements with CHO ingestion have also been observed in ice hockey. In one historic study, TOI and skating distance during a game were significantly improved when athletes consumed solutions with CHO (net 100 g) before (3.5, 2.75, 2.0, 1.25 hr) and during exercise (20, 40 min) (Simard *et al.* 1988). There was evidence of glycogen sparing (~10%) in CHO trials, but multiple dose timepoints made it impossible to discern whether this result was related to exogenous CHO. Alternatively, the results of more recent research have demonstrated that availability of exogenous CHO may enhance glycogen utilization. In a simulated ice hockey game (intermittent sprint cycling), third period glycogen use was significantly greater in trained males who consumed CES (177.5 ± 31.1 $mmol \cdot kg^{-1} \cdot d.w$) compared to no-fluid (NF; 103.5 ± 16.2 $mmol \cdot kg^{-1} \cdot d.w$) (Palmer *et al*. 2017*b*). Additionally, in the same period CES significantly improved voluntary work performed and reduced RPE. Comparably, skating speed and time at high-effort during a 70-min on-ice scrimmage were significantly greater from 30-50 min, and post-scrimmage skating was improved, when CES was consumed compared to NF (Linseman *et* *al*. 2014). As well, there were fewer puck turnovers and greater pass completion in the last 20 min of scrimmage and reduced post-scrimmage RPE during CES trials. From the results of these two latter studies, it has been speculated that consumption of CHO may have had a positive effect on mental acuity and central fatigue during hockey. However, these studies were limited by the absence of non-CES hydration trials, and thus it was impossible to distinguish whether performance enhancements were the result of consumption of exogenous CHO or the benefit of adequate hydration (Linseman *et al*. 2014; Palmer *et al*. 2017*b*).

Indeed, in a later study by McCarthy *et al.* (2020) hydration with either CES or water produced similar improvements in male recreational goaltender performance and attenuated markers of fatigue compared to NF during on-ice scrimmage and drills. Although, similar to the previous studies, there was some evidence that CHO may elicit additional benefits, as it was the only condition to significantly reduce perceptions of exertion during post-scrimmage drills. However, it remained uncertain whether the additive benefits with CES consumption were the result of CHO ingestion, oral exposure to CHO, or a combination of both. Therefore, the exact mechanisms responsible for enhanced performance with consumption of exogenous CHO in ice hockey remain unknown.

1.2.4 Summary

Since ice hockey involves numerous repeated bouts of IHI exercise, players require high anaerobic and aerobic capacities to maximize performance. Both systems contribute energy in the form of ATP throughout the activity, but have separate roles due to differences in system power and capacity. In ice hockey, the primary role of the anaerobic system is to facilitate rapid provision of energy at the onset of exercise or during transitions to higher power outputs. It is also essential when exercise demands exceed what the aerobic system can support. Meanwhile, the primary roles of the aerobic system are to continually provide fuel and facilitate the recovery of anaerobic pathways during lower-intensity exercise bouts and rest. Elevated flux through anaerobic pathways produces a metabolic disturbance over time, hence there is increased reliance on aerobic metabolism as players accumulate TOI. Given the very high intensity of game play, CHO is the dominant fuel for ice hockey and is primarily obtained from skeletal muscle glycogen stores. Across playing periods there is significant depletion of these stores, which invokes fatigue and yields observable decrements in hockey performance. Nevertheless, it has been established that consumption of CHO during IHI sport can induce significant performance enhancements. In hockey specifically, CHO consumption has improved work performed, skating speed, time at high effort, sport-specific skills and perceptions of fatigue. However, the exact origins of these improvements remain unclear.

1.3 CARBOHYDRATE MOUTH-RINSING

1.3.1 Background

It was previously established that ingestion of CHO during short-term (<1 hr) high-intensity exercise (>75% VO_2max) had minimal effect on blood glucose levels, and contributions of exogenous CHO to oxidation and muscle metabolism were considered to be negligible (McConnel *et al.* 2000; Carter *et al.* 2004*a*). Thus, researchers speculated that the mechanism responsible for performance enhancements observed with CHO ingestion was possibly non-metabolic in nature, and potentially related to increased CHO availability (Carter *et al*. 2004*a*). However, when exogenous CHO was administered via blood-glucose infusion during a 1-hr cycle time trial (TT), there was no change in performance relative to the control, despite increased muscle glucose uptake (Carter *et al.* 2004*a*). Therefore, it was proposed that the mechanism of action may be mediated by oral and/or gastrointestinal (GI) tract carbohydrate receptors.

Accordingly, the mouth-rinsing (MR) protocol was developed to isolate oral exposure to CHO, while eliminating ingestion and GI tract exposure (Carter *et al.* 2004*b*). MR requires participants to swish small aliquots (~25 mL) of solution around the oral cavity for 5-10 s, before promptly expectorating (Burke and Maughan 2015). Rinses typically have a concentration of 6-14% CHO (glucose; maltodextrin), while placebo (PLA) rinses are usually water that has been taste-matched and artificially sweetened (saccharin; sucralose; non-caloric). However, across the literature there is great inconsistency in the solution concentration, length, frequency and number of MRs.

The first MR study was conducted by Carter and colleagues (2004*b*) and it investigated the impact of oral CHO exposure on ~1 hr cycle TT performance. Trained participants (2F; 7M) were instructed to complete a set amount of work (equivalent of 1 hour @ 75% VO_2max) as fast as possible and MR with either CHO (6.4% maltodextrin) or PLA was performed after every 12.5% of TT completed. Remarkably, participants completed TTs significantly faster when they MR with CHO (59.6 ± 1.5 min) as opposed to PLA (61.4 ± 1.6 min). There was also a significant attenuation in decrement of power with CHO MR. RPE increased over time but there was no difference between conditions. Since performance improvements were obtained in the absence of CHO ingestion and GI exposure, it was therefore speculated that the mechanism responsible was related to central control (Carter *et al.* 2004*b*).

1.3.2 Mouth-Brain Connection

The role of the brain in exercise performance and fatigue has been proposed for over a century, but has gained substantial recognition in the last ~20 years (Burke and Maughan 2015).

The existence of a functional entity, coined the ‘central governor’, has been theorized to facilitate exercise performance through collection and integration of afferent signals (ventilation, muscular effort, etc.), which are communicated to the motor cortex (Kayser 2003). The motor cortex then generates efferent instructions for the peripheral systems detailing the intensity, duration and termination of exercise (Kayser 2003). Thus, the central nervous system has the ultimate control over commencement and cessation of exercise.

In an attempt to explain the novel findings of Carter *et al.* (2004*b*), the above model was combined with slightly earlier research that revealed activation of the brain primary taste cortex in response to oral glucose exposure (O’Doherty *et al.* 2001). The primary taste cortex has projections to areas of the brain which facilitate emotion and behavior in response to reward (Kringelbach 2004). Thus, it was hypothesized that there might be a specialized class of oral receptors with the ability to activate neural pathways in response to CHO, which could potentially modulate central control of exercise (O’Doherty *et al.* 2001; Kringelbach 2004; Carter *et al.* 2004*a,b*).

To test this hypothesis, Chambers and colleagues (2009) conducted a mutli-part study that explored the impact of oral sensing of different substances on brain activity and exercise performance. In the one part of the study, functional magnetic resonance imaging (fMRI) was used to characterize brain activity in response to isolated oral exposure to isocaloric sweet (glucose) and tasteless CHO (maltodextrin), as well as non-caloric sweetener (saccharin). Profoundly, oral sensing of all sweet substances produced excitation of the primary taste cortex, but only caloric substances were able to generate activity in regions of the brain associated with reward-response and motivational circuits (secondary putative taste cortex, dorsolateral prefrontal cortex, right caudate, striatum). Therefore, the results of the first experiment confirmed the presence of oral receptors that respond specifically to the energy/caloric content of CHO independent of sweetness.

The other experiment used a double-blind protocol to examine exercise performance when the subjects MR the three different solutions used in part 1 (Chambers *et al.* 2009). In a set-work cycle TT (~1 hr at ~75% W_{max}), performance was significantly improved when MR with CHO (glucose or maltodextrin) relative to PLA (saccharin). It was concluded that performance improvements were the product of increased excitability in brain regions associated with reward, motivation and motor control, mediated by the activation of oral CHO receptors.

1.3.3 Central and Peripheral Effects

Following the seminal MR studies, many groups examined the effects of oral sensing of CHO on central control and fatigue during exercise (Burke and Maughan 2015; Peart 2017; Brietzke *et al.* 2018). The most prevalent central effects identified in the literature are enhanced decision making, increased motivation, and decreased perceptions of effort. Central effects have notable impacts on physical performance and peripheral fatigue.

Decision making is an important efferent control, as it influences strategic pacing of exercise intensity and effort across time, which can help maximize efficiency (Burke and Maughan 2015). In ice hockey game play, this could influence the frequency at which individuals initiate line changes to minimize fatigue. Additionally, enhanced decision making would be advantageous to make appropriate judgements under split-second time constraints, such as when to pass versus shoot the puck. In stop-and-go sport, heightened awareness and mental clarity can have substantial impact on game play and match outcomes (Welsh *et al.* 2002).

Increased motivation and reduced discomfort with CHO MR are closely tied to athlete perceptions of effort and physical signs of fatigue. There are some studies wherein individuals who MR with CHO display reduced RPEs compared to PLA MR (Fares and Kayser 2011; Che Muhanmed *et al.* 2014). In most studies though, it was observed that individuals who MR with CHO produced greater power, performed at higher intensities, and continued for longer durations whilst they reported similar levels of exertion to PLA MR conditions (Carter et al. 2004*b*; Rollo *et al.* 2008, 2010; Chambers *et al.* 2009; Jeukendrup 2013).

It was proposed that oral sensing of CHO induces subconscious perceptions of energy availability which facilitates increased corticomotor and sensorimotor activity (Gant *et al.* 2010; Turner *et al.* 2014; Burke and Maughan 2015). This in turn, manipulates efferent motor outputs and mitigates effects of peripheral fatigue, such as reductions in skeletal muscle potentiation and contraction. There is evidence of reduced RPEs and enhanced performance with CHO ingestion in ice hockey (Linseman *et al.* 2014; Palmer *et al.* 2017*b*; McCarthy *et al.* 2020), thus it is possible that oral exposure to CHO could mediate the attenuation of performance decrements across game play.

1.3.4 Exercise Performance

The effects of CHO MR on performance have been examined in several different exercise modalities, however very little data have been collected in stop-and-go sports (Burke and Maughan 2015; Peart 2017). Since no studies have been performed in ice hockey, this section of the review will focus on IHI exercise protocols. However, it is challenging to make comparisons between analyses, as research has been conducted across a range of training levels and exercise modalities.

Previously, it has been suggested that the brief nature of MR could be favourable to IHI activities, since opportunities to refuel/consume CHO during competition are infrequent or of short duration (Jeukendrup 2013; Burke and Maughan 2015). Additionally, CHO MR could provide an outlet for performance improvement in athletes who are prone to GI discomfort, or in situations where ingestion is not desirable or feasible (Whitham and McKinney 2007). When working with professional hockey players, it has been a frequent personal observation that several athletes per team chose to abstain from CHO ingestion during training and competition out of fear of discomfort. This is understandable, given that skaters frequently approach maximum exercise intensity during shifts (Jackson *et al.* 2016, 2017; Vigh-Larsen *et al.* 2020). Lastly, individual playing times in several IHI sports, including hockey, are ≤ 60 min, which is a time frame that has previously displayed meaningful performance enhancements with CHO MR in continuous high-intensity activities (Peart 2017).

The potential ergogenic effects of CHO MR in IHI exercise were first observed in a double-blind study that had recreationally trained males MR with CHO (6%) or PLA for 5 s before each of 5 repeated sprints (6 s max effort, 10% BM resistance; 24 s passive rest) (Beaven *et al.* 2013). In the first sprint, CHO MR produced significant improvements over PLA for peak (22.1 ± 19.5 W) and mean power (39.1 ± 25.8 W). By the end of the protocol though, performance was worse under the CHO condition, which possibly indicated a detrimental metabolic cost associated with the initial improvement.

Similar short-term benefits have been observed in single sprint protocols in recreationally trained males. In one double-blind study, serial MR (8 x 5 s; 1 rinse every 2 min) was performed prior to a 30 s maximal cycle sprint (Phillips *et al.* 2014). Peak power output was significantly increased with CHO MR (13.51 ± 2.19 $W \cdot kg^{-1}$; 6.4% maltodextrin) compared to PLA MR (13.20

± 2.14 W·kg^{-1}). In a separate study, 10 m sprint speed was significantly improved when subjects MR with CHO versus PLA for 10 s prior to exercise (Clarke *et al*. 2017). Though the time frames of these performance improvements are extremely short, they are relevant to ice hockey. In elite men, it has been observed that players perform an average of ~5-7 very short (2-3.5 s) but extremely high-intensity bouts of activity per shift (Brocherie *et al.* 2018; Lignell *et al.* 2018). Moreover, the ability to rapidly increase peak power and speed is especially impactful, as movement patterns in competition involve a high number of transitions and explosive efforts (sprints, accelerations, declarations, changes of direction). In elite women for example, skaters performed an average of over 300 explosive efforts per game (Douglas *et al.* 2019*b*). Likewise, elite men have been observed to perform 113 ± 7 high-intensity skating bouts (≥17 km·h^{-1}) in a single game, with the average distances ranging from ~15-26 m (Lignell *et al.* 2018).

To maximize the effectiveness of explosive actions across multiple periods in hockey, the capacity to maintain power would be a useful attribute. In trained males, mean power across 6 rounds of IHI exercise (total 48 min) was significantly improved when subjects MR with CHO (6%) compared to PLA (Simpson *et al.* 2018). Each round consisted of 5-min SS cycling (50% VO_2max) immediately followed by 3 repeated short Wingate-like sprints (10 s maximal effort; 50 s active recovery). MR was performed ~30 s prior to each initial sprint. Though it is highly unlikely that hockey players ever experience SS exercise, the occurrence of 3 maximal sprints within a single shift is entirely plausible. Hence, CHO MR prior to on-ice shifts could be a beneficial practice, particularly as TOI is accumulated. In Simpson *et al.*'s study (2018) the ergogenic influence of CHO appeared to be greatest with accumulating fatigue, and individual significance between conditions was achieved in the 6th exercise bout (CHO: 10.5 ± 0.75; PLA: 10.22 ± 0.92 W·kg^{-1}).

To achieve a more ecologically valid interpretation of the effects of CHO MR in IHI sport performance, data should ideally be collected from trained athletes in their respective field settings. To date, there are only three studies that have attempted this (Dorling and Earnest 2013; Přibyslavská *et al.* 2016; Dolan *et al.* 2017). However, none of these studies used the same protocol, and the findings do not meet a consensus.

In male field sport athletes (rugby, soccer), the effects of CHO MR were investigated in a exercise protocol that combined 4 x 15-min cycles of the LIST, interspersed with 3 repeated sprint ability (RSA) tests at the start, middle and end of exercise (Dorling and Earnest 2013). The RSA test involved 4 x 20-m sprints, each separated by 20 s of active recovery. Short periods (2-3 min) of rest were allotted between LIST and RSA sections. A total of 27 MR with either CHO (6.4%) or taste-matched PLA solution were performed during periods of rest and low-intensity activity. Fastest and average sprint times for RSA tests were relatively unchanged with CHO MR. Indications of performance improvements across this short distance would be promising for ice hockey, as game sprints ($\geq$24 km$\cdot$h^{-1}) in elite men are an average length of 26 ± 1 m, and range from 17-34 m (Lignell *et al.* 2018).

Another CHO MR study increased sport-specificity through the inclusion of scrimmage in the exercise protocol (Přibyslavská *et al.* 2016). In this study, female collegiate soccer players repeated three rounds of: 5-min high-intensity 3v3 scrimmage, 1.5 min rest and MR with CHO (6%) or taste and colour-matched PLA, a vertical jump test, a 18 m sprint and a 72 m shuttle run (SR72: 4 x 9 m, 2 x 18 m). RPE and thirst sensation (TS) were monitored in addition to exercise performance throughout the protocol. Overall, no main effect of rinse condition was observed in any physical performance measure, nor was there statistical improvement in RPE or TS between conditions. Although, there was minor evidence of CHO MR mediated benefits during the first round of exercise, as SR72 sprint time and TS in CHO compared to PLA trials approached significance. Again, enhanced performance in short, repeated movements would be beneficial in ice hockey (Brocherie *et al.* 2018; Lignell *et al.* 2018; Douglas *et al.* 2019b).

Greater ergogenic effects of CHO MR in short repeated bouts of exercise have been observed more recently in a study that monitored the effects of four separate taste-matched rinse conditions (CHO, PLA, PLA + caffeine (CAF), CAF + CHO) and one no-rinse control on performance during the Yo-Yo Intermittent Recovery Test Level-1 (Yo-Yo IRT-1) in male collegiate lacrosse players (Dolan *et al.* 2017). The Yo-Yo IRT-1 has participants repeat two 20 m shuttle runs at increasing speeds, with 10 s of rest between each run, until failure. This protocol was designed to simultaneously challenge anaerobic and aerobic energy systems (Krustrup *et al.* 2003), which reflects the energy demands evoked in ice hockey (Green *et al.* 1979; Cox *et al.* 1995). In addition to test performance, RPE was recorded after the warm-up, the first sprint of each new stage (at progressively faster speeds), and the termination of the test. It was found that CHO MR repeatedly presented the lowest RPE values after every stage, reaching significance after level 11 ($p = 0.03$). Also, average Yo-Yo IRT-1 levels achieved with CHO MR (37.0 ± 6.3) were higher than all groups (34.4 ± 7.8). Thus, it is possible that CHO MR might reduce perceptions of fatigue between shifts or repeated on-ice bouts of high-intensity activity in ice hockey (Linseman *et al.* 2014). By prolonging the onset of fatigue, players may be able to preserve skating speed and high-intensity distance. It should be noted that only a single mouth rinse was performed per trial in this study, despite exercise duration of ~12-16 min. Therefore, greater performance enhancements might be attainable with increased MR frequency.

Lastly, there are two additional studies that exhibit enhanced resistance to fatigue in recreationally trained males with CHO MR during an exercise protocol where subjects performed 45 min of SS treadmill running (65% VO_2max), followed by high-intensity interval training (HIIT; 1 min @ 80-90% VO_2max, 1 min active rest @ 6 km·h^{-1}) to exhaustion (Kasper *et al.* 2016; Devenney *et al.* 2018). HIIT time and distance to exhaustion were greater with CHO MR compared to PLA MR in fed (Devenney *et al.* 2018) and fasted states (Kasper *et al.* 2016). The exercise protocol used in these studies had less practical relevance to ice hockey, nonetheless, the findings demonstrate enhanced performance with repeated CHO MR in prolonged IHI exercise.

1.3.5 Summary

Consumption of exogenous CHO has been observed to improve physical performance, sport-specific skill, and mental acuity in IHI sport, including ice hockey. However, there has been speculation regarding the mechanistic origins of performance enhancement, as ergogenic effects were demonstrated in short-term (< 1 hr) high-intensity (> 75% VO_2max) exercise independent of changes in blood glucose, CHO oxidation, or muscle metabolism. Seminal work demonstrated that exogenous CHO improved performance when ingested, but not when infused. Thus, it was hypothesized and later confirmed that oral sensing of exogenous CHO was able to manipulate cortical activity associated with reward, motivation and motor control. This was proposed to mediate efferent information and mitigate the effects of fatigue during exercise. CHO MR is a practice that has been observed to reliably improve performance in prolonged endurance exercise, but its effects in intermittent high-intensity exercise are underreported and inconclusive. There is some evidence that CHO MR could potentially enhance power production, explosive movements and speed, as well as decrease perceptions of fatigue in ice hockey. However, the ecological validity of these findings remains limited until further research is conducted in trained stop-and-go sport athletes in their respective field settings. To date, no research on CHO MR has been conducted in ice hockey.

1.4 ATHLETE MONITORING

The practice of athlete monitoring developed as a means to quantify and understand the physical and physiological demands experienced by athletes in sport-specific settings (Van Iterson *et al*. 2017; Douglas *et al*. 2019*a*,*b*). Collection of these data can be a valuable tool to tailor training prescriptions and increase training specificity to better prepare athletes for competition. This can enhance performance outcomes, as well as mitigate risks of injury and fatigue.

1.4.1 External Load

Measurements of external load describe the physical movement demands of athletes, and pertain to the volume and intensity of work performed (Douglas *et al*. 2019*a*). Typically, measured variables include: distance, speed, changes in direction, accelerations and decelerations. Until recently, time-motion analysis (TMA) was the prevailing method to measure workload in ice hockey (Dillman *et al*. 1984; Bracko *et al*. 1998; Jackson *et al*. 2016, 2017; Brocherie *et al*. 2018; Lignell *et al.* 2018). TMA is a vision-based tracking method that requires either live observation, or more commonly, retrospective video analysis of athlete movements (Barris and Button 2008). Though it is a relatively practical and inexpensive monitoring method, TMA has questionable validity and reliability. It can be easily influenced by several factors including camera position and quality of footage, as well as the number and expertise of observers (Barris and Button 2008). Moreover, TMA has been criticized for its lack of accuracy in measuring quick and explosive maneuvers, which are prevalent in ice hockey. For these reasons, the use of TMA in ice hockey is being phased out as more sophisticated and accurate wearable microtechnologies emerge.

Microtechnologies use a combination of triaxial devices to precisely identify direction and magnitude of movement in three plains (mediolateral; anteroposterior; transverse) (Douglas *et al*. 2019*b*). Types of triaxial devices include: accelerometers to quantify linear motion in all directions, gyroscopes to measure angular motion and rotation, and magnetometers to measure direction and orientation of body position. These devices have much higher sampling rates than historical TMA, and eliminate subjective biases.

For outdoor use, triaxial devices are incorporated into global position systems (GPS). These systems have confirmed validity and reliability, and are well used in team field sports (Scott *et al*. 2016). However, the inability to obtain strong satellite signals indoors has impeded the use of these devices in several sports, including ice hockey (Serpiello *et al*. 2018). Hence, the development of local positioning systems (LPS), which use a network of antennas ('anchors') that output radio or ultra-wideband (UWB) signals to create an indoor frame of reference to track athlete movement. Devices that combine LPS and triaxial technology provide an accurate method to monitor the external loads of indoor sports. The validity and reliability of UWB LPS has previously been confirmed in comparison to motion capture systems, as well as GPS (Van Iterson *et al*. 2017; Hoppe *et al*. 2018; Serpiello *et al*. 2018). Moreover, recent unpublished data from our laboratory demonstrated that LPS is reliable and accurate for measuring on-ice external load in hockey (Gamble *et al*. 2021).

The precision and practicality offered by wearable microtechnology makes it a far superior method for tracking on-ice performance compared to historical methods. This is particularly true for competition, where it is not feasible to use visual body markers, timing gates, and/or complex multiple camera set-ups. However, the prevalence of LPS in ice hockey research is limited by high costs and fixed installation (Roell *et al*. 2018). To date, only a handful of groups have successfully implemented this technology, including our laboratory (Douglas *et al*. 2019*a,b*; Vigh-Larsen *et al*. 2020; Gamble *et al.* 2021).

1.4.2 Internal Load

Internal loads are indicative of the physiological and psychophysiological stress that accompanies physical actions (Van Iterson *et al*. 2017; McLaren *et al*. 2018). This information can be used to prescribe and periodize training programs to develop desired fitness adaptations, and is also important for monitoring fatigue and risk of injury/illness. Direct measurement of internal load is highly complex, as it can be influenced by biochemical, biomechanical, and emotional factors. Researchers often rely on associations between internal and external loads when it comes to assessment in athletic performance. In a 2018 meta-analysis of training load in intermittent-intensity sport, McLaren and colleagues established that perceived-exertion and HR derived measures of internal load demonstrated the most consistent and reliable relationships to external loads and exercise intensities. However, the size of these relationships can be manipulated my measurement technique and exercise modality.

RPE is a subjective psychophysiological measure used to assess effort and fatigue that can be recorded within acute periods/drills, or across entire sessions (sRPE) (Laurent *et al*. 2014). In team sports, sRPE exhibits a very strong relationship to total distance (r = 0.79), a possibly large relationship with accelerometer load (r = 0.63), and a moderate relationship to high-speed distance (r = 0.47) (McLaren *et al.* 2018). While there are some considerations when using a subjective measure, the ease of collection (no equipment) and validity of RPE/sRPE in intermittent activity make it a worthwhile performance measurement in ice hockey.

HR is an objective physiological measure that provides continuous feedback regarding athlete response to workload, and is often viewed as an indicator of exercise intensity (Jackson *et al*. 2016, 2017; Ulmer *et al*. 2018). In early research, on-ice collection of these data was highly-impractical, as it required HR telemetry with surface electrodes and bulky radio transmitters (Green *et al*. 1976). Fortunately, modern HR sensors are small and light-weight, and use either electrocardiogram (ECG) or photoplethysmography technology to accurately record HR (Plews *et al*. 2017). These sensors are typically worn in a strap around the chest or upper arm, though some recent LPS/GPS devices include built-in HR sensors. Data can be passively stored or actively transmitted via Bluetooth for live observation.

HR derived training impulse (TRIMP) is a measure of internal load that combines exercise time, intensity, and relative weighting of intensity (Ulmer *et al.* 2018). TRIMP is calculated using Banister's equation: [$TRIMP = \Sigma(D \times HR_r \times 0.64e^y)$], where D is the duration of exercise in min, HR_r is heart rate as a fraction of HR reserve, and y is HR_r multiplied by a sex-dependent factor (1.92 male; 1.67 female) (Bannister and Calvert 1980). In a mixed training model, TRIMP presented a possibly very large relationship with accelerometer load ($r = 0.72$) (McLaren *et al.* 2018). In ice hockey specifically, TRIMP is considered a suitable measurement for quantifying internal load during on-ice activity (Ulmer *et al*. 2018).

Lasty, there are some reports of T_c measurements in ice hockey literature, collected by ingestible thermistor pills (Batchelder *et al*. 2010; Linseman *et al*. 2014; Boville *et al*. 2015; Palmer *et al.* 2017*a,b*; Driscoll *et al.* 2020; McCarthy *et al*. 2020). Under most circumstances though, this would be a costly and unnecessary method for daily athlete monitoring, as sweat loss and urine specific gravity (USG) can be used to as indicators of hydration status, which influences T_c.

Overall, measures of internal load are by no means perfect, but when combined with external load data, their associations to physiological and psychophysiological stress help provide a more complete understanding of individual athlete fitness and responses to different workloads (Jackson *et al*. 2017; Ulmer *et al*. 2018).

1.5 CONCLUSIONS

With recent advancements in wearable microtechnology, the physical and physiological requirements of skaters in ice hockey have been well reported. Positional differences have been observed in training and competition, but both forwards and defence experience very high exercise volumes, intensities and loads on-ice.

The intermittent high-intensity activity pattern exhibited by skaters requires immense energy contributions from the anaerobic and aerobic systems, with CHO from skeletal muscle glycogen serving as the predominant fuel. As exercise duration is prolonged, hockey players display substantial glycogen depletion and are prone to mild dehydration and impaired thermoregulation. These effects contribute to fatigue, which leads to decrements in physical and mental performance.

Consumption of exogenous CHO had been observed to attenuate the negative effects of fatigue in IHI sport, including ice hockey. However, CHO oxidation and muscle metabolism were relatively unchanged between CHO and PLA conditions. As well, there was lack of agreement in the literature regarding the role of blood glucose levels and muscle glucose uptake on performance, as ergogenic effects of exogenous CHO were observed with ingestion, but not infusion. Thus, it was proposed that the mechanisms responsible for performance improvements could be related to central control, and were possibly mediated by oral sensing of CHO.

Isolated oral exposure to CHO was established to activate cortical regions of the brain associated with reward, motivation and motor control. This was proposed to mediate efferent outputs which could influence peripheral fatigue during exercise. Indeed, isolated oral exposure to CHO through MR has demonstrated significant ergogenic effects in multiple exercise protocols. To date, few studies have examined the effects of CHO MR in IHI exercise and sport. No research has been conducted in ice hockey. However, evidence has demonstrated that CHO MR might preserve speed and power production over short durations or distances. This would be beneficial to ice hockey since players perform multiple rapid and high-intensity transitions and explosive actions. In addition, reduced perceptions of fatigue have been reported with CHO ingestion in ice hockey, and CHO MR in stop-and-go sport. Thus, it is possible that CHO MR in ice hockey might help skaters mitigate exhaustion across repeated bouts of high-intensity effort within shifts and periods.

CHO MR could be a favourable practice for hockey players to enhance performance in addition to CHO ingestion, when ingestion of CHO is not desirable or feasible, or in situations that require rapid and immediate mitigation of fatigue. However, until further ecologically valid research is conducted in IHI sport, the potential benefits of CHO MR on performance in ice hockey will remain unknown.

CHAPTER 2: AIMS OF THESIS

2.1 Rationale

Since the seminal mouth-rinsing (MR) studies of the early 2000's, there has been considerable research conducted that explored the potential beneficial or ergogenic effects of oral sensing of carbohydrate (CHO) on performance and fatigue during exercise. However, the majority of the literature has examined prolonged duration (>1 hr), low-intensity (<75 % VO_2max), or steady state exercise. Several of these studies have demonstrated performance benefits with CHO MR, though some have found no change. There is a paucity of CHO MR research in intermittent high-intensity (IHI) exercise, and only three studies that have examined performance in stop-and-go sport protocols. No research has been conducted in ice hockey.

The results of existing IHI exercise research demonstrated that CHO MR can potentially improve sport performance through preservation of speed and power production in short, repeated bouts of IHI activity, and mitigate fatigue across time. These effects could be beneficial in ice hockey, where players perform multiple very-short duration, but extremely high-intensity, actions per minute. These actions include transitions between different speeds, sudden changes in direction, and explosive efforts such as rapid accelerations, decelerations, and sprints.

Indeed, earlier ice hockey research has demonstrated significant attenuation of physical performance decrements and perceptions of effort, and enhanced hockey-specific skills, when players have ingested exogenous CHO through consumption of CHO electrolyte solutions (CES). However, these experiments compared the effects of CES to mild dehydration, which is known to cause impaired thermoregulation and increase athletes' ratings of perceived exertion (RPE). Based on the existing experiment models it has been impossible to determine whether the enhanced performance observed in ice hockey was the result of adequate hydration, CHO ingestion, oral sensing of CHO, or some combination of these factors.

Until the last few years, accurate analysis of external and internal loads in ice hockey were limited by the inability to replicate the unique movement patterns and sport-specific skills in a controlled laboratory setting, and the impracticality of measuring athletes in on-ice training and competition scenarios. Recent advancements in wearable microtechnology including local positioning systems and heart rate (HR) sensors have increased the feasibility of measuring athletes in their respective field settings. In ice hockey these technologies have been used predominantly in longitudinal cohort studies without experimental interventions. However, they could improve the ecological validity of performance research in ice hockey players, and should therefore be used for the analysis of potential performance enhancing strategies and substances.

2.2 Purpose

The purpose of this thesis was to use wearable microtechnology to examine the effects of MR a CHO solution versus placebo (PLA) solution on external and internal loads in hydrated male ice hockey players during three regulation periods and one overtime (OT) period of small-sided, 3-on-3 on-ice hockey scrimmages. As a secondary purpose, hockey-specific metrics including goals, assists and shots were analyzed in the same protocol.

2.3 Hypotheses

1) MR with CHO will attenuate decrements in external load and exacerbations of internal load (increases in HR and RPE) relative to PLA MR from period 1 to periods 2 and 3.

2) MR with CHO will attenuate decrements in external load and exacerbations of internal load relative to PLA MR in OT.

3) Hockey-specific metrics will be increased with CHO versus PLA MR in regulation and OT.

CHAPTER 3: METHODS

3.1 Subjects:

Twelve male (age: 22.6 ± 3.4 yr, height: 178.9 ± 4.7 cm; BM: 84.0 ± 6.5 kg) high-level ice hockey players (U18 AA- University Varsity) volunteered to participate in this study. All participants were regularly active (~1.5 hrs/day, 5 days/week) and had played organized competitive hockey within the last 12 months. Five skilled goaltenders (U18 AA- NCAA D1) also volunteered throughout the study (2 per trial), but data were collected from skaters only. The experimental protocols, subject requirements, and potential risks and benefits of this study were explained in detail to all players orally and in writing before oral and written consent were obtained. This study was approved by the Research Ethics Board of the University of Guelph (REB# 20-02-005).

3.2 Study Design:

All microtechnology equipment used in this project were sourced from a longitudinal varsity ice hockey athlete monitoring project conducted through 2019-2020 by JL Bigg and ASD Gamble. However, the present work was original and all data collection was independent of the aforementioned project. The current study a had a double-blind, randomized, crossover design. Each participant took part in one familiarization trial and four experimental trials across three weeks. Trials were ~2.5 hr in length and occurred at the Gryphon Centre Arena (1.5 ± 0.9 ^{o}C, 56.4 ± 4.2 % humidity) at the same time daily (1:00-3:30 pm). There was a minimum of 48 hrs between trials. Skaters were instructed to maintain the same dietary habits on the day of each trial. Caffeine intake was not restricted, but participants were told to refrain from alcohol consumption and strenuous exercise in the 24 hrs preceding each skate. The morning of each skate, participants were reminded via text message to consume 500 mL of water 1 hr prior to their arrival at the arena to ensure adequate hydration.

Skaters arrived 30-45 min before the scheduled ice-time (1:40 pm) to provide a urine sample (~100 mL), measure BM, and put equipment on (Figure 1A).

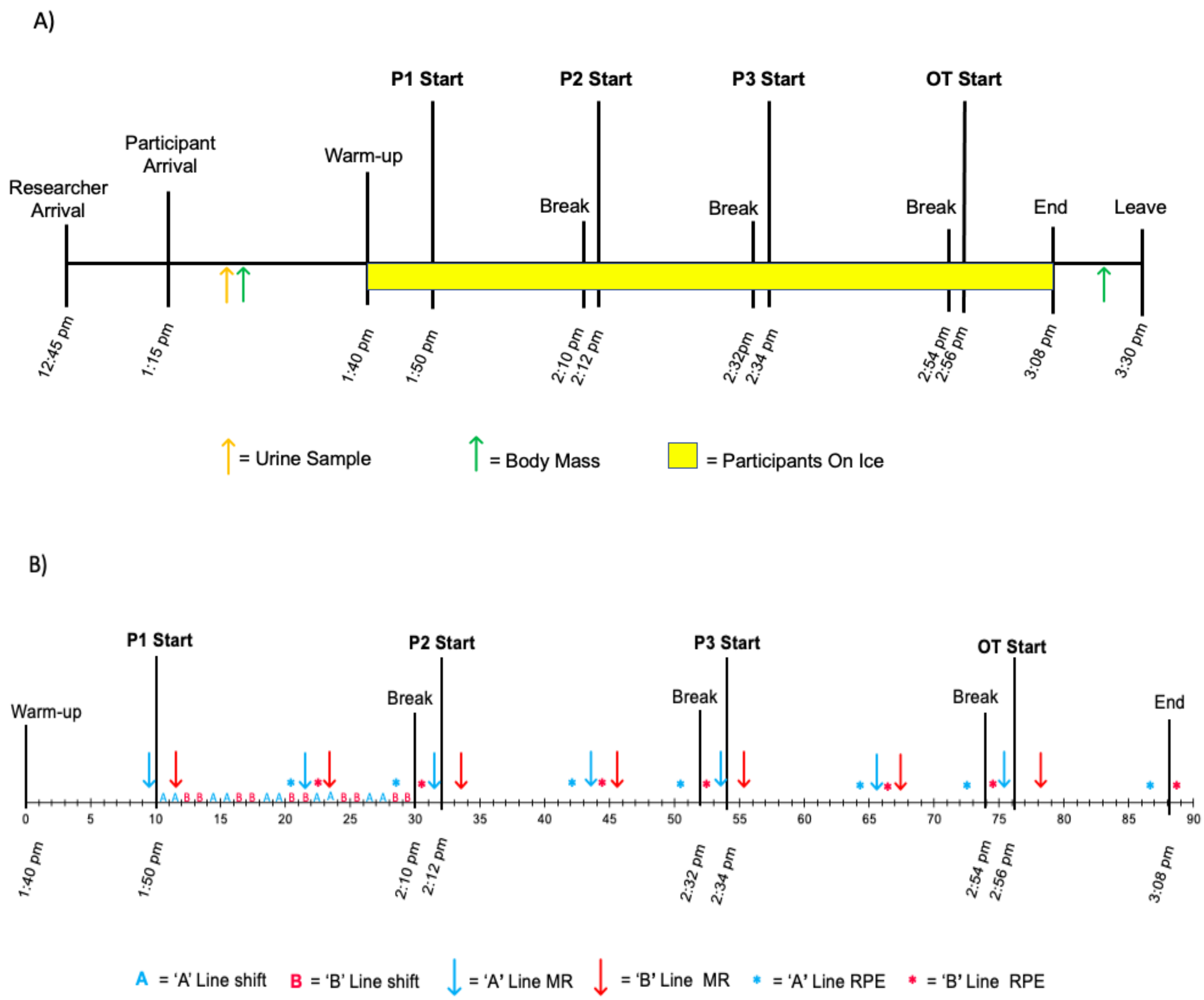

Figure 1: Timelines depicting the **A)** trial day overview, and the **B)** specific on-ice scrimmage protocols including shifts, rating of perceived exertion (RPE; Borg-10 scale) measurements and mouth-rinsing (MR). Scrimmage was 3v3 and played between two teams. Each team had two lines (A and B) of three players. Lines rotated every 2 min. There were three 20-min regulation periods (P1, P2, P3), and one 12-min overtime period (OT), separated by 2-min intermissions. RPE was recorded immediately after a player's third and last shifts in P1-P3, and last shift in OT. MR occurred at the start of every period, and midpoint of P1-P3, ~30 s before a player's next shift.

Each trial consisted of ~90 min of ice-time, which included 10-min of warmup, followed by a 72-min controlled 3-on-3 (3v3) small-sided across the ice scrimmage with goaltenders. During each scrimmage, skaters hydrated with water and performed MR every ~10 min with either a commercially available electrolyte solution that contained CHO (CHO MR; Gatorade: 6 % CHO, 19 mM sodium, 11 mM chloride, 3 mM potassium), or a non-caloric, artificially sweetened, taste and electrolyte-matched PLA (PLA MR; Gatorade Zero: 19 mM sodium, 11 mM chloride, 3 mM potassium) (Figure 1B).

3.3 Athlete Monitoring:

Player on-ice movements and external loads were tracked using a tri-axial local positioning system (LPS) installed in the arena (Kinexon Sports & Media, New York, NY, USA). The LPS system (Figure 2) operated through a combination of specific local network access, one Power over Ethernet switch, one server (located in the media booth), 16 anchors (secured to the arena rafters), and individual player sensors (~40 x 35 x 20 mm). The sensors were placed into a pouch sewn onto the exterior upper-middle portion of the shoulder pads, positioned between the scapulae.

Each player also wore a heart rate (HR) sensor (Polar OH1, Polar Electro OY, Kempele, Finland) in a band around the mid-bicep which connected via Bluetooth to the player LPS sensor. This HR sensor placement was chosen over the conventional chest strap to minimize interference by upper body protective equipment (chest and shoulder pads). Participants were assigned the same LPS and HR sensors for the duration of the study to limit inter-device variability. Commencement and cessation of data collection from individual sensors occurred automatically as players entered and exited the ice surface. Ultrawideband (UWB) channels (3244.88-4742.40 MHz) allowed for communication between player sensors and LPS anchors, enabling real-time collection of data (sampling rate of 20 Hz) which was transmitted to the server via hardwired connection. Data were stored on the LPS platform and could be retrieved on a secure tablet or computer for either live or retrospective analysis. Additionally, each scrimmage was video-recorded (HDR-CX405BKIT, Sony, Toronto, ON) to allow retrospective analysis of hockey-specific performance metrics (e.g. goals, assists, shots).

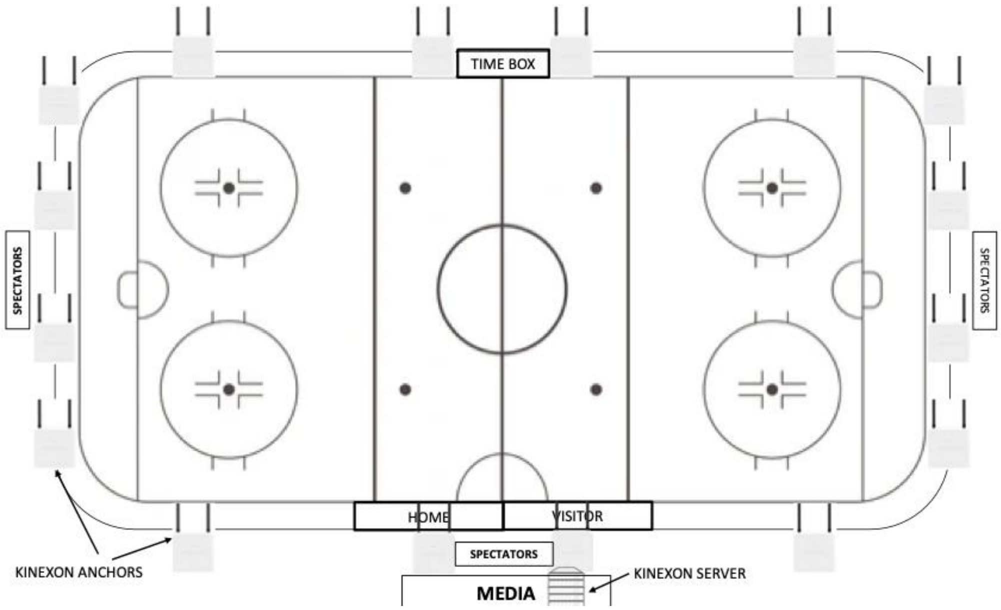

Figure 2: Schematic diagram outlining the location of one server and 16 anchors of an ultra-wideband local positioning system (LPS; Kinexon, Munich, Germany) used to measure on-ice movements of skaters during hockey scrimmage (Gamble *et al.* 2021).

3.4 Scrimmage Protocol:

All trials took place on an Olympic-sized rink, with the surface set up to contain two smaller playing areas to accommodate small-sided 3v3 scrimmages (Figure 3). Each area was used for only two scrimmage periods to mitigate poor ice conditions. Scrimmages were played across the ice between the blueline and end boards. Nets were set up ~2 m from the boards on the midline of the area. The space between the two blue lines (neutral zone) was used as a rest area for players. Each participant had an assigned rest station with a chair, water bottles and MR supplies (syringes, collection bucket).

This ‘small-sided game’ set-up had previously been observed to elicit high-intensity game play which mimicked the demands of standard 5v5 competition (Lauchaume *et al.* 2017). Moreover, the limited space provided by this set-up encouraged player battling and enforced quick decision making. However, in the present study the 3v3 structure was primarily an adaptation to COVID-19, as it maximized the number of skaters that could be tested safely and effectively at one time and within a short time frame.

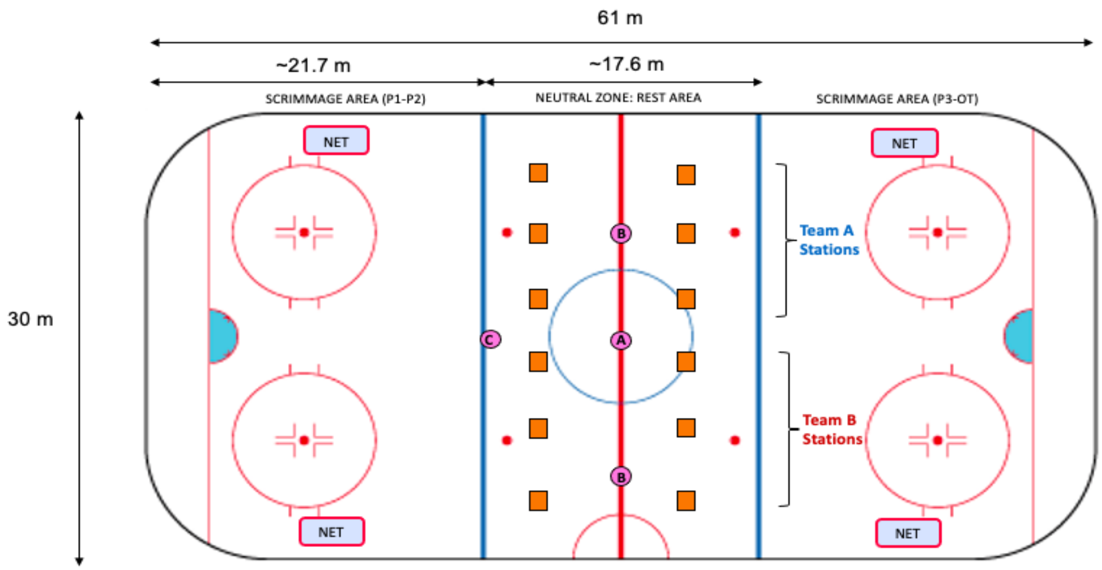

Figure 3: Ice rink set-up for multiple periods of small-sided 3v3 hockey scrimmage between 2 teams. Scrimmages were played across Olympic sized ice, between the blue-line to end boards (30 x 21.7 m). Nets were placed on the midline of these areas, ~2 m from the boards. To minimize poor ice conditions, period 1 (P1) and period 2 (P2) were played in one end, while period 3 (P3) and overtime (OT) were played in the other end. The extra space between blue lines (neutral zone) housed player rest stations (orange squares). Stations were assigned to individual skaters and contained a chair, water bottles and MR supplies (syringes, collection bucket). Pink circles represent researchers with the roles of scorekeeper (A), team monitor (B), and referee/puck passer (C).

For each trial, players were on the ice for ~90 min. The first 10 min of ice time were allocated to self-led warmup, where players were allowed to lightly skate, stretch, and shoot. This was followed by 72 min of small-sided 3v3 scrimmage, which was divided into three 20-min regulation periods and one 12-min OT period, each separated by a 2-min intermission

(Figure 1A). In this protocol, OT was treated as a separate game, and unless tied at the end of regulation, scores were reset at the start of this period.

The scrimmage was played between two teams of 6 players, who rotated two talent-matched lines of 3 players. To normalize individual playing time and work/rest ratio between participants, shifts were timed and lines changed on a whistle. Players repeated a pattern of 2-min of playing time with 2-min of rest between shifts (Figure 1B). Each skater played 5 shifts per period in regulation, and 3 shifts in OT, for a total of 18 shifts across the entire scrimmage. Throughout the scrimmage, each team was monitored by a researcher who gave instructions and ensured that skaters remained at their assigned station and did not partake in unnecessary skating during rest phases. Goaltenders played the entire scrimmage, but switched teams halfway through regulation and OT to limit their influence on a single team's performance.

Each period commenced with both teams lined up at the centre of the playing area to battle for possession of the puck, which was passed in by a researcher on a whistle. At the end of shifts, lines simultaneously entered/exited the playing area, and the game would continue immediately. In the event the puck exited the playing area, it was considered out of bounds, and a researcher would immediately pass a new puck to the non-responsible team for possession. Likewise, if a goal was scored, or the goaltender covered the puck, the defensive party gained puck possession. At the researcher's discretion, minor penalties rewarded the opposing team with puck possession. Body checking was forbidden, however body contact in the form of grappling/battling was permitted.

A designated researcher kept score throughout the scrimmage and players were regularly made aware of the score. To encourage and maintain a high level of competition amongst participants and across trials, two monetary awards were offered every scrimmage. The first award ($10/player) was granted to each player of the winning team at the end of regulation. A second smaller monetary reward ($5/player) was granted to each player of the winning team in OT. In the event of a tie at the end of regulation, OT was used to decide the winner of both awards. There were no situations wherein teams remained tied following OT. Both goaltenders were compensated ($15/player) at the end of each trial.

3.5 Familiarization Trial:

All skaters took part in one familiarization trial to adjust to the scrimmage format and to learn the MR protocol. This trial was also used to assess athlete skills in order to ensure equal assignment of talent between teams for upcoming scrimmages. Net fluid loss was recorded and sweat amounts were calculated across the scrimmage. This information was used to establish the fluid intake parameters necessary to prevent mild dehydration in experimental trials.

Prior to every skate, each participant provided a urine sample (~100 mL) to identify pre-scrimmage hydration status. Urine specific gravity (USG) was determined using a hand-held 'pen' refractometer (ATAGO USA Inc., Bellevue, WA, USA), and values >1.020 were considered indicative of mild dehydration. Participants were then weighed on a digital scale wearing dry, minimal clothing to determine their pre-scrimmage BM. Following weigh-in, participants were not permitted to drink until they were on the ice. On-ice, players were provided with two full bottles of water (~2 L), and instructed to drink *ad libitum*. These bottles had been weighed pre-skate with a food scale (Starfrit, Atlantic Promotions Inc., QC, Canada). Following scrimmage, players removed their equipment, and then weighed-out in the same dry clothes as before. Water bottles were collected and mass values were recorded. Percent body mass loss was calculated as [(pre-BM – post-BM)/(pre-BM) x 100]. Body mass loss >1.5% was recognized as mild dehydration. Sweat amount was equal to [(pre-BM – post-BM) + (fluid intake – urine output)].

3.6 Experimental Trials and Mouth-Rinse Protocol:

Participants followed the same off-ice pre- and post-scrimmage routines as the familiarization trial. On-ice, each player was provided with two bottles that together contained a volume of water that was approximately equivalent to their individual sweat amount. Players were instructed to consume one bottle per half scrimmage, and were given verbal reminders to drink when resting. Drinking was allowed only from these bottles and spitting/spraying/rinsing were not permitted.

MR was performed at rest in the final 30 s before the first shift of every period, and the fourth shift of the three regulation periods (Figure 1B). This resulted in one MR every ~10 min, and seven MRs total. Each rinse aliquot was premeasured (25 mL) and administered orally via a plastic syringe (Air-Tite All Plastic Norm-Ject Syringe-30 mL, Fisher Scientific, ON, Canada). Researchers verbally led the players through every MR, which required vigorous swishing of the rinse solution around the oral cavity for 10 s before expectorating into a bucket. Participants were instructed not to drink any water in the remaining time after their MR, before the next shift. Individuals received a single MR condition for the duration of each trial, however, CHO and PLA MR conditions were randomized within teams and lines as to not confound scrimmage outcome. Over the course of the study, all participants performed duplicate trials of each condition.

3.7 Measured Variables:

Hydration status was monitored with pre-skate USG and change in BM from pre- to post-scrimmage. Blinding effectiveness was assessed via a post-skate questionnaire that asked participants whether they felt they knew which rinse condition they received after each trial. If the participants answered 'yes' to this question, they were asked to identify which condition they thought they had received and why.

All on-ice external load variables were derived from LPS data. Definitions of these metrics were adapted from One & Media - KNX ONE Hockey Metrics (Kinexon, Munich, Germany). In addition to total distance, distance skated in each period was measured and categorized according to 6 specific speed zones with defined thresholds: zone 1–very slow = 1.0-10.9 $km \cdot h^{-1}$, zone 2–slow = 11.0-13.9 $km \cdot h^{-1}$, zone 3–moderate = 14.0-16.9 $km \cdot h^{-1}$, zone 4–fast = 17.0-20.9 $km \cdot h^{-1}$, zone 5–very fast = 21.0-24.0 $km \cdot h^{-1}$, zone 6–sprint = >24.0 $km \cdot h^{-1}$ (Lignell *et al.* 2018). Distances traveled at low-intensity (<17 $km \cdot h^{-1}$) and high-intensity (≥17 $km \cdot h^{-1}$) speeds were also reported (Vigh-Larsen *et al.* 2020). Average and peak speeds ($km \cdot h^{-1}$) were determined from instantaneous changes in position and time. Explosive movements were categorized as sprints, accelerations, and decelerations. Sprints were the number of movements that occurred ≥22 $km \cdot h^{-1}$ and were maintained for at least 1 s. Accelerations were defined by positive rates of change of velocity (> 2.0 $m \cdot s^{-2}$), while decelerations were defined by negative rates of change of velocity (< -2.0 $m \cdot s^{-2}$), with respect to time. The peak magnitudes and number of accelerations and decelerations were also recorded.

Physiological indicators of internal load were captured by HR, measured in beats per min (bpm), and used to calculate HR derived training impulse (TRIMP). TRIMP was calculated using Banister's equation: [$TRIMP = \mathbf{\Sigma}(D \times HR_r \times 0.64e^{y})$], where D is the duration of exercise in min, HR_r is heart rate as a fraction of HR reserve, and y is HR_r multiplied by a sex-dependent factor (1.92 for males) (Banister and Calvert 1980). Average and peak HR were recorded each period. However, it is important to note that, unlike external load metrics, HR could not be controlled during rest phases. Incumbent on player tracking software, HR was analyzed across the entire period instead of a shift by shift basis observed in earlier hockey research.

A psychophysiological measure of internal load and fatigue during scrimmage was RPE (Borg-10 scale). This was recorded immediately following a player's third and last shifts in periods 1-3, and the last shift in OT (Figure 1B). Players were provided with a visual scale and prompted to verbally score their current RPE.

Metrics of hockey-specific performance were goals, assists and shot attempts. To be credited with an assist, the player(s) had to have direct involvement in the play immediately before the goal. Shot attempts encompassed shots on goal, missed shots, and blocked shots. A shot on goal was any shot directed at the net that would have entered the net if not for the actions of the goaltender. A missed shot was any shot directed at the net that went high or wide of the net or hit a post or cross bar. A blocked shot was any shot directed at the net that was blocked or deflected by an opponent besides the goaltender. These variables were recorded live by a designated researcher. However, due to the fast pace of game play, video from each trial was reviewed by experienced analysts (10+ years hockey experience) to ensure accuracy of the reported metrics.

3.8 Statistical Analysis:

Data are presented as mean ± *SD*. Differences in all variables in the three regulation periods were analyzed with two-way repeated measures ANOVAs (condition x period). Effect sizes (ES) were reported as partial η^2. When a significant F ratio was found, a *post hoc* analysis was performed using Tukey's multiple comparisons test with adjusted p values. Paired t-tests were used to compare the effects of CHO vs PLA MR in all measured variables in OT. All statistical analyses were performed with GraphPad Prism 9.1.0 for Mac (Graphpad Software, LLC, San Diego, CA). Significance was accepted at $p \leq 0.05$, with confidence intervals (CI) of 95%.

CHAPTER 4: RESULTS

4.1 BLINDING EFFECTIVENESS

Few participants felt they could correctly identify their rinse condition, and out of 48 trials there were only 10 instances where players (n = 5) were confident that they knew which MR solution they used. Out of these 10 trials, players correctly identified their condition 50% of the time. Thus, blinding was highly effective, as MR solution was correctly identified a mere 5/48 times (~10%).

4.2 HYDRATION STATUS

The average pre-scrimmage USG for all trials was 1.007 ± 0.006, and there were no instances where a player had a USG above 1.020, which indicated that participants arrived adequately hydrated for all trials. Average player sweat loss was 1.38 ± 0.31 L, and average calculated sweat rate was 0.97 ± 0.22 $L \cdot h^{-1}$. Participants were effective at hydrating throughout the scrimmages and lost an average of 0.32 ± 0.01% and 0.33 ± 0.01% BM during CHO and PLA MR trials, respectively.

4.3 EXTERNAL LOAD

4.3.1 Total Distance

Regulation— There was no difference in total distance skated between MR conditions (CHO: 6176 ± 287 m, PLA: 6292 ± 402 m). However, there was a main effect of period for total distance skated per period ($F(2,22) = 6.45$, $p = 0.006$, partial $\eta^2 = 0.71$). Across both conditions, total distance in period 1 (2130 ± 19 m) was significantly greater than periods 2 (2062 ± 11 m, $p = 0.008$) and 3 (2072 ± 29 m, $p = 0.024$).

Overtime— There was no difference in total distance skated in OT between CHO MR (1229 ± 78 m) and PLA MR (1225 ± 99 m).

4.3.2 Distance Per Speed Zone

Regulation—In zone 1–very slow speed, there was a statistically significant two-way interaction between period and MR condition ($F(2,22) = 5.07$, $p = 0.015$, partial $\eta^2 = 0.46$) (Figure 4A). *Post-hoc* analysis revealed a simple main effect of MR condition in period 2, and significantly less distance was skated with CHO MR (695 ± 108 m) compared to PLA MR (737 ± 92 m, $p = 0.005$). As well, a simple main effect of period was found within the PLA MR condition, and significantly greater distance was skated in period 2 (737 ± 92 m) compared to period 1 (677 ± 108 m, $p < 0.001$) and period 3 (701 ± 116 m, $p = 0.21$).

In zone 2–slow speed there was a main effect of period ($F(2,22) = 4.58$, $p = 0.022$, partial $\eta^2 = 0.93$). Across both conditions, more distance was traveled in period 1 (581 ± 1 m) than period 2 (540 ± 7 m, $p = 0.018$) (Figure 4B).

In zone 3–moderate speed there was a main effect of period ($F(2,22) = 3.58$, $p = 0.045$, partial $\eta^2 = 0.53$), and across both MR conditions distance in period 2 (450 ± 15 m) was less than period 1 (496 ± 10 m, $p = 0.037$) (Figure 4C).

In zone 4–fast speed there was a main effect of period ($F(2,22) = 9.15$, $p = 0.001$, partial $\eta^2 = 0.79$), and across both MR conditions distance in period 3 (264 ± 6 m) was less than period 1 (307 ± 9 m, $p < 0.001$) (Figure 4D).

No significance was observed for distance skated in zone 5–very fast speed or zone 6–sprint speed (Figure 4E,F).

Overtime— In zone 2, significantly greater distance was skated with PLA MR (336 ± 47 m) compared to CHO MR (300 ± 33 m, $p = 0.034$) (Figure 5). Within the other 5 speed zones, distance skated was comparable between MR conditions.

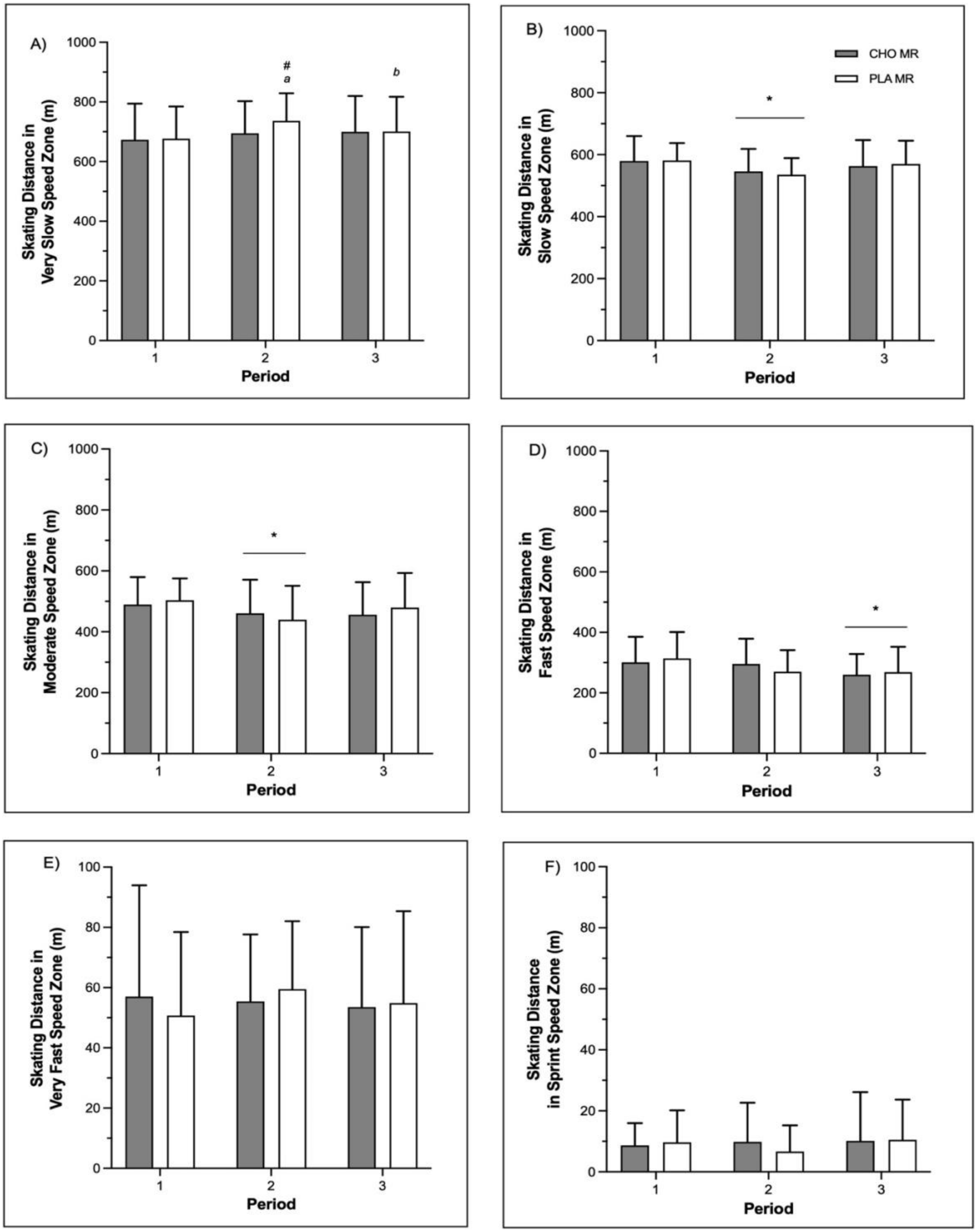

Figure 4: Distance traveled by male high-level hockey players (n=12) in **A)** very slow (1.0-10.9 km·h^{-1}), **B)** slow (11.0-13.9 km·h^{-1}), **C)** moderate (14.0-16.9 km·h^{-1}), **D)** fast (17.0-20.9 km·h^{-1}), **E)** very fast (21.0-24.0 km·h^{-1}), and **F)** sprint (>24.0 km·h^{-1}) speed zones when mouth-rinsing (MR) with carbohydrate (CHO) or placebo (PLA) solution during three 20-min regulation periods of small-sided 3v3 ice hockey scrimmage. Data are presented as mean ± SD. *Main effect of period, significantly lower than period 1. [a]Significantly greater than period 1, same condition. [b]Significantly lower than period 2, same condition. [#]Signifcantly greater than other MR condition, same period. Significance accepted at $p \leq 0.05$.

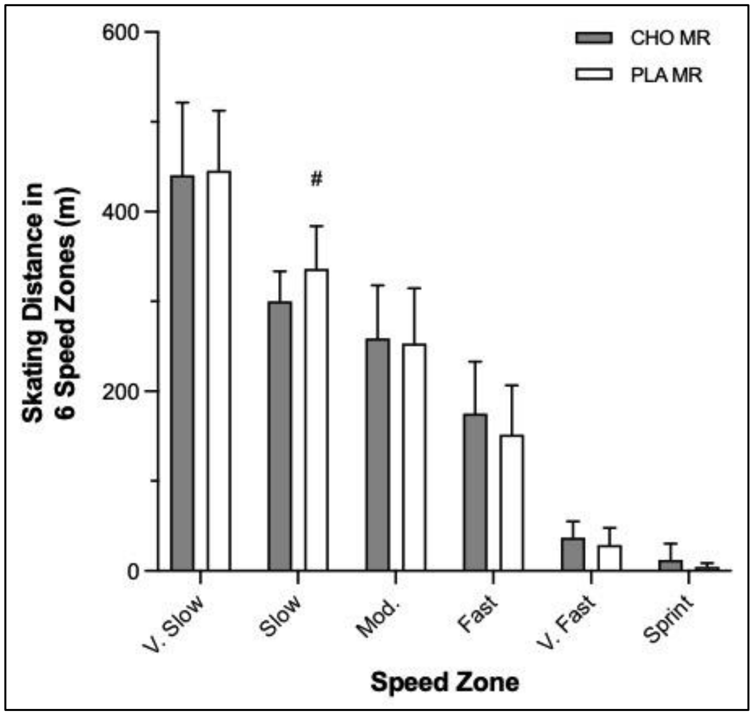

Figure 5: Distance traveled by male high-level hockey players (n=12) in very slow (1.0-10.9 km·h^{-1}), slow (11.0-13.9 km·h^{-1}), moderate (14.0-16.9 km·h^{-1}), fast (17.0-20.9 km·h^{-1}), very fast (21.0-24.0 km·h^{-1}), and sprint (>24.0 km·h^{-1}) speed zones when mouth-rinsing (MR) with carbohydrate (CHO) or placebo (PLA) solution during one 12-min overtime period of small-sided 3v3 ice hockey scrimmage. Data are presented as mean ± SD. $^{\#}$Signifcantly greater than other MR condition, same zone ($p \leq 0.05$).

4.3.3 Low- and High-Intensity Distance

Regulation— There was a main effect of period for distance skated at high-intensity speed ($F(2,22) = 6.04$, $p = 0.008$, partial $\eta^2 = 0.40$), and across both conditions it was found that distance in period 3 (328 ± 7 m) was significantly less than period 1 (370 ± 5 m, $p = 0.006$) (Figure 6). No effects were observed for distance skated at low-intensity speed.

Overtime— Significantly greater distance was skated at high-intensity speed with CHO MR (224 ± 77 m) relative to PLA MR (185 ± 66 m, $p = 0.042$) (Figure 7). Greater distance was skated at low-intensity speed with PLA MR (1035 ± 87 m) compared to CHO MR (999 ± 54 m), but did not reach significance ($p = 0.176$).

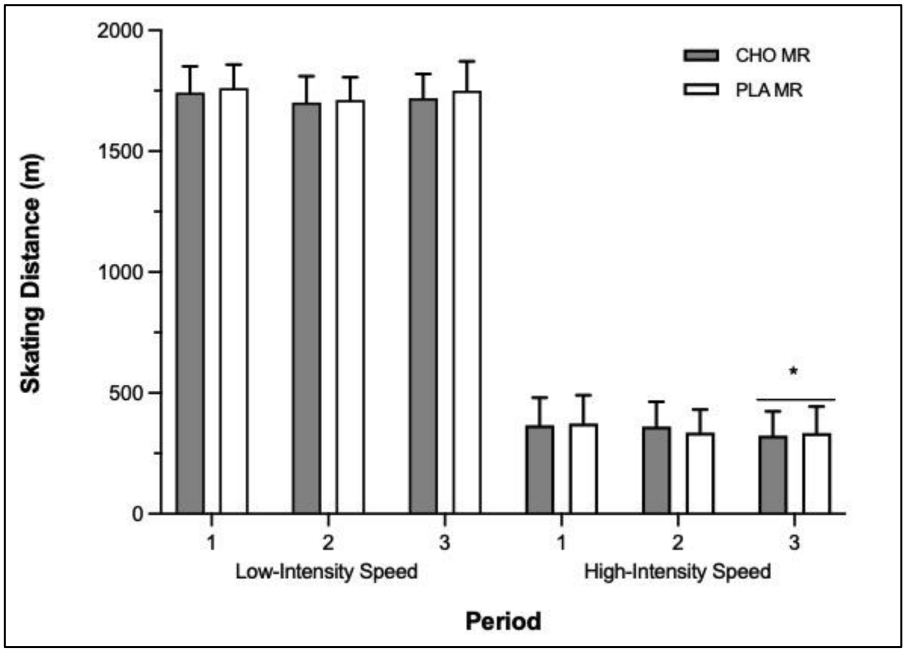

Figure 6: Distance traveled by male high-level hockey players (n=12) at low-intensity (<17 km·h^{-1}) and high-intensity (≥17 km·h^{-1}) speeds when mouth-rinsing (MR) with carbohydrate (CHO) or placebo (PLA) solution during three 20-min regulation periods of small-sided 3v3 ice hockey scrimmage. Data are presented as mean ± SD. *Main effect of period, significantly lower than period 1 ($p \leq 0.05$).

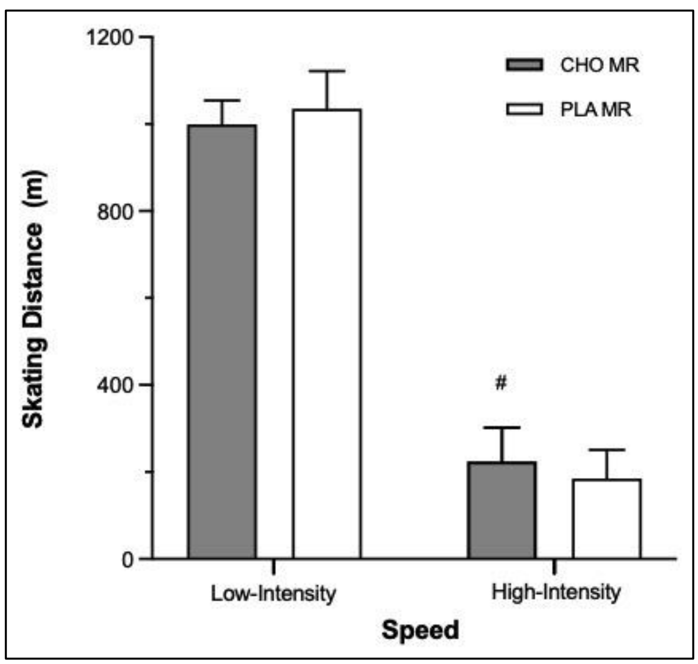

Figure 7: Distance traveled by male high-level hockey players (n=12) at low-intensity (<17 km·h^{-1}) and high-intensity (≥17 km·h^{-1}) speeds when mouth-rinsing (MR) with carbohydrate (CHO) or placebo (PLA) solution during one 12-min overtime period of small-sided 3v3 ice hockey scrimmage. Data are presented as mean ± SD. #Signifcantly greater than other MR condition, same speed ($p \leq 0.05$).

4.3.4 Speed

Regulation— There was no significance found for peak speed (Table 1). A main effect of period was observed for average speed ($F(2,22) = 5.73$, $p = 0.010$, partial $\eta^2 = 0.41$), which decreased across both MR conditions from period 1 (12.7 ± 0.1 $km \cdot h^{-1}$) to period 2 (12.3 ± 0.9 $km \cdot h^{-1}$, $p = 0.12$) and period 3 (12.4 ± 0.2 $km \cdot h^{-1}$, $p = 0.41$) (Table 1).

Overtime— Peak speed was significantly higher with CHO MR (24.6 ± 1.6 $km \cdot h^{-1}$) over PLA MR (23.7 ± 1.3 $km \cdot h^{-1}$, $p = 0.016$) (Figure 8). There was no difference in average speed between MR conditions.

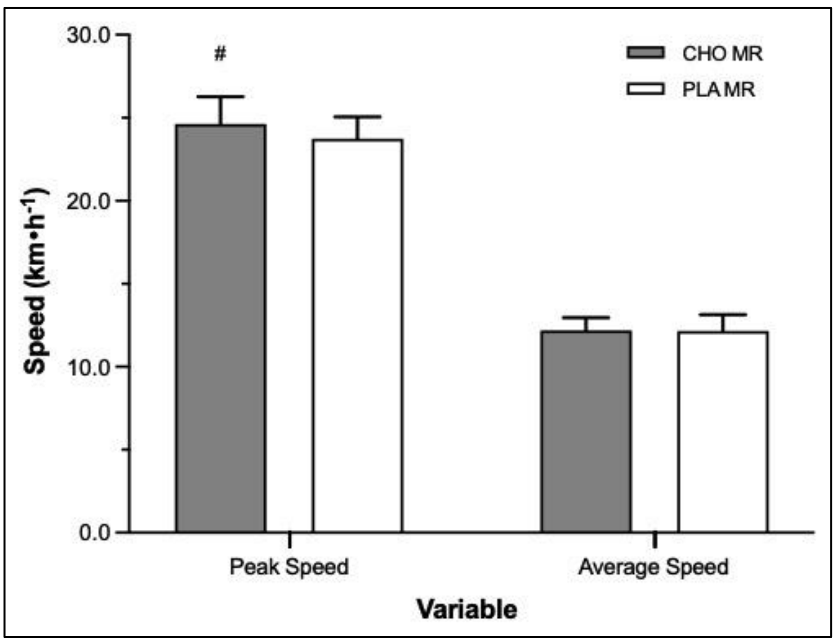

Figure 8: Peak and average speeds of male high-level hockey players when mouth-rinsing (MR) with carbohydrate (CHO) or placebo (PLA) solution during one 12-min overtime period of small-sided 3v3 ice hockey scrimmage. Data are presented as mean ± SD. #Signifcantly greater than other MR condition, same variable ($p \leq 0.05$).

4.3.5 Explosive Movements

Regulation— There was a main effect of period on number of decelerations ($F(2,22) = 17.39$, $p < 0.001$, partial $\eta^2 = 1.93$), which significantly decreased across both MR conditions from period 1 to periods 2 and 3 ($p < 0.001$ for both) (Table 1). No significance was observed between periods or MR conditions for number of sprints and number of accelerations performed, or peak acceleration and peak deceleration recorded (Table 1).

Overtime— Individuals performed a significantly greater number of sprints when MR with CHO (1.9 ± 1.2) as opposed to PLA (1.2 ± 0.9, p = 0.011) (Figure 9). No significance was found in any acceleration or deceleration variables (Table 2).

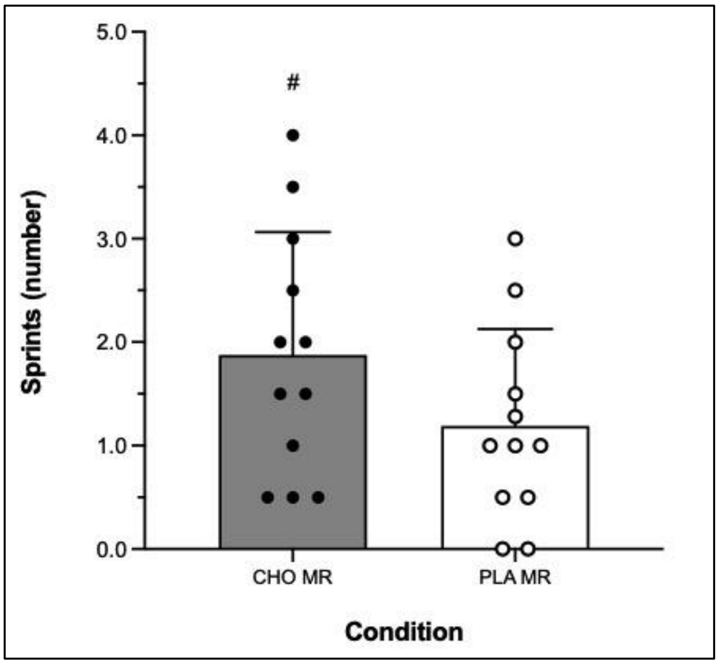

Figure 9: Number of sprints performed by male high-level hockey players when mouth-rinsing (MR) with carbohydrate (CHO) or placebo (PLA) solution during one 12-min overtime period of small-sided 3v3 ice hockey scrimmage. Values are an average from 2 trials per condition. A sprint is a movement at any speed ≥ 22 $km \cdot h^{-1}$, maintained for at least 1 second. Circles represent individual values. Bars present data as mean ± SD. #Signifcantly greater than other MR condition ($p \leq 0.05$).

Table 1: Speed and explosive movement external load variables of male high-level hockey players (n =12) when mouth-rinsing (MR) with carbohydrate (CHO) or placebo (PLA) solution during three 20-min periods of small-sided 3v3 ice hockey scrimmage. A sprint is a movement at any speed ≥ 22 km·h^{-1}, maintained for at least 1 second. Accelerations (> 2.0 m·s^{-2}). Decelerations (< -2.0 m·s^{-2}). Values are presented as mean ± SD. *Main effect of period, significantly lower than period 1 ($p \leq 0.05$)

Variable	Condition	Period 1	Period 2	Period 3
Peak Speed (km·h^{-1})	*CHO MR*	24.3 ± 1.3	24.2 ± 1.3	24.4 ± 1.6
	PLA MR	24.5 ± 1.2	24.4 ± 1.4	24.6 ± 1.7
Average Speed (km·h^{-1})	*CHO MR*	12.6 ± 0.9	12.4 ± 0.9*	12.3 ± 0.7*
	PLA MR	12.8 ± 0.7	12.3 ± 0.9*	12.6 ± 1.0*
Sprints (number)	*CHO MR*	2.7 ± 1.9	2.5 ± 1.5	2.4 ± 1.6
	PLA MR	1.9 ± 1.1	2.4 ± 1.1	2.3 ± 1.2
Peak Acceleration (m·s^{-2})	*CHO MR*	3.5 ± 0.3	3.4 ± 0.3	3.3 ± 0.3
	PLA MR	3.5 ± 0.2	3.6 ± 0.2	3.6 ± 0.2
Accelerations (number)	*CHO MR*	12.8 ± 4.8	12.0 ± 3.9	11.5 ± 3.9
	PLA MR	13.3 ± 4.6	12.4 ± 3.7	12.5 ± 4.4
Peak Deceleration (|m·s^{-2}|)	*CHO MR*	4.7 ± 0.5	4.6 ± 0.5	4.4 ± 0.4
	PLA MR	4.6 ± 0.4	4.7 ± 0.3	4.4 ± 0.5
Decelerations (number)	*CHO MR*	19.3 ± 4.2	15.6 ± 4.1*	15.7 ± 3.8*
	PLA MR	19.9 ± 5.9	16.0 ± 3.5*	15.8 ± 5.2*

Table 2: Select explosive movement external load variables of male high-level hockey players (n =12) when mouth-rinsing (MR) with carbohydrate (CHO) or placebo (PLA) solution during one 12-min overtime period of small-sided 3v3 ice hockey scrimmage. Accelerations (> 2.0 $m \cdot s^{-2}$). Decelerations (< -2.0 $m \cdot s^{-2}$). Values are presented as mean ± SD.

Variable	Condition	Overtime Period
Peak Acceleration ($m \cdot s^{-2}$)	*CHO MR*	3.4 ± 0.4
	PLA MR	3.5 ± 0.4
Accelerations (number)	*CHO MR*	8.5 ± 3.5
	PLA MR	7.7 ± 2.1
Peak Deceleration ($|m \cdot s^{-2}|$)	*CHO MR*	4.4 ± 0.5
	PLA MR	4.0 ± 0.5
Decelerations (number)	*CHO MR*	9.7 ± 3.5
	PLA MR	10.3 ± 2.8

4.4 INTERNAL LOAD

4.4.1 Heart Rate and TRIMP

Regulation— A main effect of time was found for peak HR ($F(2,22) = 11.94$, $p < 0.001$, partial $\eta^2 = 0.79$), which was significantly lower across both MR conditions in period 1 (183.6 ± 1.2 bpm) compared to periods 2 (187.5 ± 0.4 bpm, $p < 0.001$) and 3 (186.9 ± 1.7 bpm, $p = 0.002$). Within periods, peak heart rate was not different between MR conditions (Table 3).

A significant two-way interaction between period and MR condition was observed for average HR ($F(2,22) = 5.09$, $p = 0.015$, partial $\eta^2 = 0.46$). *Post hoc* analysis revealed simple main effects of period within each MR condition independently, and for CHO and PLA MR, HR in period 1 was significantly lower than periods 2 and 3 ($p < 0.001$ for all) (Table 3).

A significant two-way interaction between period and MR condition was also observed for TRIMP ($F(2,22) = 4.11$, $p = 0.030$, partial $\eta^2 = 0.37$). Simple main effects of period were observed within each MR condition independently. For CHO MR, period 1 was significantly lower than periods 2 ($p = 0.002$) and 3 ($p = 0.016$) (Table 3). For PLA MR, TRIMP in period 1 was lower than periods 2 and 3 ($p < 0.001$ for both).

Overtime— No statistical differences were found between MR conditions for HR. For CHO and PLA MR, peak HRs were 183.3 ± 9.1 and 185.7 ± 9.0 bpm, average HRs were 153.7 ± 11.8 and 155.2 ± 11.3 bpm, and TRIMP values were 24.9 ± 8.5 and 26.4 ± 8.2 AU, respectively.

Table 3: Heart rate (HR) internal load variables of male high-level hockey players (n =12) when mouth-rinsing (MR) with carbohydrate (CHO) or placebo (PLA) solution during three 20-min periods of small-sided 3v3 ice hockey scrimmage. HR measured in beats per min (bpm). Training derived impulse (TRIMP) calculated using Banister's exponential HR scaling equation. Values are presented as mean ± SD. *Main effect of period, significantly greater than period 1 ($p \leq 0.05$)

Variable	Condition	Period 1	Period 2	Period 3
Peak HR (bpm)	*CHO MR*	184.5 ± 7.5	187.2 ± 7.5*	185.7 ± 8.8*
	PLA MR	182.8 ± 9.8	187.8 ± 8.2*	188.1 ± 8.3*
Average HR (bpm)	*CHO MR*	147.8 ± 11.1	155.3 ± 10.3*	155.0 ± 10.9*
	PLA MR	145.6 ± 11.1	156.9 ± 10.4*	157.4 ± 11.3*
TRIMP (AU)	*CHO MR*	36.6 ± 11.4	43.4 ± 13.2*	42.1 ± 14.8*
	PLA MR	34.6 ± 11.7	45.2 ± 12.4*	46.1 ± 15.4*

4.4.2 Ratings of Perceived Exertion

Regulation— A main effect of period was observed ($F(5,55) = 8.28$, $p < 0.001$, partial $\eta^2 = 1.01$), and across both conditions average RPE values were significantly lower in period 1 (6.7 ± 0.03) versus periods 2 (7.3 ± 0.1, $p = 0.001$) and 3 (7.2 ± 0.4, $p = 0.007$) (Figure 10A). There was no significance found for MR condition, however, there was a trend for RPE to be lower with CHO compared PLA MR within all 3 periods.

Overtime— There was no significance in RPE values between rinse conditions, although CHO MR was slightly higher than PLA MR ($p = 0.55$) (Figure 10B).

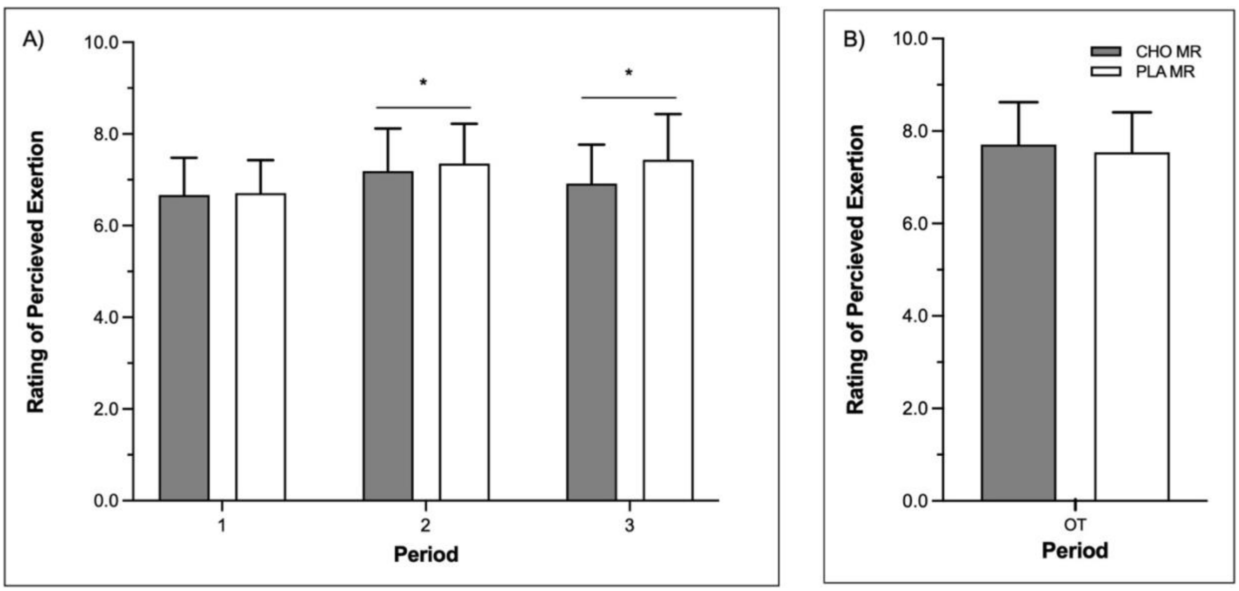

Figure 10: Average rating of perceived exertion (RPE; Borg-10 scale) of male high-level hockey players during **A)** three 20-min periods and **B)** one 12-min overtime period of 3v3 ice hockey scrimmage while mouth-rinsing (MR) with carbohydrate (CHO) or placebo (PLA) solution. RPE was recorded immediately after 2-min shifts at the mid and end points of periods 1-3, at the end of overtime (every ~10 min). Data are presented as mean ± SD. *Main effect of period, significantly higher than period 1 ($p \leq 0.05$).

4.5 HOCKEY-SPECIFIC METRICS

Regulation— No significance was observed between MR conditions for goals, assists, or any type of shots (on goal, blocked, missed), or when the latter were combined as shot attempts (Table 4).

Overtime— Number of assists was significantly greater with CHO MR (0.9 ± 0.6) compared to PLA MR (0.4 ± 0.3, p = 0.021). There were no differences between CHO and PLA MR for goals (0.5 ± 0.6 vs. 0.8 ± 0.8) or shot attempts (3.6 ± 1.3 vs. 3.3 ± 1.4).

Table 4: Hockey-specific performance variables for high-level male hockey players (n =12) during three 20-min periods of small-sided 3v3 ice hockey scrimmage when mouth-rinsing (MR) with carbohydrate (CHO) or placebo (PLA) solution. Shot attempts are the sum of blocked shots, missed shots and shots on goal. Values are presented as mean ± SD.

Variable	Condition	Period 1	Period 2	Period 3
Goals	*CHO MR*	1.1 ± 0.9	1.1 ± 0.7	1.0 ± 0.6
	PLA MR	1.2 ± 0.8	1.3 ± 0.7	1.4 ± 1.6
Assists	*CHO MR*	1.2 ± 0.7	0.7 ± 0.7	1.0 ± 0.6
	PLA MR	1.2 ± 0.7	1.1 ± 1.0	1.1 ± 0.6
Shot Attempts	*CHO MR*	5.2 ± 1.8	5.1 ± 2.0	6.1 ± 1.7
	PLA MR	5.5 ± 1.4	6.7 ± 1.7	6.3 ± 2.1

CHAPTER 5: DISCUSSION

The purpose of this research was to examine the potential benefits of CHO MR on external and internal loads in hydrated male ice hockey players in three regulation periods and one OT period during small-sided, 3v3 on-ice hockey scrimmages. The principle findings of this study were that: a) in regulation, there was similar development of fatigue across both MR conditions observed as decreases in external load metrics of total distance, high-intensity distance, number of decelerations and average speed, and increases in internal load metrics of peak HR, average HR, TRIMP and RPE, from period 1 to periods 2 and 3, b) in OT, CHO MR increased peak speed, high-intensity distance and number of sprints compared to PLA MR, c) in OT there were no differences in HR, TRIMP, or RPE between conditions, despite increases in external load, and d) CHO MR had no effect on hockey-specific metrics in regulation and minimal effect in OT. Therefore, the results of this study reject the first hypothesis that CHO MR would attenuate decrements in external load and exacerbations of internal load in regulation, but accept the second hypothesis that CHO MR would attenuate decrements in external load and exacerbations of internal load in OT. The third hypothesis that CHO MR would increase hockey-specific metrics in regulation and OT is partially true, as one hockey-specific metric improved with CHO MR in OT.

5.1 EXTERNAL LOAD

To the best of the author's knowledge, there are two studies that have assessed loads in 3v3 ice hockey (Lachaume *et al.* 2017; Lignell *et al.* 2018). Only one of these studies included direct assessment of external loads, which were recorded during a full-ice 3v3 OT period (5-min) in a National Hockey League (NHL) game (Lignell *et al.* 2018). The remaining body of athlete monitoring research in ice hockey examined external load in 5v5 scrimmages and competition

(Brocherie *et al.* 2018; Lignell *et al.* 2018; Douglas et al. 2019*a,b*; Douglas and Kennedy 2020; Vigh-Larsen *et al.* 2020).

The ability to make comparisons between the present and existing research is limited by numerous factors. First, the playing area in small-sided 3v3 hockey is approximately one-third (~22 x 30 m) of the full-ice surface (~26-31 x 61 m). Next, skaters in the present study accumulated greater time on ice (TOI; 36 min) than professional (16-17 min) and U20 males (24 min) (Brocherie *et al.* 2018; Lignell *et al.* 2018; Vigh-Larsen *et al.* 2020). In addition, shift length in this study was 2-min as opposed to 30-80 s. Lastly, movement patterns and game play strategies in small-sided 3v3 hockey vary from 5v5 competition, and typically rely more heavily on technical skills (e.g. passing, shooting) than skating (e.g. breakaways, odd man rushes) to generate offensive chances (Lachaume *et al.* 2017).

In addition to the existing differences within ice hockey literature, there has also been no CHO MR research in hockey. To date, only the effects of CHO ingestion on performance in ice hockey have been studied. There is some MR research in IHI exercise, but there is a paucity of work in stop-and-go athletes.

5.1.1 Regulation

In the present study, players demonstrated similar evidence of fatigue within both MR conditions as TOI increased. Total distance skated per period decreased from period 1 to periods 2 and 3, predominantly due to decrements in speed zones 2, 3 and 4. The only difference between conditions in regulation occurred within period 2, where players skated further distance in zone 1—very slow, when MR with PLA versus CHO MR. There were no between period differences observed in zone 5 or zone 6. However, very little distance was covered in these zones within any period, likely due to the difficulty of reaching and maintaining high speeds in such a small area. Even in full-ice 5v5 hockey, no change in distance has been reported in the top speed zone between periods (Lignell *et al.* 2018).

In addition to decreased distances, player fatigue in small-sided 3v3 hockey also manifested as reduced capacity to perform at high-intensity effort. Compared to period 1, players traveled at slower speed in periods 2 and 3, and covered less high-intensity distance in the latter. Likewise, fewer decelerations were performed in periods 2 and 3 compared to 1. Difficulty maintaining high speed and performing explosive efforts with increased playing time is a shared observation with elite men's 5v5 competition (Lignell *et al.* 2018; Vigh-Larsen *et al.* 2020).

In ice hockey, anaerobic metabolism is the primary source of energy for high-intensity skating, transitions to higher speeds, and explosive efforts, such as accelerations, decelerations, and sprints (Hargreaves and Spriet 2020). CHO in the form of muscle glycogen is the dominant fuel source and is depleted at much higher rates in anaerobic versus aerobic pathways. Recently, Vigh-Larsen and colleagues (2020) established that marked skating fatigue was associated with the significant depletion of muscle glycogen. The greatest rate of depletion occurred within the first period of 5v5 scrimmage, after players skated approximately ~900 m of high-intensity distance. In the present study, players traveled approximately ~1000 m at high-intensity speed across regulation. In addition, small-sided 3v3 players accumulated more total distance (~6200 m) than the 5v5 players (~6000 m). Therefore, it is proposed that the development of fatigue from period 1 to periods 2 and 3 in the current investigation was due to significant depletion of muscle glycogen stores from baseline and did not appear to be affected by MR condition in regulation.

5.1.2 Overtime

In the present study, beneficial effects of CHO MR were observed in skating intensity, skating speed and explosive efforts in OT. There was no difference in total distance skated, but the distribution of distance within low- and high-intensity speeds varied between conditions. Players traveled less distance in zone 2, but greater distance at high-intensity, when MR with CHO versus PLA MR. In addition, peak speed was faster and a greater number of sprints were performed with CHO MR.

There is practical relevance in these findings, as measured values indicated performance enhancement with CHO MR in small-sided 3v3 scrimmage, and these values resemble those recorded in both 5v5 regulation play and 3v3 OT in a full-ice NHL hockey game (Lignell *et al.* 2018). In 5v5 play, average sprint distances ranged from 17-34 m, which in some cases is greater than the space athletes had to move in the present investigation. In NHL 3v3 OT, players skated less high-intensity distance (118 ± 17 m) than was observed in small-sided 3v3 OT (CHO: 224 ± 77 m, PLA: 185 ± 66 m). Likewise, average NHL OT sprint speed (24.5 ± 0.1 $km \cdot h^{-1}$) was remarkably similar to the average peak speed (24.6 ± 1.7 $km \cdot h^{-1}$) in the present study attained with CHO MR in small sided 3v3 scrimmage. Players have additional room to maneuver and accelerate in the former situation, thus it is feasible that the disparity between MR conditions in measures of external load could be even greater in a full-ice environment.

Outside of ice hockey, numerous earlier studies displayed evidence of enhanced performance with CHO MR in IHI exercise. In recreational men, CHO MR significantly increased peak and mean power in short (< 30 s), maximal cycle sprints (Beaven *et al* 2013; Phillips *et al.* 2014). In trained men, 10 m sprint running time was significantly faster (Clarke *et al.* 2017), and mean power over 48 min of IHI cycle exercise was significantly greater (Simpson *et al.* 2018), when subjects MR with CHO. Findings with greater ecological validity to stop-and-go sport have been presented in three studies in field sport athletes. In female soccer players, CHO MR improved speed in short shuttle sprint performance (4 x 9 m, 2 x 18 m) and approached significance (p = 0.069) (Přibyslavská *et al.* 2016). CHO MR did not affect repeated sprint performance in male soccer and rugby players (Dorling and Earnest 2013), but prolonged the onset of fatigue and reduced perceptions of effort in increasing-speed shuttle running (2 x 20 m) to exhaustion in male lacrosse players (Dolan *et al.* 2017).

The present findings along with others provide evidence that CHO MR may enhance muscular power production, which is required to facilitate rapid propulsion of skaters, and aid the transition to and acquisition of higher speeds (Cox *et al.* 1995). CHO MR may also help maintain power, which is equally important in ice hockey as players repeat several high-intensity bouts of activity per minute (Brocherie *et al.* 2018; Lignell *et al.* 2018; Douglas *et al.* 2019*a,b*). Due to frequent line changes, this intermittent pattern of work is continued across the entire game, making the ability to sustain external loads with minimal exhaustion highly favourable.

Additionally, the results of the present research demonstrated that earlier improvements in ice hockey performance observed with exogenous CHO ingestion may have been at least partially related to oral exposure to CHO. In recreational males, hydration with CES during 5v5 hockey significantly increased time at high effort and skating speed late in scrimmages (30-50 min), as well as improved post-scrimmage maximal shuttle sprint performance (total 126 m) (Linseman *et al.* 2014). In a cycling protocol designed to simulate the shifts in ice hockey games, exogenous CES improved voluntary work performed across three periods of hockey (Palmer *et al.* 2017*b*).

Though the present performance improvements induced with CHO MR in OT were not large, it is proposed that the collective effects could have a worthwhile impact on the outcome of ice hockey games that extend past regulation. In high-level hockey competition, OT is a common occurrence and the game is immediately won and ended by the team that scores first (Rosenberg *et al.* 2021). This structure is unforgiving to mistakes, which makes maximal effort and superior performance over the opponent compulsory for success. Therefore, the use of CHO MR as a potential physical performance aid could be extremely valuable in situations that extend past regulation.

5.1.3 Possible Explanation for External Load Improvements

Consumption of exogenous CHO has been established to enhance exercise performance prior to contributions of peripheral substrate availability being limiting in contracting muscle (Juekendrup *et al.* 1997; Carter *et al.* 2004a). Thus, it was theorized that afferent information pertaining to imminent fuel availability had the capability to modify efferent motor information (Gant *et al.* 2010; Turner *et al.* 2014). A special class of oral receptors that sense the energy content of CHO were identified and proven to facilitate increased excitability of brain neural regions involved with reward, motivation, and motor control during voluntary contraction and task-specific actions (Chambers *et al.* 2009; Gant *et al.* 2010; Turner *et al.* 2014; Lim *et al.* 2019). Essentially, the presence of CHO in the mouth increases sensorimotor cortex activity, which attenuates declines in motor function and neural drive to contracting muscle that are associated with fatigue (Taylor *et al.* 2006; Hargreaves *et al.* 2008; Gant *et al.* 2010; Turner *et al.* 2014). Notably, this response appears to be greatest when energy status is low (Gant *et al.* 2010; Turner *et al.* 2014; Durkin *et al.* 2021)

5.2 INTERNAL LOAD

5.2.1 Heart Rate and TRIMP

In the present study, there was no difference between MR conditions in peak HR, mean HR or TRIMP within the three regulation periods. However, all three metrics were greater in the second and third periods compared to the first, indicating the development of fatigue. In U18 AAA males, 3v3 was determined to be the most demanding small-sided game protocol (vs. 1v1, 2v2, 4v4), and based on HR, produced similar physiological intensity to regular 5v5 game shifts (Lauchame *et al.* 2017).

There were no differences in peak HR, mean HR or TRIMP between MR conditions in OT, despite a greater external load with CHO MR. So, in spite of more work being done with CHO MR, HR responses were not increased, and oral sensing of CHO did not appear to have an effect on physiological measures of internal load. However, dependent on LPS software, HR was observed across entire periods instead of a shift-by-shift basis. As a result, average HR and TRIMP were reflective of both active and rest time. It is possible that this could have confounded effects between MR conditions. Thus, future research should examine mean shift and recovery HRs separately (Jackson *et al.* 2016, 2017).

5.2.2 Ratings of Perceived Exertion

In regulation, RPE was higher in periods 2 and 3 compared to period 1, but there was no difference between MR conditions. There was also no difference between conditions in OT, despite enhanced physical performance with CHO MR.

In previous hockey research, ingestion of exogenous CHO effectively mitigated increasing RPE values over time while also enhancing physical performance (Linseman *et al.* 2014; Palmer *et al.* 2017*b*; Driscoll *et al.* 2020; McCarthy *et al.* 2020). However, in most cases this was in comparison to mild dehydration. Only one study has shown further benefit with CHO compared to hydration with water, but this was in goaltenders (McCarthy *et al.* 2020).

Nonetheless, the results of the present study in OT with the same RPE for greater work are a common observation in the majority CHO MR exercise research (Carter *et al.* 2004*b*; Chambers *et al.* 2009; Jeukendrup 2013). It has been known that oral sensing of CHO activates areas of the brain associated with reward and motivation. Thus, earlier studies proposed that CHO MR decreases athlete perceptions of effort and fatigue, which allows them to perform more work while identifying similar rates of exertion to PLA conditions. This effect may have contributed to the observable performance improvements with CHO MR in small-sided 3v3 ice hockey.

5.3 HOCKEY-SPECIFIC METRICS

MR conditions were randomized within lines and teams for every scrimmage. This limited the ability to make meaningful observations regarding hockey-specific metrics, as it is possible that one player's performance could have had a negative or positive effect on other players. In future, it may be advantageous to have one team perform MR with the same condition and the other team be a no MR control. This way the collective effects of CHO versus PLA MR on hockey-specific metrics could be compared between scrimmages.

No differences were found in goals, assists, or shot attempts between MR conditions within any regulation period in this study. In OT, players had a higher number of assists when MR with CHO versus PLA.

In previous work by our lab, it had been discovered that consumption of exogenous CES reduced the number of turnovers and improved pass completion in 5v5 scrimmage, indicating a possible central effect of exogenous CHO on mental acuity and decision making (Linseman *et al.*

2014). This was in comparison to a no-fluid condition, which made it impossible to determine whether these effects were due to increased cortical activity from oral sensing of CHO, provision of CHO as fuel for the brain, mitigation of dehydration, or some combination of these factors. However, in male and female basketball players, mental function measured by performance in a motor-skills test was significantly improved when CES was consumed compared to PLA during a modified LIST protocol (4 x 18 min; walking, jogging, running, jumping) (Welsh *et al.* 2002). Thus, it appears that exogenous CHO has at least some effect on sport-specific skills.

In addition to having better MR controls, it would be worthwhile to conduct further MR research in hydrated skaters in 5v5 hockey scrimmage to determine whether the oral-sensing of CHO might improve hockey-specific metrics when fatigue is exacerbated.

5.4 PRACTICAL APPLICATIONS

CHO MR is a simple practice that can easily be added to athlete nutrition and hydration regimes during ice hockey to facilitate heightened physical performance, maintain perceptions of effort and possibly improve decision making in situations where fatigue is greatest, such as the third period, OT, and shootouts. For similar reasons, CHO MR might also be a valuable practice prior to power plays and penalty kills. The ability to enhance speed and power production in these situations would be particularly advantageous, as the uneven number of players on the ice awards greater space and opportunities for offensive chances (Douglas and Kennedy 2020).

Though the results of this study demonstrated that ingestion of CHO is not necessary to attain beneficial effects, swallowing after MR may be a more realistic practice for many athletes in real-world competitions (Burke and Maughan 2015). Drinking a CES throughout IHI sport is simple way to introduce oral CHO exposure, but it can also help prevent or alleviate the negative effects of dehydration by replenishing fluids and electrolytes lost through sweat (Williams and

Rollo 2015). In addition, several IHI team sports have matches that exceed 60 min, at which point consumption of exogenous CHO would be an additional fuel source and contribute to CHO oxidation rates (Krings *et al.* 2017). It is possible that exogenous CHO could be beneficial before this time point in ice hockey, as there was extreme glycogen depletion across only 24 min of TOI in international 5v5 competition (Vigh-Larsen *et al.* 2020).

In spite of these benefits, there are still some instances where expectoration of MR solutions may be a favourable practice for some individuals. Although exercising under fasted conditions is generally discouraged in real-life competition scenarios, the behaviour was frequently observed at early morning practices in the college athlete demographic (Přibyslavská *et al.* 2016; Clarke *et al.* 2017; Dolan *et al.* 2017). Common reasons for athletes to avoid CHO consumption before or during training and competition include time constraints and fear of experiencing GI discomfort. CHO MR therefore provides an outlet to attain the benefits of oral CHO exposure whilst ingesting minimal or no CHO.

There are not any clear performance decrements associated with carbohydrate MR identified in IHI exercise or sport literature. Ideally, carbohydrate supplementation practices (MR and/or ingestion) should be customized based on individual preferences and designed to meet the needs of each athlete (Burke *et al.* 2011). Regimes should be tailored frequently to correspond to the requirements of daily training and anticipated workloads.

5.5 LIMITATIONS AND FUTURE DIRECTIONS

The majority of limitations in this thesis were a product of the COVID-19 pandemic. Social distancing guidelines and restrictions on in-person gatherings affected study length, number of trials, trial size and scrimmage protocol.

In the initial design for this study, scrimmages were meant to replicate elite male competition and take place on full-ice. Regulation periods would have been the same duration, but 5v5. OT periods would have been 3v3 and shortened to ~6 min instead of 12 min, since OT in the elite male population is typically ≤ 5 min. Teams would still rotate two lines, but shift and rest length would be only 1 min.

Though small-sided 3v3 hockey is played at high-intensity, the protocol has less ecological validity as movement patterns and game play strategies vary from conventional 5v5 competition (Lachaume *et al.* 2017). Increased proximity between skaters meant there was rarely opportunities for breakaways and odd-man rushes compared to full-ice hockey. In addition, reduced space may have prevented several athletes from achieving their true maximum skating speed and limited the distance and duration of high-intensity actions.

The values of many external load variables may have also been manipulated by shift-length (2 min), which was substantially longer than typical shift length (30-80 s) in elite male 5v5 competition (Brocherie *et al.* 2018; Lignell *et al.* 2018; Vigh-Larsen *et al.* 2020). In international U20 males, significant disruption of anaerobic energy pathways occurred within 1-minute of playing time (Vigh-Larsen *et al.* 2020). Thus, it is plausible that by the second minute of shifts skaters in the present study were heavily reliant on the aerobic system, and under these circumstances skating at low-intensities would be most feasible (Hargreaves and Spriet 2020).

For these reasons future research should adopt a 5v5 scrimmage protocol and a work-to-rest ratios that mimics competition to strengthen the validity of the present study findings. Tailoring the original study design, teams should have 3 lines each. This would allow for 2 min of rest between shifts, which is more characteristic of elite male game-play (Vigh-Larsen *et al.* 2020). The inclusion of an OT period would remain beneficial, as it is a common occurrence in professional hockey (Rosenberg *et al.* 2021). However, there are two possible approaches to take. The first adheres to the original study protocol, which mimics regular season OT in elite males. The second approach would be to have a fourth 20-min period of 5v5 hockey, as this is the OT period structure used in playoffs. Performance in the latter is especially important, as games have particularly high-stakes, and loss can lead to elimination of a team from the post-season.

Another component of the initial design that was modified was the number of conditions. In addition to CHO and PLA MR, there was supposed to be CHO and PLA ingestion in trials. This would have targeted the findings of previous hockey research, which questioned whether the performance benefits observed with ingestion of exogenous CHO were due to oral exposure to CHO alone, or if there might be an additive effect with MR and ingestion (Linseman *et al.* 2014; Palmer *et al.* 2017b; McCarthy *et al.* 2020). Future research should include parameters of CHO MR alone, CHO ingestion alone, and combination of CHO MR and ingestion in hydrated players to gain a better understanding of how to optimally administer exogenous CHO to enhance ice hockey performance.

Since the effects of CHO MR were not apparent until late in the scrimmage protocol, oral sensing of CHO in the first and second period may have no value. This was a similar observation in CES ingestion trials in earlier research (Linseman *et al.* 2014). The magnitude of effects invoked from oral sensing of CHO appear to be related to state of fatigue (Gant *et al.* 2010; Turner *et al.* 2014; Durkin *et al*. 2021). Moving forward, it should be examined whether similar performance enhancements can be induced when MR is performed only in the third and OT periods. If this protocol is effective, it would be a more efficient practice in real world competitions.

A strength of the current protocol was its sport-specificity, but it could be advantageous to include controllable performance tests between scrimmage periods in future studies. This would permit analyses of the effects of CHO MR on external load without movement pattern biases from game score or opposition skill. This protocol has previously been implemented in other ice hockey research (Linseman *et al.* 2014; Vigh-Larsen *et al.* 2020).

In addition to the above recommendations, future ice hockey and MR research would benefit considerably from the inclusion of female participants. There is a paucity of MR research that includes female participants, including only one IHI sport study (Přibyslavská *et al.* 2016). There was evidence in the latter that CHO MR could improve performance in female athletes, but this cannot be confirmed until further research is performed in this population. In the general pool of ice hockey literature, there is slightly greater number of studies that examine the female population (Jackson *et al.* 2016; Douglas *et al.* 2019*a,b*). However, these are predominately characterization studies, which therefore identifies a gap in the literature pertaining to the use of performance enhancing strategies and substances in female ice hockey players.

5.6 CONCLUSIONS

This is the first study to demonstrate multiple significant physical performance enhancements with CHO MR in a real-world, IHI sport scrimmage, and the only study to examine CHO MR in ice hockey. There was considerable development of fatigue in regulation, but benefits of CHO MR were not observed until OT. In the latter, distance skated at high-intensity, peak speed and number of sprints were higher, and distance skated at very slow speed was lower, when players MR with CHO compared to PLA. It is proposed that improvements in external load were associated with increased motor function stemming from alteration of central control by oral CHO receptors. Despite greater external load in OT with CHO MR, there were no differences in physiological or psychophysiological measures of internal load between MR conditions. However, evidence suggests that CHO MR may have decreased athlete perceptions of effort, allowing them to perform at higher workloads while identifying similar levels of exertion to PLA. The number of assists in OT were also increased with CHO MR, but randomization of subject conditions within lines makes it difficult to confirm whether CHO MR might improve other aspects of hockey-specific performance. The movement patterns and strategies of small-sided 3v3 hockey vary greatly from standard 5v5 competition, therefore future MR research is warranted in this area. Nonetheless, there is apparent improvement in speed and power production across short distances and durations with CHO MR, which is advantageous in any style of scrimmage. In conclusion, the results of this study suggest that CHO MR may be a valuable practice to protect against decrements in external load with increased playing time in ice hockey.

REFERENCES

Akermark C, Jacobs I, Rasmusson M, Karlsson J. Diet and muscle glycogen concentration in relation to physical performance in Swedish elite ice hockey players. *Int J Sports Nutr*. 1996;6(3):272–284.

Banister EW, Calvert TW. Planning for future performance: implications for long term training. *Can J Appl Sports Sci.* 1980;5(3):170-176.

Barris S, Button C. A review of vision-based motion analysis in sport. *Sports Med*. 2008;38(12):1025-1043.

Batchelder BC, Krause AB, Seegmiller JG, Starkey CA. GI temp increases and hypohydration exists after collegiate men's ice hockey participation. *J Strength Cond Res.* 2010;24(1):68–73.

Beaven CM, Maulder P, Pooley A, Kilduff L, Cook C. Effects of caffeine and carbohydrate mouth rinses on repeated sprint performance. *Appl Physiol Nutr Metab.* 2013; 38(6):633-637.

Bigg JL, Gamble AS, Vermeulen TF, Boville SM, Eskedjian GS, Palmer MS, Spriet LL. Sweat loss and hydration habits of female Olympic, varsity and recreational ice hockey players. *Int J Sports Med.* 2019;40(06):416-422.

Boville S. Effects of on-ice mild dehydration on thermoregulation, performance and mental fatigue in female ice hockey players. MSc Thesis, University of Guelph; 2015.

Boyd LJ, Ball K, Aughey RJ. The reliability of MinimaxX accelerometers for measuring physical activity in Australian football. *Int J Sports Physiol Perform.* 2011;6(3):311-321.

Bracko MR, Fellingham GW, Hall LT, Fisher AG, Cryer W. Performance skating characteristics of professional ice hockey forwards. *Res Sports Med: Int J.* 1998;8(3):251-263.

Brietzke C, Franco-Alvarenga PE, Coelho-Júnior HJ, Silveira R, Asano RY, Pires FO. Effects of carbohydrate mouth rinse on cycling time trial performance: a systematic review and meta-analysis. *Sports Med.* 2019;49(1):57-66.

Brocherie F, Girard O, Millet GP. Updated analysis of changes in locomotor activities across periods in an international ice hockey game. *Biol Sport*. 2018;35(3):261–267.

Burke LM, Maughan RJ. The Governor has a sweet tooth–mouth sensing of nutrients to enhance sports performance. *Eur J Sports Sci*. 2015;15(1):29-40.

Burr JF, Jamnik VK, Dogra S, Gledhill N. Evaluation of jump protocols to assess leg power and predict hockey playing potential. *J Strength Cond Res*. 2007;21(4):1139-1145.

Burr JF, Jamnik RK, Baker J, Macpherson A, Gledhill N, McGuire EJ. Relationship of physical fitness test results and hockey playing potential in elite-level ice hockey players. *J Strength Cond Res*. 2008;22(5):1535-1543.

Burr JF, Slysz JT, Boulter MS, Warburton DER. Influence of active recovery on cardiovascular function during ice hockey. *Sports Med-Open.* 2015;1(27):1-8.

Carter JM, Jeukendrup AE, Mann CH, Jones DA. The effect of glucose infusion on glucose kinetics during a 1-h time trial. *Med Sci Sports Exerc*. 2004a;36(9):1543-1550.

Carter JM, Jeukendrup AE, Jones DA. The effect of carbohydrate mouth rinse on 1-h cycle time trial performance. *Med Sci Sports Exerc.* 2004b;36(12):2107-2111.

Chambers ES, Bridge MW, Jones DA. Carbohydrate sensing in the human mouth: effects on exercise performance and brain activity. *J Physiol*. 2009;587(8):1779-1794.

Che Muhamed AM, Mohamed NG, Ismail N, Aziz AR, Singh R. Mouth rinsing improves cycling endurance performance during Ramadan fasting in a hot humid environment. *Appl Physiol Nutr Metab*. 2014;39(4):458-464.

Clarke ND, Hammond S, Kornilios E, Mundy PD. Carbohydrate mouth rinse improves morning high-intensity exercise performance. *Eur J Sports Sci.* 2017;17(8):955-963.

Coyle EF, Coggan AR, Hemmert MK, Ivy JL. Muscle glycogen utilization during prolonged strenuous exercise when fed carbohydrate. *J Appl Physiol*. 1986;61(1):165-172.

Cox MH, Miles DS, Verde TJ, Rhodes EC. Applied physiology of ice hockey. *Sports Med*. 1995;19(3):184–201.

Devenney S, Mangan S, Shortall M, Collins K. Effects of carbohydrate mouth rinse and caffeine on high-intensity interval running in a fed state. *Appl Physiol Nutr Metab.* 2018;43(5):517-521.

Dillman CJ, Stockholm AJ, Greer N. Movement and velocity patterns of ice hockey players during a game. In: *Sports Biomechanics Proceedings of the international symposium of biomechanics in sports*; Colorado Springs, CO.1984;189-194.

Dolan P, Witherbee KE, Peterson KM, Kerksick CM. Effect of carbohydrate, caffeine, and carbohydrate+ caffeine mouth rinsing on intermittent running performance in collegiate male lacrosse athletes. *J Strength Cond Res.* 2017;31(9):2473-2479.

Dorling JL, Earnest CP. Effect of carbohydrate mouth rinsing on multiple sprint performance. *J Int Soc Sports Nutr.* 2013;10(1):1-8.

Douglas A, Johnston K, Baker J, Rotondi MA, Jamnik VK, Macpherson AK. On-ice measures of external load in relation to match outcome in elite female ice hockey. *Sports*. 2019*a*;7(7):173.

Douglas A, Rotondi MA, Baker J, Jamnik VK, Macpherson AK. On-ice physical demands of world-class women's ice hockey: from training to competition. *Int J Sports Physiol Perf.* 2019*b*;14(9):1227-1232.

Douglas AS, Kennedy CR. Tracking in-match movement demands using local positioning system in world-class men's ice hockey. *J Strength Cond Res.* 2020;34(3):639-646.

Driscoll RL, McCarthy DG, Palmer MS, Spriet LL. Mild dehydration impaired intermittent sprint performance and thermoregulation in females. *Appl Physiol Nutr Metab.* 2020;45(9):1045-1048.

Durkin M, Akeroyd H, Holliday A. Carbohydrate mouth-rinse improves resistance exercise capacity in glycogen lowered state. *Appl Physiol Nutr Metab.* 2021;46(2):126-132.

Fares EJ, Kayser B. Carbohydrate mouth rinse effects on exercise capacity in pre-and postprandial States. *J Nutr Metab.* 2011;1-6.

Foskett A, Williams C, Boobis L, Tsintzas K. Carbohydrate availability and muscle energy metabolism during intermittent running. *Med Sci Sports Exerc.* 2008;40(1):96-103.

Gaitanos GC, Williams C, Boobis LH, Brooks S. Human muscle metabolism during intermittent maximal exercise. *J Appl Physiol.* 1993;75(2):712-719.

Gamble ASD, Bigg JL, Vermeulen TF, Boville SM, Eskedjian GS, Jannas-Vela S, Whitfield J, Palmer MS, Spriet LL. Estimated sweat loss, fluid and carbohydrate intake, and sodium balance of male major junior, AHL, and NHL players during on-ice practices. *Int J Sports Nutr Exerc Metab*. 2019;29(6):612-619.

Gamble ASD, Bigg JL, Pignanelli C, Nyman DLE, Burr JF, Spriet LL. Reliability and validity of an indoor local positioning system for measuring external load in ice hockey players. *Unpublished;* 2021.

Gant N, Stinear CM, Byblow WD. Carbohydrate in the mouth immediately facilitates motor output. *Brain Res*. 2010;1350:151-158.

Green H, Bishop P, Houston M, McKillop R, Norman R, Stothart P. Time-motion and physiological assessments of ice hockey performance. *J Appl Physiol.* 1976;40(2):159-163.

Green HJ. Glycogen depletion patterns during continuous and intermittent ice skating. *Med Sci Sports*. 1978;10(3):183-187.

Green HJ, Daub BD, Painter DC, Thomson JA. Glycogen depletion patterns during ice hockey performance. *Med Sci Sports*. 1978;10(4):289–293.

Green HJ. Metabolic aspects of intermittent work with specific regard to ice hockey. *Can J Appl Sport Sci.* 1979 Mar 1;4(1):29-34.

Greenhaff PL, Nevill ME, Soderlund K, Bodin K, Boobis LH, Williams C, Hultman E. The metabolic responses of human type I and II muscle fibres during maximal treadmill sprinting. *J Physiol.* 1994;478(1):149-155.

Hargreaves M. Fatigue mechanisms determining exercise performance: integrative physiology is systems biology. *J App Physiol*. 2008;104(5):1541-1542.

Hargreaves M, Spriet LL. Skeletal muscle energy metabolism during exercise. *Nat Metab*. 2020;2(9):817-828.

Hoppe MW, Baumgart C, Polglaze T, Freiwald J. Validity and reliability of GPS and LPS for measuring distances covered and sprint mechanical properties in team sports. *PloS One*. 2018;13(2):e0192708.

Jackson J, Snydmiller G, Game A, Gervais P, Bell G. Movement characteristics and heart rate profiles displayed by female university ice hockey players. *Int J Kin Sports Sci.* 2016;4(1):43-54.

Jackson J, Snydmiller G, Game A, Gervais P, Bell G. Investigation of positional differences in fitness of male university ice hockey players and the frequency, time spent and heart rate of movement patterns during competition. *Int J Kin Sports Sci.* 2017;5(3):6-15.

Jeukendrup AE. Carbohydrate intake during exercise and performance. *Nutrition*. 2004;20(7-8):669-677.

Jeukendrup AE. Oral carbohydrate rinse: placebo or beneficial. *Curr Sports Med Rep.* 2013;12(4):222-227.

Jeukendrup A, Brouns FJ, Wagenmakers AJ, Saris WH. Carbohydrate-electrolyte feedings improve 1 h time trial cycling performance. *Int J Sports Med.* 1997;18(2):125-129.

Jentjens RL, Achten J, Jeukendrup AE. High oxidation rates from combined carbohydrates ingested during exercise. *Med Sci Sports Exerc.* 2004;36(9):1551-1558.

Kasper AM, Cocking S, Cockayne M, Barnard M, Tench J, Parker L, McAndrew J, Langan-Evans C, Close GL, Morton JP. Carbohydrate mouth rinse and caffeine improves high-intensity interval running capacity when carbohydrate restricted. *Eur J Sports Sci.* 2016;16(5):560-568.

Kayser B. Exercise starts and ends in the brain. *Eur J Appl Physiol.* 2003;90(3):411-419.

Kringelbach ML. Food for thought: hedonic experience beyond homeostasis in the human brain. *Neuroscience*. 2004;126(4):807-819.

Krings BM, Peterson TJ, Shepherd BD, McAllister MJ, Smith JW. Effects of carbohydrate ingestion and carbohydrate mouth rinse on repeat sprint performance. *Int J Sport Nutr Exerc*. 2017;27(3);204-212.

Krustrup P, Mohr M, Amstrup T, Rysgaard T, Johansen J, Steensberg A, Pedersen PK, Bangsbo J. The yo-yo intermittent recovery test: physiological response, reliability, and validity. *Med Sci Sports Exerc*. 2003;35(4):697-705.

Krustrup P, Mohr M, Steensberg A, Bencke J, Kjaer M, Bangsbo J. Muscle and blood metabolites during a soccer game: implications for sprint performance. *Med Sci Sports Exerc*. 2006*a*;38(6):1165–1174

Krustrup P, Mohr M, Nybo L, Jensen JM, Nielsen JJ, Bangsbo J. The Yo-Yo IR2 test: physiological response, reliability, and application to elite soccer. *Med Sci Sports Exerc.* 2006*b*;38(9):1666–1673.

Lachaume CM, Trudeau F, Lemoyne J. Energy expenditure by elite midget male ice hockey players in small-sided games. *Int J Sports Sci Coach.* 2017;12(4):504-513.

Laurent CM, Fullenkamp AM, Morgan AL, Fischer DA. Power, fatigue, and recovery changes in national collegiate athletic association division I hockey players across a competitive season. *J Strength Cond Res*. 2014;28(12):3338-3345.

Lignell E, Fransson D, Krustrup P, Mohr M. Analysis of high-intensity skating in top-class ice hockey match-play in relation to training status and muscle damage. *J Strength Cond Res*. 2018;32(5):1303–1310.

Lim J, Pullicin AJ. Oral carbohydrate sensing: Beyond sweet taste. *Physiol Behav.* 2019;202:14-25.

Linseman ME, Palmer MS, Sprenger HM, Spriet LL. Maintaining hydration with a carbohydrate-electrolyte solution improves performance, thermoregulation, and fatigue during an ice hockey scrim- mage. *Appl Physiol Nutr Metab*. 2014;39(11):1214–1221.

Logan-Sprenger HM, Palmer MS, Spriet LL. Estimated fluid and sodium balance and drink preferences in elite male junior players during an ice hockey game. *Appl Physiol Nutr Metab.* 2011;36(1):145-152.

McCarthy DG, Wickham KA, Vermeulen TF, Nyman DL, Ferth S, Pereira JM, Larson DJ, Burr JF, Spriet LL. Impairment of thermoregulation and performance via mild dehydration in ice hockey goaltenders. *Int J Sports Physiol Perf.* 2020;15(6):833-840.

McConell GK, Canny BJ, Daddo MC, Nance MJ, Snow RJ. Effect of carbohydrate ingestion on glucose kinetics and muscle metabolism during intense endurance exercise. *J App Physiol.* 2000;89(5):1690-1698.

McLaren SJ, Macpherson TW, Coutts AJ, Hurst C, Spears IR, Weston M. The relationships between internal and external measures of training load and intensity in team sports: a meta-analysis. *Sports Med.* 2018;48(3):641-658.

Montpetit RR, Binette P, Taylor AW. Glycogen depletion in a game-simulated hockey task. *Can J Appl Sport Sci*. 1979;4(1):43–45.

Montgomery DL. Physiology of ice hockey. *Sports Med*. 1988;5(2):99–126.

Montgomery DL. Physiological profile of professional hockey players-a longitudinal comparison. *Appl Physiol Nutr Metab.* 2006;31(3):181-185.

Nicholas CW, Williams C, Lakomy HK, Phillips G, Nowitz A. Influence of ingesting a carbohydrate-electrolyte solution on endurance capacity during intermittent, high-intensity shuttle running. *J Sports Sci.* 1995;13(4):283-290.

Nicholas CW, Tsintzas KO, Boobis LE, Williams CL. Carbohydrate-electrolyte ingestion during intermittent high-intensity running. *Med Sci Sports Exerc.* 1999;31(9):1280-1286.

Nicholas CW, Nuttall FE, Williams C. The Loughborough Intermittent Shuttle Test: a field test that simulates the activity pattern of soccer. *J Sports Sci.* 2000;18:97–104.

Noonan B, Mack G, Stachenfeld N. The effects of hockey protective equipment on high-intensity intermittent exercise. *Med Sci Sports Exerc.* 2007;39(8):1327-1335.

O'Doherty J, Rolls ET, Francis S, Bowtell R, McGlone F. Representation of pleasant and aversive taste in the human brain. *J Neurophysiol.* 2001;85(3):1315-1321.

Ørtenblad N, Nielsen J, Saltin B, Holmberg HC. Role of glycogen availability in sarcoplasmic reticulum Ca2+ kinetics in human skeletal muscle. *J Physiol*. 2011;589(Pt 3):711–725.

Palmer MS, Heigenhauser GJ, Duong M, Spriet LL. Mild dehydration does not influence performance or skeletal muscle metabolism during simulated ice hockey exercise in men. *Int J Sports Nutr Exerc Metab.* 2017a;27(2):169-177.

Palmer MS, Heigenhauser G, Duong M, Spriet LL. Ingesting a sports drink enhances simulated ice hockey performance while reducing perceived effort. *Int J Sports Med*. 2017b;38(14):1061–1069.

Parolin ML, Chesley A, Matsos MP, Spriet LL, Jones NL, Heigenhauser GJ. Regulation of skeletal muscle glycogen phosphorylase and PDH during maximal intermittent exercise. *Am J Physiol End Metab.* 1999;40:E890-E900.

Peart DJ. Quantifying the effect of carbohydrate mouth rinsing on exercise performance. *J Strength Cond Res*. 2017;31(6):1737-1743.

Peterson BJ, Fitzgerald JS, Dietz CC, Ziegler KS, Ingraham SJ, Baker SE, Snyder EM. Aerobic capacity is associated with improved repeated shift performance in hockey. *J Strength Cond Res.* 2015;29(6):1465-1472.

Phillips SM, Turner AP, Gray S, Sanderson MF, Sproule J. Ingesting a 6% carbohydrate-electrolyte solution improves endurance capacity, but not sprint performance, during intermittent, high-intensity shuttle running in adolescent team games players aged 12–14 years. *Eur J Appl Physiol.* 2010;109(5):811-821.

Phillips SM, Findlay S, Kavaliauskas M, Grant MC. The influence of serial carbohydrate mouth rinsing on power output during a cycle sprint. *J Sports Sci Med.* 2014;13(2):252.

Plews DJ, Scott B, Altini M, Wood M, Kilding AE, Laursen PB. Comparison of heart-rate-variability recording with smartphone photoplethysmography, Polar H7 chest strap, and electrocardiography. *Int J Sports Physiol Perf.* 2017;12(10):1324-1328.

Přibyslavská V, Scudamore EM, Johnson SL, Green JM, Stevenson Wilcoxson MC, Lowe JB, O'Neal EK. Influence of carbohydrate mouth rinsing on running and jumping performance during early morning soccer scrimmaging. *Eur J Sports Sci.* 2016;16(4):441-447.

Quinney HA, Dewart R, Game A, Snydmiller G, Warburton D, Bell G. A 26 year physiological description of a National Hockey League team. *Appl Physiol Nutr Metab.* 2008;33(4):753-760.

Roell M, Roecker K, Gehring D, Mahler H, Gollhofer A. Player monitoring in indoor team sports: concurrent validity of inertial measurement units to quantify average and peak acceleration values. *Front Physiol.* 2018;9:141.

Rollo I, Williams C, Gant N, Nute M. The influence of carbohydrate mouth rinse on self-selected speeds during a 30-min treadmill run. *Int J Sports Nutr Exerc Metab.* 2008;18(6):585-600.

Rollo IA, Cole M, Miller R, Williams C. Influence of mouth rinsing a carbohydrate solution on 1-h running performance. *Med Sci Sports Exerc.* 2010;42(4):798-804.

Rosenberg SI, Baker HP, Rizzi A, Terry MA, Tjong VK. Frequency of overtime and consecutive games and their impact on injury rate in the National Hockey League (NHL). *Physician Sportsmed.* 2020;1-6.

Scott MT, Scott TJ, Kelly VG. The validity and reliability of global positioning systems in team sport: a brief review. *J Strength Cond Res.* 2016;30(5):1470-1490.

Serpiello FR, Hopkins WG, Barnes S, Tavrou J, Duthie GM, Aughey RJ, Ball K. Validity of an ultra-wideband local positioning system to measure locomotion in indoor sports. *J Sports Sci.* 2018;36(15):1727-1733.

Sigmund M, Kohn S, Sigmundová D. Assessment of basic physical parameters of current Canadian-American National Hockey League (NHL) ice hockey players. *Acta Gymnica*. 2016;46(1):30-36.

Simard C, Tremblay A, Jobin M. Effects of carbohydrate intake before and during an ice hockey game on blood and muscle energy substrates. *Res Q Exerc Sport.* 1988;59(2):144-147.

Simpson GW, Pritchett R, O'Neal ER, Hoskins G, Pritchett K. Carbohydrate mouth rinse improves relative mean power during multiple sprint performance. *Int J Exerc Sci.* 2018;11(6):754-763.

Stanula A, Roczniok R, Maszczyk A, Pietraszewski P, Zając A. The role of aerobic capacity in high-intensity intermittent efforts in ice-hockey. *Biol Sport*. 2014;31(3):193.

Stetter BJ, Buckeridge E, Nigg SR, Sell S, Stein T. Towards a wearable monitoring tool for in-field ice hockey skating performance analysis. *Eur J Sports Sci.* 2019;19(7):893-901.

Taylor JL, Todd G, Gandevia SC. Evidence for a supraspinal contribution to human muscle fatigue. *Clin Exp Pharm Physiol*. 2006;33(4):400-405.

Thompson KM, Safadie A, Ford J, Burr JF. Off-ice resisted sprints best predict all-out skating performance in varsity hockey players. *J Strength Cond Res.* 2020.

Triplett AN, Ebbing AC, Green MR, Connolly CP, Carrier DP, Pivarnik JM. Changes in collegiate ice hockey player anthropometrics and aerobic fitness over 3 decades. *Appl Physiol Nutr Metab.* 2018;43(9):950-955.

Turner CE, Byblow WD, Stinear CM, Gant N. Carbohydrate in the mouth enhances activation of brain circuitry involved in motor performance and sensory perception. *Appetite*. 2014;80:212-219.

Ulmer JG, Tomkinson GR, Short S, Short M, Fitzgerald JS. Test-retest reliability of TRIMP in collegiate ice hockey players. *Biol Sport.* 2019;36(2):191.

Van Iterson EH, Fitzgerald JS, Dietz CC, Snyder EM, Peterson BJ. Reliability of triaxial accelerometry for measuring load in men's collegiate ice hockey. *J Strength Cond Res.* 2017;31(5):1305-12.

Vigh-Larsen JF, Beck JH, Daasbjerg A, Knudsen CB, Kvorning T, Overgaard K, Andersen TB, Mohr M. Fitness characteristics of elite and subelite male ice hockey players: A cross-sectional study. *J Strength Cond Res.* 2019;33(9):2352-2360.

Vigh-Larsen JF, Ermidis G, Rago V, Randers MB, Fransson D, Nielsen JL, Gliemann L, Piil JF, Morris NB, De Paoli FV, Overgaard K. Muscle metabolism and fatigue during simulated ice hockey match-play in elite players. *Med Sci Sports Exerc.* 2020;52(10):2162-2171.

Welsh RS, Davis JM, Burke JR, Williams HG. Carbohydrates and physical/mental performance during intermittent exercise to fatigue. *Med Sci Sports Exerc.* 2002;34(4):723-731.

Whitham M, McKinney J. Effect of a carbohydrate mouthwash on running time-trial performance. *J Sports Sci.* 2007;25(12):1385-1392.

Williams C, Rollo I. Carbohydrate nutrition and team sport performance. *Sports Med*. 2015;45(1):13-22.