SPORTS SCIENCE: TOOLS AND TRANSLATION FOR PARA-ATHLETES

BY

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THESIS

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ABSTRACT

Sports scientists employ a variety of validated tools for the identification of numerous physiological and performance markers that can assist in the advancement of knowledge pertaining to athletic events, thus providing critical information to serve in improving competitiveness and reducing instances of injury. As the Paralympic Games continue to grow in depth and popularity, with more athletes competing in each subsequent Games alongside increased media coverage, tools for improving athletic performance need to be evaluated for their utility within the para-athlete population. The wheelchair marathon (WCM) is an important subset within the Paralympic program as this sport provides a high level of financial opportunities and media platform for top finishers that should be expected to expand exposure to and awareness of the sport, indirectly serving to influence sport entrance. While the foot race component of the marathon has been defined as a traditional endurance-type activity, leading to the generation of well-defined metabolic and exercise recommendations, the WCM, due to several factors, may differ from its counterpart. It is therefore integral to characterize the metabolic and physiological demands of the WCM in order to develop evidence-based guidelines to advance the training and nutritional strategies undertaken by these para-athletes. To do this, it is important to investigate the utility of commonly used sports science tools within the able-bodied population for their validity within the para-athlete population.

This thesis aims to explore two sports science tools and discusses their potential utility for para-athletes who compete in the WCM. Specifically, core temperature response to chilled whole food ingestion, and recovery kinetics as measured by lactate responses, may provide useful information for the WCM, yet have not been explored in the para-athlete.

We show that ingestion of a chilled whole food (potatoes), was effective at reducing core temperature in highly trained, able-bodied cyclists. These results implicate a potential opportunity to use chilled nutrition products in performance settings with para-athletes. Future studies need to explore this in para-athletes to understand the effects and the limitations from such a strategy.

We also show that an elite, female WCMer experienced early (time=5 min.) maximal lactate concentration following an all-out 1-minute exercise bout and that her total lactate concentration after 60-minutes of inactivity was still elevated from baseline. More participants are needed to ascertain what these data mean in terms of the physiological demands of the WCM.

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CHAPTER 1: UTILITY OF COMMONLY UTILIZED TOOLS WITHIN ABLE-BODIED ATHLETE POPULATION FOR APPLICATION IN PARA-ATHLETE

Introduction

This thesis aims to describe the unique characteristics of wheelchair marathoners (WCMer), who represent a subset within the para-athlete population, in the context of the associated considerations required for the application of commonly used sports science tools into the sport. This chapter serves as a general introduction to sports science, para-athletes (in particular, the WCMer) and two commonly used tools that provide application for performance in addition to the specific aims of the current thesis.

Sports Science

At the inaugural congress of the Australian Association for Exercise and Sports Science in 2006, a panel of experts with credentials of both academic and applied backgrounds defined sports science research as the generation of evidence that is relevant to sport or can be applied in the sporting environment to enhance performance or reduce the incidence of injury (Bishop et al., 2006). Therefore, the field should be thought of as multidisciplinary; incorporating principles of physiology, psychology, biomechanics and biochemistry to form evidence-based recommendations to help athletes and coaches train and compete optimally.

Para-Athletes: Wheelchair Marathoners

Of its important contributions, sports science has led to a better understanding of how the nature of an exercise bout may predict the ensuing metabolic demands on the body, thereby providing useful information to practitioners and athletes to guide optimal fuel selection and timing. Specifically, endurance-type, sprint-type, and intermittent prolonged exercise events have been thoroughly characterized in the literature (Nevill et al., 1993), (Joyner & Coyle, 2008), (A. E. Jeukendrup et al., 2000a), (Coyle, 1999a), (PADILLA et al., 2000), (Coyle, 1999b) (A. Jeukendrup & Diemen, 1998), (Bangsbo et al., 1992), (Esposito et al., 2004), (Ekblom, 1986), (Krustrup et al., 2004) resulting in well-established nutritional recommendations to support sport performance. While extensive investigations into performance by sports scientists have led to identifying the fundamental metabolic systems contributing to ATP demand, and how exercise-induced alterations ought to be enhanced through nutritional and exercise interventions, the bulk of this work has been done in able-bodied (AB) athletes leaving far less to be known about the para-athlete. Para-athletes are defined as athletes who have one of ten eligible impairment types as classified by the International Paralympic Committee, encompassing a wide range of impairment types and levels including spinal cord injuries, amputations, cerebral palsy and acquired brain injuries, visual and hearing impairments, short stature, multiple sclerosis (International Paralympic Committee, n.d.)(International Paralympic Committee, n.d.)(International Paralympic Committee, n.d.)(International Paralympic Committee, n.d.)(International Paralympic Committee, n.d.)(International Paralympic Committee, n.d.).

Since debuting in 1960, the Paralympic Games have continued to offer more events and host larger numbers of para-athletes in each consecutive Games (Robert Lewis, 2021). Within this program of adaptive sports, WCMers remain an important subset. Indeed, the introduction of the WCM into the Abbott World Marathon Major series in 2017 improved financial opportunities for WCMers by degrees of tens of thousands of dollars (World Marathon Majors, n.d.) in addition to increasing the frequency of top tier competition available to the athletes. WCMers are financially incentivized to perform at all 6 (7 in a Paralympic Games year) major marathons each year, which is a far greater number than the traditional para athletics calendar offers, which consists of events mainly in the summer and offers little compensation in terms of monetary prize awards. Prize purses for the WCM at the individual major marathons have also seen gradual increases since 2017, allowing solvency for many athletes who compete in other sports as part of their national teams as well as improving sponsorship opportunities. Furthermore, this series has served to increase media representation of WCMers, and in doing so should be expected to increase the knowledge of, interest in, and access to the WCM globally. Combined, these figures highlight the growing importance of characterizing this understudied sport in order to develop optimized training and nutritional guidelines to support the increasing number of participants.

Importantly, the WCMer may have unique metabolic needs when compared to their AB counterparts, and even to para-athletes competing in other upper body sports such as handcycling. Many factors lead to these variances including gastrointestinal dysmotility resulting from spinal cord injury (SCI), altered thermal regulation below injury level, predominant reliance upon smaller muscle groups of upper body to perform exercise (in addition to everyday activities), and even the physical positioning inside of the sports chair that may lead to increased gastric discomfort during exercise. Moreover, the nature of the race itself must be distinguished from the able-bodied foot race (Olympics.NBCSports,n.d.)(Knechtle et al., 2012). Specifically, the world record for men's and women's WCM is 1:17:47 and 1:35:42, respectively, compared to the AB men's and women's of 2:01.09 and 2:14:04/ 2:17:01 (the International Amateur Athletics Federation recognizes two world records for women; one for combined women's and men's race and one for a women's only marathon). Notably, course profiles, climate and field composition greatly influence leading times. For example, on non-world record eligible courses, the fastest WCM recorded (termed world bests) are 1:18:04 and 1:27:31 for males and females, respectively. Of note, the male athlete who achieved 1:18:04 took a wrong turn on the course which may explain why the male world best is actually slower than the male world record (IPC.org).

Additionally, while drafting plays a role in the foot race, this conservation strategy remains a significant element in the WCM and would theoretically enable the athletes to complete competitive times at a more metabolically economical intensity, thus lowering energy demands of the exercise. Finally, biomechanical proficiency is a key aspect in this event, and remains an important difference from upper body cranking exercises which have less dependence on technique. Of course, all of these factors will affect each athlete differently based on the exact level of injury or position in the race (i.e., leading or drafting), but must be considered to influence energy needs of this event.

It is important to identify and synthesize these factors in order to recognize the contribution of various metabolic systems at play within a WCM. Understanding how much and when an athlete will be able to apply nutritional interventions to support marathon performance could significantly enhance this increasingly popular event and should therefore continue to be a topic of priority by sports and nutrition scientists. A working knowledge of metabolic contributions to multiple exercise types is critical to understanding the nutritional needs of this sport. However, factoring in the unique physiological demands of the WCM must still underpin concluding findings, i.e., muscle groups being used, GI-motility and thermoregulatory variations.

Sports Science Tools

Performance may be impacted by many variables, involving intrinsic (meaning within the body) as well as extrinsic (relating to the external environment) factors. For example, while carbohydrate availability, hydration and anthropometric characteristics can influence exercise capacity, external factors like heat, humidity, terrain and even position within a group of racers may affect performance outcomes. A great deal of work has led to the current understanding of how intrinsic variables contribute to performance and this has resulted in well-defined strategies to mitigate deleterious effects in AB athletes. Specifically, carbohydrate and fluid recommendations exist to offset exercise-induced deficiencies of these sports fuels and are relatively simple to incorporate. However, extrinsic factors present a more challenging area to overhaul. For instance, outdoor course profiles, weather and upkeep of road course surfaces are arguably out of anyone's control yet remain routine variables that must be overcome as part of most competitive outdoor sporting endeavors. Excitingly, sports scientists continue to investigate these issues and have progressed the knowledge base to lessen the degree of their impact.

Core Temperature

Of particular interest, core temperature is believed to play a critical role in exercise performance and may be influenced by both intrinsic and extrinsic drivers. Specifically, hyperthermia has been implicated in the reduced time to exhaustion (TTE) observed when exercise elicits elevated thermal strain beyond one's innate compensatory systems (González-Alonso et al., 1999a), (DUFFIELD et al., 2010), (Che Muhamed et al., 2016), (Maughan et al., 2012). Indeed, several mechanisms responsible for this have been proposed pointing to both peripheral (Drust et al., 2005), (González-Alonso et al., 1999a), (Che Muhamed et al., 2016) as well as central roles (Nybo et al., 2002), (González-Alonso et al., 1999a), (SIEGEL et al., 2010), (Mariak et al., 1999), (Che Muhamed et al., 2016), (Maughan et al., 2012). Moreover, strategies to attenuate the impact of hyperthermia have been well documented, providing opportunities to athletes in scenarios that otherwise seem uncontrollable e.g., in hot and or humid environments.

The exact causes of exercise impairment due to hyperthermia remain unknown, but studies demonstrating robust declines in prolonged performance due to high ambient temperatures (with and without humidity) promote the notion that exercise intensity, duration and environmental factors elevate the risk. Indeed, the issue becomes relevant when the homeostatic process of releasing endogenously produced core heat from the skin to the environment becomes inadequate for the rate of heat development. As body temperature rises, whole body sweat rate (WBSR) increases which can lead to significant fluid and electrolyte imbalances (Baker et al., 2019), (Armstrong et al., 1997), (Sawka et al., 2012). However, with proper hydration this impact can be recovered (Armstrong et al., 1997). Nonetheless, when ambient temperatures are elevated and / or humidity is present, the ability to compensate elevated heat storage is compromised (Che Muhamed et al., 2016), (Maughan et al., 2012), (Pandolf et al., 1974), (Kabayashi et al., 1980) as demonstrated by performance decrements, reduced WBSR and heightened ratings of perceived exertion (González-Alonso et al., 1999b), (Che Muhamed et al., 2016), (Maughan et al., 2012).

VO_2 Kinetics

The ability to perform repeated sprints (also referred to as repeat sprint ability or RSA) is important for many sports and has received research attention in several settings including team cycling, soccer and track running. In addition to neuromuscular proficiency (i.e., running economy), RSA requires maximal utilization of anaerobic metabolism with reliance on aerobic energy systems as well. For instance, professional soccer players are involved in over 1000 sprint actions per match with these moments being most pivotal to game score (Sasaki et al., 2015), (Faude et al., 2012). Moreover, while maximal sprint ability has been shown to be higher in predominantly anaerobic athletes (sprinters; SPR), RSA appears to be superior with backgrounds containing aerobic training, such as middle-distance (MID) runners and soccer players.

Interestingly, the WCM requires athletes to perform several sprint and high intensity actions throughout the event including; the initial start to gain a position within a draft, uphill ascents, other various strategic moments throughout the course, and at the final sprint. It could be of great importance to sport scientists and WCM coaches to understand the factors related to RSA and how these can be measured in wheelchair marathoners.

Investigations into VO_2 kinetics have sought to interpret the basis for the RSA. Absolute, $VO_{2\text{-on}}$ and $VO_{2\text{-off}}$ kinetic responses have shown to be features of the biological response to exercise including RSA (KOPPO et al., 2004), showed that higher relative VO_2 max is directly proportionate to the fast component of oxygen uptake. In other words, VO_2 max, which represents the highest amount of adenosine triphosphate (ATP) that may be synthesized using solely oxidative pathways, may be a useful indicator of RSA. A highly effective aerobic system, as seen in athletes with elevated VO_2 maximums, may enable expedited recovery between exercise sets which may delay onset of fatigue (McMahon & Wenger, 1998). (Bishop & Edge, 2006) showed that higher VO_2 max is related to a reduced fatigue index. This may be due to the proficiency of Phosphocreatine (Pcr) resynthesis seen in predominantly aerobic athletes (McCully et al., 1992) as the ability to repeat high-intensity efforts is, in part, related to PCr resynthesis (BISHOP et al., 2004), which is itself O_2 dependent (Hogan et al., 1999). Although aerobic fitness as measured by absolute VO_2 plays a role in the ability to perform continuous exercise, other components of the dynamic VO_2 response to exercise have been shown to be important contributors to RSA.

It has long been known that the non-linear oxygen-uptake response observed at exercise onset ($VO_{2\text{-on}}$) is related to the cardiorespiratory efficiency of the aerobic system (Grassi et al., 1996),(Koga et al., 2005), (Rossiter et al., 1999), (Poole et al., 2005). At the beginning of exercise, the rate of this oxygen uptake, so-called the fast component, determines the subsequent oxygen deficit that will be experienced before VO_2 steady state is attained. It is thought by some that the oxygen deficit incurred during this anaerobically metabolic period impacts the following capacity to exercise, especially if involving repeated bouts. The hypothesis of (Poole et al., 2005) is that the limited anaerobic substrates used during this portion of the exercise and the resulting metabolic consequences (i.e., Phophagen, H^+ and Lactate accumulation) may entail additional recovery mechanisms that could compromise the ability to perform successive sprints.

Thus, having a more rapid fast component may reduce this metabolic toll and promote the ability to recover and perform subsequent exercise. Indeed, (KOPPO et al., 2004) observed significantly more rapid $VO_{2\text{-on}}$ responses at exercise onset in trained versus untrained cyclists, which may point to the effectiveness of this quick turnover for performance, however this investigation did not measure RSA. The benefits of training in this investigation likely are linked to muscle fiber type characteristics, mitochondrial density, oxidative enzyme activity, oxygen availability, capillary density and muscle perfusion (Dupont et al., 2010). While a combination of the aforementioned causes may be responsible for the observed improvement in exercise tolerance, as outlined earlier, faster VO_2 kinetics may help enhance exercise tolerance by reducing the magnitude of the oxygen deficit incurred (Burnley & Jones, 2007).

Explorations into the ability to return to baseline after exercise have shed light into possible mechanisms responsible for recovery and subsequent performance. This portion of the VO_2 kinetic response could indirectly help explain the improved ability to perform after exercise (RSA) seen in some athletes over others. The idea that maximal exercise such as a sprint taxes the anaerobic system elevates the value in understanding how the resulting recovery processes (e.g., Pcr resynthesis, acid/base homeostasis and lactate oxidation) are undertaken. Specifically, upon cessation of exercise above the aerobic threshold, a bicompartmental series of processes follow (Ichikawa et al., 2020). The first component, known as the rapid component (T_{off}), lasts approximately 1-3 minutes and encompasses the period where ATP and Pcr are resynthesized (Hagberg et al., 1980). After this, an extended period (60-90 minutes denoted as T_{2off}) follows in which time accumulated lactate becomes oxidized and VO_2, heart rate, core temperature and glycogen are restored to pre-exercise values. (Dupont et al., 2010) explored the relationship between $VO_{2\text{-off}}$ kinetics, maximal aerobic speed (MAS) and RSA in amateur soccer players. Their results revealed significant correlations between the percent decrement (%Dec) and $VO_{2\text{-off}}$ as well as between MAS and $VO_{2\text{-off}}$. While this experiment employed only 7 repeated sprints, the stimulus (7x30-meter with 20-seconds recovery) was robust enough to induce significantly slower times in the last five sprints compared to the first two and resulted in significant correlations between maximal sprint speed (MSS) and total sprint time. Because %Dec and MAS proved to be related to $VO_{2\text{-off}}$, it could be concluded that these aerobic features are of benefit to RSA and may drive the advantageous recovery expedition required in prolonged repeat sprint situations. A limitation to this investigation is that $VO_{2\text{-off}}$ kinetics were monitored for only 6 minutes following exercise to exhaustion and this is unable to capture the entire slow component of the off-kinetic response.

To look at both components of $VO_{2\text{-off}}$ in relation to RSA, (Aguiar et al., 2015) monitored sprinters (SPR), endurance athletes (END) and active controls (ACT) for 60-minutes following a one-minute all out exercise bout. This protocol was chosen because pulmonary and blood lactate concentration (BLC) recovery kinetics are highly sensitive to movement, thus becoming impossible to measure when taken between sets in a repeat sprint test (RST). The idea was that a longer maximal sprint (60-seconds), which taxes anaerobic supplies similarly to those expected in RST, enables the measurement of recovery kinetics during an extended period of time ($T_{2\text{-off}}$). Additionally, in this experiment participants completed both an incremental test to exhaustion to determine VO_2 max as well as a RST consisting of 10 x 35-meter sprints interspersed by 20-seconds of active recovery to evaluate RSA. Results, agreeing with (Dupont et al., 2010), showed that SPR achieved both faster maximal sprint times as well a faster sprint average throughout the RST and that END suffered less %Dec. Examination of the VO_2 and lactate recovery curves showed that SPR presented higher anaerobic energy turnover (PCr and total lactate production), but slower lactate exchange and T_{2off} compared to END. These results demonstrate the importance in sprint-specific training in order to advance RSA. However, as compared to the active control, these data again illustrate the importance of aerobic adaptations (lactate exchange, running economy and MAS) that influence fatigue resistance, which indirectly promote RSA.

It is hereto unknown whether the WCM ought to be characterized as a traditional endurance activity like its able-bodied counterpart. As mentioned previously, for various reasons, the WCM may resemble a more intermittent-type activity with repeated sprint activities occurring throughout the duration of the event. To our knowledge, there have been no investigations into measuring the descriptive features of the WCM, i.e., number of sprint activities per race, average time spent sprinting, average time between sprints, average time spent climbing, or maximal speed attainments. Moreover, comparisons of these variables between top finishers and others could be of interest, as races have been completed by athletes utilizing strategies like drafting, as well as those who have not, and thereby likely experienced a different metabolic taxation. Characterization of the sport through the use tools like $VO_{2\text{-on}}$ and $VO_{2\text{-off}}$ kinetic responses with concomitant lactate exchange have never before been used in this population and may prove to be relatively simple procedures to implement. However, more information describing the event are needed to determine the meaningfulness and applicability of the observed kinetic VO_2 and lactate responses.

Specific Aims

The overall objective of this thesis is to examine the utility of commonly used sports science tools within the sport of WCM. To do this, results from two separate studies were examined. In the first study, the core temperature responses to ingestion of different carbohydrate sources throughout an endurance cycling challenge in highly trained cyclists (not WCMers) was measured using ingestible thermometers in capsules. This study was undertaken in able bodied trained cyclist to ultimately provide the obligatory framework to decide whether this tool should be pursued in WCMers—a population that is much more challenging to recruit given the rigors of their travel and training/competing schedule. The second project, which exists as a case study, examined the VO_2 and lactate kinetic response over 60-minutes after an all-out exercise bout in an elite WCMer.

Aim 1: Determine the potential utility of monitoring core temperature in elite WCM and discuss considerations needed to achieve this effectively in para-athletes.

Hypothesis: Based on previous research, core temperature is related to performance. Para-athletes face various challenges related to maintaining optimal core temperature while exercising due to physiological dysregulation as well as logistical challenges due to the use of adaptive sports equipment. We hypothesize that monitoring nutritionally mediated core temperature will provide useful information to athletes, coaches and sports scientists to better support sport activity.

Aim 2: Examine the lactate response to an all-out exercise bout for the improved characterization of the WCM.

Hypothesis: Due to the significant effects of drafting and coasting, we hypothesize that the WCM is more closely aligned with intermittent sports that require the ability to perform repeated sprints (RSA) for a prolonged period of time, than with the traditional foot race marathon which is classified as a traditional endurance-type sport. As a case study, these data allow for the singular glimpse of one world-class WCMer only, yet the information gained will hopefully motivate others to contribute more participants to the project, thereby helping understand the metabolic requirements of WCM and subsequently the ensuing optimal training and nutritional support that will ultimately lead to improved performance.

CHAPTER 2: CORE TEMPERATURE RESPONSE TO NUTRITIONALLY MEDIATED ENDURANCE CYCLING CHALLENGE IN HIGHLY TRAINED CYCLISTS

Introduction

Strategies to attenuate hyperthermia during activity are important for the improvement in exercise capacity as well as performance. Notably, a variety of strategies have been shown to improve performance in non-compensatory environments, i.e., heat with humidity. It appears that a combination of methods targeting the pre-cooling as well as the intra-exercise periods are most effective at offsetting heat storage capacity. Many of the current strategies, however, may be impractical for various situations with this reality being exacerbated for many para-athletes. Therefore, continuing to discover novel strategies that enhance practicality and effectiveness are needed.

Causes of elevated core temperature

Investigations into the physiological responses to elevated core temperature reveal peripheral as well as central mediation. In terms of peripheral responses, elevated sweat loss, fluid and electrolyte imbalances, high skin and core temperature, changes in cardiac output as observed by impaired maximal VO_2 attainment with hyperthermia (González-Alonso et al., 1999b), (Che Muhamed et al., 2016) and impaired repeat sprint performance (Drust et al., 2005) are well documented in the literature and illustrate the thermoregulatory and cardiovascular strain. It has been shown that when core and skin temperatures are elevated, the reduction in temperature gradient abolishes the ability to remove excess heat storage which can lead to venous blood flow and vascular compliance (Sawka et al., 2012). In contrast, (González-Alonso et al., 1999b) showed that despite differing initial esophageal temperatures (35.9 +/- 0.2, 37.4 +/- 0. 1^{o}C, or 38.2 +/- 0.1^{o}C), time to exhaustion (TTE) was dictated by absolute core temperature attainment of 40 °C alone, with no significant effect of skin temperature. This was also shown by (Nielsen et al., 1993) who ascertained that core temperature attainment of 39.7 +/- 0.15 °C determined TTE regardless of ambient temperature (20 °C versus 40 °C). However, (Bongers et al., 2017) did not find any difference in 8km performance of highly trained athletes running with core temperatures < or> 40 °C. This may be explained by the level of training and competitiveness of these participants and their subsequent motivation to persevere throughout the distance.

Along those lines, central mechanisms may also be responsible for the deleterious effects experienced on performance during hyperthermia. Several authors have suggested that the will or drive to exercise might be diminished by hyperthermia (Nielsen et al., 1993), (Brück & Olschewski, 1987). Studies examining the effect of temperature on the central nervous system report exercise impairment independent from peripheral mediators. To do this, it is common to employ maximal isometric contractions superimposed with electrical stimulation (Morrison et al., 2004), (Todd et al., 2005), (Racinais et al., 2008), (Nybo & Nielsen, 2001).(Nybo & Nielsen, 2001) demonstrated a significantly reduced maximal voluntary contraction of the knee extensor after exercising to exhaustion in the heat. Upon analyzing the voluntary activation percentage between the hyperthermic group compared to the control, results revealed that the degree of central activation was significantly attenuated with hyperthermia. Additionally, brain temperature itself has been demonstrated to influence exercise as shown in 1986 by (Caputa et al., 1986) who performed experiments on goats utilizing implanted heat exchangers that enabled them to manipulate brain temperature. Their results showed that while the highest tolerable brain temperature was high (42 °C), goats did exhaust sooner when brain temperature was manually elevated above a trunk temperature that the animal had previously successfully completed activity at.

Tools Used for Measurement of Core Temperature

Several tools exist for the measurement of core temperature that have been shown to be effective in exercising participants. These include gastrointestinal (ingestible), rectal and esophageal thermometers. Each option provides accurate temperature recording yet comes with various limitations. For example, ingestible core temperature thermometers are relatively non-invasive, yet they are costly and can become problematic if the consumer requires an MRI procedure. Rectal thermometers remain the gold standard for core temperature measurement during exercise (Casa et al., 2007) as they are practical and cost-effective, however, this tool may be uncomfortable to use and challenging to use outside of the laboratory setting. Importantly, this tool is infeasible for WCM as access will be impractical in the racing wheelchair. Esophageal temperature probes, which are inserted through the oral cavity, may be uncomfortable as well as unrealistic in sport setting (Dolson et al., 2022).

Methods Used to Attenuate Elevated Core Temperature

Currently, cooling approaches have targeted the before exercise period (pre-cooling), the intra-exercise timeframe, as well as combination protocols. There are various reasons an athlete may wish or need to utilize a different strategy. Pre-cooling approaches are described as the rapid removal of heat from the body before exercise to create a larger heat storage capacity (M. Ross et al., 2013) and include cold air or water exposure (González-Alonso et al., 1999b), (DUFFIELD et al., 2010), ice vest applications (Quod et al., 2008) and consumption of cold or frozen fluids/ foods (Hasegawa et al., 2006). However, many of these may be impractical (Bongers et al., 2015),(M. Ross et al., 2013). Specifically, access to a thermic-chamber for cool air immersion presents a challenge due to cost as well as access when traveling to a competition site. Additionally, while water for ice baths may be easier to procure, the amount needed and the 30-minute recommended submersion period (DUFFIELD et al., 2010) make this an understandably challenging strategy for every competition. Use of ice vests may be burdensome to travel with, difficult to maintain proper temperature at all competition venues and may be bulky which could possibly interfere with warm up effectiveness (Hasegawa et al., 2006), (Bongers et al., 2017). However, despite these limitations, para-athletes may preferentially adopt such practices due to logistical practicality. For example, an athlete who may not fit inside their sport chair with an ice vest on may be able to utilize the ice vest in the period of time before transferring into the sport equipment. Care must be taken to determine what works best for each athlete.

For the reasons listed above, internal interventions, e.g., the addition of a cold medium via the mouth or nose, may provide a more portable and therefore more practical approach for athletes to utilize at a wider range of competitions. Within the literature, evidence for effective cooling practices point to ingestion of cold fluids or ice slurries. Because ice requires nearly 80% more thermal energy to change phase (as explained by the enthalpy of fusion theory (Merrick et al., 2003), preparing ice slurries and covering skin with an ice vest and cold towels remain efficient strategies. This may be especially valuable when the volume of dose to be ingested needs to be considered i.e., when gastrointestinal tolerability becomes an issue. Moreover, introducing ice to the internal body core increases internal heat storage capacity and is a simpler practice than transporting an ice vest. Ice slurries are well documented in the literature, and have been shown to improve running capacity (Siegel et al., 2012), (SIEGEL et al., 2010) as well as cycling time trial performance (Ihsan et al., 2010). Importantly, (SIEGEL et al., 2010) reported lower perceptions of thermal discomfort as well as effort during their run to exhaustion protocol after consuming 7.5 $g\cdot kg^{-1}$ of ice slurry as compared with the same volume of cold (4 °C) water. Interestingly, the same authors later compared ice slurry ingestion to cold water immersion and demonstrated comparable performance benefits (Siegel et al., 2012) thus providing evidence for the potential of a more feasible cooling option (slushie) when cold water immersion in unavailable.

Until now, attention has been focused on the pre-cooling period prior to exercise. For several reasons, curtailing hyperthermia during exercise is more challenging. For example, while Burdon et al., successfully lowered body temperature during a 90-minute cycling trial by feeding participants 30 mL of slushie every 5 minutes (Burdon et al., 2010), a feat like this would be impossible in many real-world scenarios. By nature, maintaining frozen or cold beverages across the span of a sporting event undertaken in the heat is unrealistic without the action of a support team as may only be possible in multi-stage events such as cycling, endurance running, or throughout the match of a prolonged team sport such as soccer (MINETT et al., 2011).

Moreover, investigations into the neural response to thermic foods may explain improvements in motivation and perception following the ingestion of cold sports foods and beverages. Indeed, (Guest et al., 2007) concluded that a network of taste- and reward-responsive regions of the human brain is also activated by intra-oral thermal stimulation, and that the subjective states elicited by oral thermal stimuli are correlated with the activations in the orbitofrontal cortex and pregenual cingulate cortex. This area is also enticing and in need of further research into its applicability to sporting performance.

Implications for the Para-Athlete

While competitive athletes at peak motivation may override the performance decrements during hyperthermia (M. L. Ross et al., 2014),(González-Alonso et al., 1999b), strategies to mitigate deleterious effects of hyperthermia on exercise performance are warranted. A great deal of work has been undertaken to develop effective cooling methods. However, some of these methods may be impractical for elite athletes and therefore this area remains an important focus for sport scientists. Para-athletes may be at an even higher risk of thermoregulatory dysregulation due to the variable amount of recruitable muscle mass as well as the incomplete sympathetic nervous system function that can occur with spinal cord injury (SCI) (Price, 2006) This is because the key thermoregulatory effectors for heat dissipation, namely sweating and changes in cutaneous blood flow, are sympathetically driven (Price, 2016) and these athletes are at elevated risk of hyperthermia. In addition to these intrinsic risk factors, para-athletes may also experience limited opportunities to utilize cooling strategies that require use of hands to adopt. Specifically, many para-athletes rely on use of their hands to perform their sport which may exclude cooling strategies that entail ingestion of a substance that must first be opened or must be manually brought to one's mouth. Additionally, many para-athletes utilize equipment that may make other cooling strategies impractical as well. For example, external devices such as cooling vests may not fit within a close-fitting piece of sporting equipment.

Para-athletes face a variety of unique challenges that impact their ability to regulate temperature and hydration. For example, athletes with amputations, multiple sclerosis or SCI have reduced thermal perception and impaired ability to thermoregulate owing to a reduced sweat rate (Guttmann et al., 1958) and sweat gland density (R. Pritchett et al., 2015) Athletes with paraplegia generally have lost degrees of motor and sensory function which includes impairments to bowel and bladder control (K. Pritchett et al., 2020). This becomes important as athletes may voluntarily choose to restrict food and/or fluid intake, elevating risk of hyperthermia due to concerns of dehydration, which can also result in fatigue and increased risk of urinary tract infections (Pritchett K et al., 2019).

From a practical view, several cooling strategies have been reviewed for their utility within the para-athlete. Of these, cold water immersion has been shown to be more effective than slushie ingestion with or without cold towel application at reducing core temperature in athletes with SCI, yet is likely unavailable at several sporting sites (Forsyth et al., 2016) and therefore not logistically favorable. Similarly, hand and foot cooling are much more simple to apply and have been shown to be effective at reducing auditory canal temperature with concomitant improvements in 1km performance time trials during exercise in the heat in athletes with SCI. However, these methods are likely to be impractical for para-athletes who depend on hand dexterity for their sport (Goosey-Tolfrey et al., 2008) and whose feet are tucked within their equipment (for example, in sports like the WCM). Artificial sweat, which can be understood as the application of water to skin via a water spray bottle (R. C. Pritchett et al., 2010) , has yet to be investigated in athletes with SCI, however has other limitations for WCMers. Specifically, the interface that occurs between the racing gloves and the hand rim of a racing wheelchair is reliant upon friction generation because both surfaces are made of rubber. WCMers are hesitant to use spray bottles as a cooling strategy because the water may contact their equipment, resulting in detrimental abilities to use their equipment effectively. Ice slurries have been shown to delay the rise in core temperature in a group of wheelchair rugby players up to the midpoint of a 60-minute training session and remains a cost effective and easy to use strategy (K. Pritchett et al., 2020). While their applicability has yet to be researched in WCMers, it is likely that this strategy will entail some limitations. For instance, WCMers take on a very tight body position within their racing wheelchair and may have issues consuming adequate volume due to gastric discomfort. However, this is a strategy that will require more research in addition to the possibility that individualizing the doses of slushie may improve usability in this population. Lastly, cooling garments like ice vests and cooling towels have been investigated within the para-athlete population (Webborn et al., 2010) and have proven to be cost effective and practical in addition to their effectiveness at lowering core temperature during high intensity arm crank exercise in the heat in athletes with tetraplegia. Again, this method is not without limitations. As stated earlier, considerations must be made to the tight-fitting equipment used by para-athletes, which may mean the cooling garment cannot fit within the competition position. More fieldwork needs to be done to examine the usability of these various methods to better understand how para-athletes across different sports may benefit.

The purpose of this study was to evaluate the core temperature response, via an ingestiable sensor, during different nutritional manipulations in highly trained able-bodied cyclists. This population was used to provide the obligatory framework to ultimately recruit para-athletes; a population that is much more challenging to recruit due to their training and competition commitment. Of note is that carbohydrate intake during prolonged exercise is believed to be important to support the metabolic demands of training and competition in para-athletes. As such, we sought to define the impact of specifically formulated sports gels and/or a whole food alternative on the core temperature response. This is significant as whole food ingestion during prolonged exercise is another option that is gaining popularity within the greater athlete population as well as in the para-athlete.

Methods

Participants and Ethical Approval. This analysis is part of a larger study investigating the time-trial performance impact of ingesting potato versus commercially available sports gels during an endurance cycling challenge in highly trained cyclists. Twelve cyclists (n = 9 male, n = 3 female; 70.7 ± 7.7 kg, 173 ± 8 cm, 30.6 ± 8.7 yr, 21.6 ± 5.1% body fat) volunteered to participate in this study. Participants cycled on average 267 km/wk (range 120–480 km/wk) and had been training an average of 7 yr (range 3–20 yr). Based on peak oxygen consumption (V̇o2peak, 60.7 ± 9.0 mL·kg−1·min−1), peak workload (Wpeak, 350 ± 63 W), and Wpeak/kg (4.9 ± 0.7 W/kg), the participants were classified as endurance trained and competitive. Experimental trials were completed during the midfollicular phase of the menstrual cycle for the female participants. All participants were considered healthy on the basis of a self-reported medical screening questionnaire. Each participant was informed of the purpose of the study, the experimental procedures, and all the potential risks before providing their written consent to participate. The study was approved by the University of Illinois Institutional Review Board and conformed to standards for the use of human participants in research as outlined in the Declaration of Helsinki.

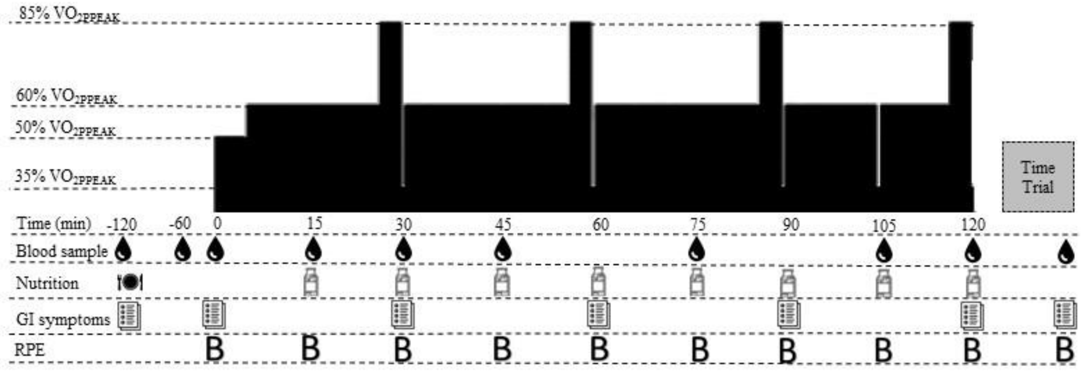

Figure 1: *A postabsorptive blood sample was obtained before ingestion of a standardized breakfast (−120 min). The cycling challenge (0–120 min, 60% $\dot{V}O_{2ppeak}$) was initiated with a 5-min warm-up (50% $\dot{V}O_{2peak}$), with hills (85% $\dot{V}O_{2peak}$/3 min) followed by downhills (35% $\dot{V}O_{2ppeak}$/1 min) every 30 min. A downhill at 105 min allowed for mask placement to collect gas exchange. A 6 kJ/kg time trial was initiated after cycling challenge completion. $\dot{V}O_{2ppeak}$, peak O_2 consumption workload; GI, gastrointestinal; RPE, rate of perceived exertion (Borg scale, 6–20).*

Experimental design. An overview of the experimental trial is illustrated in **figure 1**. Each participant arrived at the laboratory at the same time in the morning after an overnight fast. On arrival, an intravenous catheter was inserted into an antecubital vein and kept patent with 0.9%

saline drip for repeated blood sampling. After baseline blood sampling, participants were provided with a standardized breakfast (1 g/kg CHO, 0.4 g/kg protein) with water provided ad libitum. Participants rested in the laboratory for 2 h before the commencement of the cycling challenge. Before the cycling challenge, participants provided a urine sample to determine baseline urine osmolality and urine specific gravity (USG; osmometer model 3320, Advanced Instruments, Norwood, MA) and were towel dried before pre-exercise weight measurements.

The exercise protocol consisted of a 120-min cycling challenge immediately followed by a TT (6 kJ/kg body mass) completed as fast as possible. As shown in **figure 1**, the cycling challenge started with a 5-min warm-up at 50% V̇o2peak followed by steady-state exercise at 60% V̇o2peak, with four intermittent, high-intensity bursts (each 3 min at 85% V̇o2peak) to simulate hill climbs. Each burst was immediately followed by a low-intensity period (1 min at 35% V̇o2peak) to simulate descents. “Hills” and “descents” were performed once every 30 min. On two of the trials, participants were administered supplemental CHO (15 g of CHO administered every 15 min) in the form of chilled, baked russet potato flesh purée (128.5 g per bolus) or room-temperature CHO gels (PowerBar; 23 g per bolus). All treatments were supplemented with 2% enriched (0.3 g) [U-13C6]glucose to provide a proxy for gastric emptying rates and the subsequent appearance of exogenous glucose into circulation (BEELEN et al., 2012). Blood sampling, heart rate, core temperature, RPE (Borg scale 6–20), and GI symptoms were assessed throughout the cycling challenge as indicated in **figure 1**. For the TT, the ergometer was set in linear mode with the linear factor based on their personal 70% power peak and preferred cycling cadence determined during the incremental test. In this ergometer mode, an increase in cadence resulted in an equivalent increase in the required workload. During the TT, encouragement was withheld until the last 10% of the TT and no information about performance was provided. After completion of the TT, participants were towel dried and weighed, and subsequently provided a urine sample. For the RPE analysis of the TT, we adopted a ratio of RPE by workload, as previously described (Fontes et al., 2010). This calculation accounts for the Borg scale’s ceiling effect (BORG, 1982). The GI symptoms (i.e., overall symptoms, abdominal pain, abdominal bloating, gut rumbling, flatulence, abdominal discomfort) were rated against a standardized 0- to 100-mm visual analog scale (VAS) questionnaire. Blood samples were collected in EDTA-containing tubes and centrifuged at 3,000 g at 4°C for 10 min. Aliquots of plasma were frozen and stored at −80°C until subsequent analysis.

Core Temperature. Participants were given ingestible and disposable core temperature sensors in capsules (HQInc, Palmetto FL) and instructed to swallow one capsule 6-12 hours before each experimental trial day. The capsules transmitted core temperature data to a wireless physiological monitoring system. Core temperature was recorded every 60 seconds throughout each experimental trial. The device's data recorder was attached directly to the subject close to the area at the small of the back per manufacturer instructions.

We examined other relevant variables that might be related to exercise performance and nutrient bioavailability, such as symptoms of GI discomfort, plasma intestinal fatty acid-binding protein concentrations (I-FABP; a marker of small intestine injury), and core temperature (i.e., impact of exogenous CHO source on thermoregulatory capacity). Finally, [U-13C6]glucose was orally administered to provide (indirect) insight into the appearance rate of ingested glucose into the circulation. We hypothesized that potato and gels ingested at 60 g CHO/h during a 2-h cycling challenge would be more effective on subsequent cycling TT performance than consuming only water in trained cyclists.

Statistical Analysis. Based on a priori power analysis, twelve participants exceeded the minimum sample size required to detect a difference in TT performance with a power of 0.80. This power calculation was based on a two-tailed α-level of 0.05. For analysis of core temperature, the fixed factors were time and condition (water, potatoes, or gel), and the random factor was the subject. For analysis of TT performance, condition was the only fixed factor. The TT was divided into four quartiles for performance, RPE, and heat rate analyses. Bonferroni's post hoc tests were performed to determine differences between means for all significant main effects and interactions.

Results. There was no difference in core temperature (P = 0.779) among conditions during the cycling challenge. The core temperature increased significantly from the beginning of the exercise in water (P = 0.003), potato (P = 0.037), and gel (P = 0.015) conditions at 24, 17, and 19 min, respectively. In addition, even with no differences (P = 0.685) in the baseline value among water (36.9 ± 0.3°C), potato (36.8 ± 0.3°C), and gel conditions (37.0 ± 0.4°C), core temperature value at the onset of the TT was lower (P = 0.045) in potato (37.8 ± 0.5°C) than in gel (38.3 ± 0.5°C) condition, with no differences compared with the water condition (37.9 ± 0.5°C). TT performance was improved (*P* = 0.032) in both potato (33.0 ± 4.5 min) and gel (33.0 ± 4.2 min) conditions compared with water condition (39.5 ± 7.9 min). Moreover, no difference was observed in TT performance between CHO conditions (*P* = 1.00).

Discussion.

While chilled potato purée ingestion during exercise demonstrated a protective effect on core temperature in the present study, it is important to consider the utility of a strategy such as this for the para-athlete, and specifically for the purpose of this thesis, the WCMer. In our study, able-bodied cyclists were fed potato purée by members of the research team. While we know that para-athletes are at a higher risk of hyperthermia, the ability to consume potato puree during exercise is highly impractical for WCMers whose hands are contained in their sport-specific racing gloves. Additionally, the physical position a WCMer takes within their sports chair, may potentially increase gastrointestinal symptoms experienced with consumption of whole food as athletes are tightly secured in a kneeling position. This type of ingestion has not been examined in WCMers and is an area that requires more research.

Strategies for achieving cooling needs should be individualized to the athlete within the context of their sport and impairment type. Approaches to consider include maintaining proper hydration status, cold-water immersion (Forsyth et al., 2016), hand and foot cooling (Goosey-Tolfrey et al., 2008), artificial sweat/ spray mister fans (R. C. Pritchett et al., 2010), ice slurry ingestion (Forsyth et al., 2016), cooling garments (Griggs et al., 2015), and heat acclimation (Price, 2016), (Castle et al., 2013). It is likely that a combination of interventions ought to be utilized for greater success (K. Pritchett et al., 2020).

Given the impracticality and insufficient literature of whole-food ingestion during exercise in a WCMer, attention ought to be focused on the pre-exercise protocol. In this regard, literature does exist and points to various cooling strategies for para-athletes. During this period athletes may opt to use a variety of cooling tactics including use of external garments (ice vests and cold towels), immersion in cold water or cold air, and/or the ingestion of nutrition products such as ice slurries. With our findings, it remains possible that alternative food products such as chilled whole foods may be an additional option. Given the reality that each strategy may contain its own limitations, having more effective tools to choose from remains a great conclusion from the present work.

CHAPTER 3: LACTATE RESPONSE TO 1-MINUTE ALL OUT EXERCISE IN ELITE WHEELCHAIR MARATHONER (CASE STUDY)

Introduction

The ability to perform repeated sprints (also referred to as repeat sprint ability or RSA) is important for many sports and has received research attention in several settings including team cycling, soccer and track running. In addition to neuromuscular proficiency i.e., running economy, RSA requires maximal utilization of anaerobic metabolism with reliance on aerobic energy systems as well. For instance, professional soccer players are involved in over 1000 sprint actions per match with these moments being most pivotal to game score (Sasaki et al., 2015), (Faude et al., 2012). Moreover, while maximal sprint ability has been shown to be higher in predominantly anaerobic athletes (sprinters; SPR), RSA appears to be superior with backgrounds containing aerobic training, such as middle-distance (MID) runners and soccer players. Furthermore, the WCM requires athletes to perform several sprint and high intensity actions throughout the event ranging from the initial start, uphill ascents, during various strategic moments throughout the course and at the final sprint to finish. It could therefore be of great importance to sport scientists and WCM coaches to understand the factors related to RSA and how these can be measured in wheelchair marathoners.

To understand the impact of RSA on the WCM, a general overview of basic exercise metabolism is helpful to conceptualize and reason its impact. First, the production of power, which can be simplified into the rate at which ATP is used to generate muscle contraction, is dictated by both the rate of muscle contraction as well as the supply of substrate. A sprint action will be related to the total amount of ATP that can be used in a very short period e.g., fast rate. ATP itself is stored in very small quantities (~5 mmol/kg wet weight) and this can be used for the first few seconds of maximal work. As ATP stores become depleted, Phosphocreatine (PCr) is broken down rapidly and accounts for energy production for the next 10 seconds. Beyond this point of exercise, anaerobic glycolysis accounts for the continued ATP synthesis during maximal efforts. Importantly, PCr is resynthesized by aerobic metabolism which may implicate the importance of both anaerobic and aerobic energy supply, in addition to intermittent recovery periods, for RSA (Hargreaves & Spriet, 2020). Due to the series of enzymatic reactions required, this process is not as rapid but provides energy with high capacity for up to ~ one minute (Medbo et al., 1988). Lastly, at high exercise intensities (maximal sprints), a large concomitant flux of ions (H+) can result in cellular acidosis and this environment has been associated with fatigue due to its attenuation of glycolytic enzyme activity (Medbo et al., 1988). This last point is especially relevant for RSA as short recovery periods between efforts may compromise the ability to perform subsequent maximal work.

RSA has been explored from multiple angles. Timed repeated sprints conducted using validated repeat sprint test (RST) challenges such as the blink test and the shuttle endurance test have provided insight into the characteristics of the efforts, however the number of sprints, sprint duration, recovery duration and intensity of recovery will all influence performance outcomes and vary routinely between studies (Aziz et al., 2000); (BISHOP et al., 2004)(Dupont et al., 2005) (McMahon & Wenger, 1998). (Ufland et al., 2013) examined the relationship between maximal aerobic speed (MAS), maximal sprinting speed (MSS) and RSA to compare 100–400-meter runners (SPR) with 800-3,000-meter runners (MID) and found that SPR performed faster maximal and average sprints across the repeated sprint exercise but observed that MID suffered the smallest percent decrement (%Dec), calculated as [100 × (total sprint time/RSbest)] – 100, and had the highest MAS. Muscle oxygen uptake recovery kinetics were also measured using near-infrared spectroscopy, and the protocol demonstrated faster recovery rates for MID compared to SPR. The performance results agree with findings by (Aguiar et al., 2015) who also showed the superior maximal and average sprint time of SPR in contrast to the attenuated %Dec and elevated MAS in the middle and long-distance runners. However, with regards to muscle oxygen uptake kinetics, findings were in contrast to (Krustrup et al., 2004) who were unable to show a significant relationship between muscle oxygen uptake kinetics at the onset and following supramaximal exercise. Thus, this area still requires attention into the mediating factors contributing to VO_2 kinetic responses.

Wheelchair Marathon

As detailed in the introduction of the current thesis, the WCM deviates from the foot race analogue in several important ways. Primarily, the nature of the event is highly influenced by the effect of drafting amongst participants. Briefly, drafting is a technique used to reduce the effects of drag by positioning oneself immediately behind another competitor in order to experience less aerodynamic resistance and enable higher speeds to be attained with less effort. Due to this strategy, WCMers experience periods of lessened intensity (i.e., when directly behind an athlete or when coasting down a hill) as well as periods of high intensity (i.e., when taking a turn at the front of the pace line, when climbing up a hill, when sprinting during an attack and also while coming out of a corner). This is in stark difference to the predominantly endurance-based footrace which sees relatively constant intensity pacing by athletes (Billat et al., 2020). For all of these reasons, the course itself may also dictate the number of sprint-like activities (RSA) encountered.

Few studies have examined the exact physiological responses during a WCM, however one can expect that the aforementioned tactics will describe this race as more of an intermittent, repeated-sprint like activity and therefore the importance of RSA within the para-athlete population may be of importance. (Edwards et al., 2018) measured the physiological responses amongst elite wheelchair marathoners during a simulated 25km time-trial race. While this is the only field-based test to assess metabolic outcomes during a long-distance activity in elite WCMers, some important limitations exist. For example, athletes were specifically instructed not to draft with one another which differs from commonly used race strategies. Additionally, it is difficult to replicate exact competition settings, and therefore actual race responses may be underestimated (Jeffrey C. Ives et al., 2020). However, findings from this report demonstrated that WCMers completed the time trial at 73.7± 11.9 %VO2. It should be noted that this is an average across a small, gender-mixed, sample size (n=5). Individual responses throughout the course may provide interesting information as to how tactical moments might impact VO_2 kinetics in these athletes.

Because of the increasing popularity and competitiveness of the WCM (Lepers et al., 2014) and in light of the dearth of available information regarding characterization of the event and of its athlete population, we conducted a case study to examine the VO_2 and lactate kinetic response surrounding a one-minute all-out exercise bout in an elite wheelchair marathoner. The purpose of this project was to analyze the metabolic response (i.e., VO2, Lactate, Glucose and heart rate) before, during and 60-minutes after a prolonged sprint action (one-minute). The goal of this experiment was to provide insight into the novel characterization of the WCM with respect to recovery kinetics and to provide a framework for future investigators to follow in order to increase the understanding of what these data represent.

Methods

Participants

The athlete who participated in this case study was a 28-year-old female professional wheelchair marathoner with an acquired complete spinal cord injury (SCI), class T54 by World Para Athletics. SCI is a common physical impairment, affecting between 250,000 and 500,000 individuals each year, globally (Joe Bennett et al., 2022). SCI can result from traumatic or non-traumatic causes, with resulting consequences in the affected individual's motor, sensory, and autonomic systems. The athlete was a highly accomplished competitor, having competed at two Paralympic Games in addition to holding the national record for the marathon in her sport class (1:30:33) and having podium finishes at major marathons including Boston, Tokyo, Chicago, Berlin and London. Her main descriptive features are: height = 1.6 m; body mass = 42.27 kg; VO2 max =65 mL/kg/min; training 8,000 km per year.

The participant provided written informed consent to be a research participant in this case study. All the procedures were approved by the Ethics Research Committee of the University of Illinois (Urbana, Illinois).

The participant was asked to arrive fully rested to the research laboratory and to abstain from caffeine and rigorous exercise for 12 hours and 48 hours respectively.

Metabolic Testing

During the 1-min and incremental test, the respiratory gas exchange variables were collected using a breath-by-breath automated open-circuit gas analysis system (Parvo Medics TruOne 2400, Salt Lake City, Utah). The exchanger was fitted to the participant using a head strap per manufacturer's instructions. Calibration procedures were performed before each test according to the manufacturer's recommendations.

Repeated Blood Sampling

Ear-lobe capillary blood samples (25 µL) were taken for the determination of maximal blood lactate concentration after incremental test and blood lactate recovery curve after the 1-min test.

Blood samples were collected immediately and 3 and 5 min post-incremental test, and in the 1-min test were collected at rest, immediately prior to the test, and for 60 min post-test (every 1- min from 0 to 10 min, every 2 min from 10 to 20 min, and every 5 min from 20 to 60 min). Arterialized capillary blood was sampled by micropuncture at the earlobe, and then stored in Eppendorf tubes containing 50 L of 1% sodium fluoride in a –30 °C environment. Later, samples were analyzed by enzyme electrode technology (YSI 1500, Yellow Springs, Ohio, USA).

<u>Incremental test</u>

The incremental test was performed using an indoor stationary wheelchair roller (Revolution Sports, CAN) and was set up to match the usual position taken by the athlete when training on this equipment. Briefly, the length of the roller was set so that the midpoint of the rear wheel was at the midpoint of the highest position upon the roller's steel drum. From there, the front wheel was stabilized with a clamp. The racing chair's rear tires were inflated to 140 parts per square inch (PSI) per the athlete's preference. An open-circuit spirometry system (TrueOne, Parvo Medics, Sandy, UT) was utilized to analyze expired gases. The participant was fitted with headgear and a mouthpiece for collecting expired gases during the exercise test. Prior to beginning the test, the participant mounted her personal racing wheelchair to the roller and was fitted with a Polar heart rate monitor (Polar Electro, Kempele, Finland). The initial speed of the test was set at 12m·h^{-1} and was increased by 1 m·h^{-1} per minute until the participant terminated the test owing to volitional exhaustion. Maximal oxygen uptake ($\dot{V}O_{2peak}$) was determined as the highest recorded 20-s $\dot{V}O_2$ value when at least three criteria were satisfied: *1*) a plateau in $\dot{V}O_2$ despite an increase in work rate, *2*) respiratory exchange ratio ≥1.10, *3*) heart rate peak within 10 beats/min of age-predicted maximum (i.e., 220-age), or *4*) ratings of perceived exertion (RPE; Borg scale 6–20) ≥ 17. The maximal aerobic speed (MAS) was calculated as the highest speed the athlete was able to maintain for 1 minute.

<u>1-minute test</u>

The 1-minute test was performed using the same equipment and settings as the incremental test. Upon arrival to the trial, the athlete was instructed to remain seated and to abstain from voluntary movement for 5-minutes in order to collect baseline respiratory gas exchange measurements. An open-circuit spirometry system (TrueOne, Parvo Medics, Sandy, UT) was utilized to analyze expired gases. The participant was fitted with headgear and a mouthpiece for collecting expired gases during the entirety of the trial. Additionally, a 25µL aliquot of blood was collected from the earlobe for baseline glucose and lactate calculation. The athlete was then verbally described the procedures of the test and asked to mount her racing chair that was fixed upon the stationary roller.

The assessment began with a self-paced warm up of 10-minutes followed by 3 sets of 3-second accelerations designed to simulate a standard warm up for the athlete. Next, a 5-minute rest period occurred in which time another 25 μL earlobe blood sample was collected. A three command "on your mark, set, go" verbal instruction was given to the athlete and upon "go" the athlete pushed maximally for 1-minute. Immediately upon cessation of sprinting, another earlobe sample was taken (t=0) along with rated perceived exertion (BORG scale). Earlobe blood samples were collected at regular intervals thereafter for the following 60-minutes(Aguiar et al., 2015)Additionally, respiratory gases were collected continuously. The athlete was instructed to remain stationary for the entire hour, abstaining from voluntary movements as able. To help with this, the members of the research team physically assisted the athlete out of her racing chair and into her everyday wheelchair to reduce as much movement as possible in order to reduce impact of voluntary movement on lactate recovery values.

Results.

All variables analyzed in the present case study are presented in **table 1**. Due to analytical difficulties on the part of the research team, only lactate responses are shown and discussed. Of note, VO_2 responses were measured concomitantly with lactate, as previously described (Aguir, 2017), however these results will not be included. Lactic acid metabolism demonstrated a rapid rise as evidenced by the maximal lactate concentration, denoted as amplitude, was reached at time= 2 min (BLC(2)). The subsequent decline in lactate followed a steady line until a final concentration (BLC(60)) of 0.77 was attained. Interestingly, this athlete did not return to baseline (Rest BLC) even after 60 minutes. Of note, Salvador et al., performed a similar 60-minute lactate recovery monitoring of an elite para-athlete with cerebral palsy (Salvador et al., 2016). This athlete was a male, world-class sprinter. In **figure 2**, a comparison between his 60-minute lactate recovery kinetics and the female WCMer who participated in the current study are shown.

Table 1: Characterization and blood lactate responses (BLC) before, during and after 1-minute all out exercise test in elite WCMer.

Variable	
Anthropometric measurements	
Height, m	1.6
Total body mass, kg	42.27
VO_2 max, mL/kg/min	65
Maximal Aerobic Speed, mph	19
Athletic Characterization	
World Para Athletics Classification	T54
Training volume, km/yr	8,000
Blood Lactate Response	
Rest BLC, mmol/L	0.31
Pretest BLC, mmol/L	0.31
BLC(0), mmol/L	4.53
Amplitude: BLC(2), mmol/L	5.61
BLC(60), mmol/L	0.77

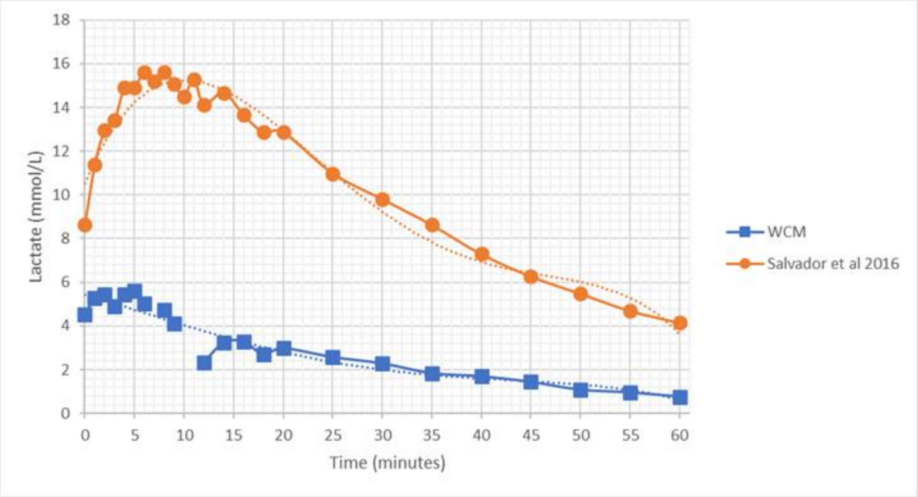

Figure 2: A comparison between the lactate kinetic responses to maximal exercise between an elite male para-athlete (sprinter) with cerebral palsy (orange circle) and an elite female WCMer (blue squares) over 60-minutes.

Discussion.

Characterization of the athletes who compete in the WCM is important for improving the understanding of the physiological demands of this increasingly popular and lucrative sport. In the present study, we measured the lactate kinetic response to a 1-minute maximal exercise effort in an elite, world-class, female WCMer. We demonstrated that this athlete reached maximal lactate concentration (BLC) early in the 60-minute recovery period (t=2min). Interestingly, this athlete did not return to baseline BLC even after 60-minutes of inactivity. We have compared the response of this elite female WCMer with the results from a similar case study that was conducted in an elite para-athlete with Cerebral Palsy (CP). This athlete had a background as a sprinter and the results may provide some interesting information. Specifically, the overall and maximal lactate concentration recorded from the athlete with CP was higher and the recovery curve more steep than the WCMer, denoting a more rapid return to baseline. More research is needed to examine the differences in para-athletes who are sprinters and WCMers, however the results from these two case studies may point to a physiological difference between sprinters and WCMers, which may mean that the WCMer is not phenotypically identical to a sprinter. It is likely that the overall lactate elevations between the athlete with CP and the WCMer are related to the increased amount of active muscle mass used by the athlete with CP.

In the present study, blood lactate recovery kinetics were measured due to the relative simplicity of this procedure, i.e., collection of capillary blood sampling is relatively non-invasive and of minimal cost. Furthermore, information gained from this tool can provide insight into metabolic pathways that have been shown to differ between athletes with sprinting, middle distance, and endurance training backgrounds. We chose to measure the lactate recovery following a 1-minute maximal exercise bout as this length of time would theoretically tax both anaerobic as well as aerobic energy supplies. The lactate recovery kinetics following such a bout can theoretically provide a framework for understanding whether the WCMer demonstrates characteristics more closely aligned with sprinters, middle distance, or endurance athletes. This information is only one piece of the full picture, however the knowledge gained can help athletes and support staff to better support the activity with more specific fueling and training recommendations.

CHAPTER 4: FUTURE DIRECTIONS AND CONCLUSIONS

Introduction

In this thesis, we discussed two sports science tools that have been implemented within the able-bodied athlete population, and commented upon their utility within the para-athlete community, in particular for para-athletes competing in the WCM. Specifically, monitoring of core temperature during exercise and evaluation of lactate kinetics following all-out exercise are both tools that contribute to the support and knowledge base of athletic endeavors.

The para-athlete may require unique considerations compared to able-bodied athletes which may impact the utility of classical sports science tools within this population. Many factors lead to this reality including gastrointestinal dysmotility resulting from spinal cord injury (SCI), altered thermal regulation below injury level, predominant reliance upon smaller muscle groups of upper body to perform exercise, and even the physical positioning inside of the sports chair that may lead to increased gastric discomfort during exercise along with logistical limitations relating to the restricted ability to use one’s hands when they are inside the racing gloves.

For the para-athlete competing in the WCM, additional factors contribute to the physiological demands of the event. For instance, the nature of the race itself must be distinguished from the able-bodied foot race. Specifically, the WCM has been accomplished in under 80 minutes by lead men (Olympics.NBCSports, n.d.) or take up to 3 hours, and these times may significantly change the metabolic demands encountered when compared to traditionally defined marathon-type exercises. Additionally, while drafting plays a role in the foot race, this conservation strategy remains a significant element in the WCM and would theoretically enable the athletes to complete competitive times in a more metabolically economical intensity, thus lowering energy demands of the exercise. Finally, biomechanical proficiency is a key aspect in this event, and remains an important difference from upper body cranking exercises, which have less dependence on technique but have frequently been utilized within the literature. Moreover, all of these factors may affect each athlete differently based on the exact level of injury or position in the race (i.e., leading or drafting), but must be considered to influence the characterization of this event. It is important to identify and synthesize these factors in order to understand the metabolic demands of the WCM.

Major Findings and future directions.

Core Temperature

With regards to core temperature and its impact upon athletic performance, much is already known showing that strategies to help prevent hyperthermia result in performance improvements. In our study, a whole food alternative (potatoes) to commercially available sports gels was able to significantly improve the core temperature response to an endurance cycling challenge in highly trained cyclists.

While this study did not employ para-athletes, findings may be useful points of discussion to help form applications for para-athletes, specifically WCMers. Currently, many WCMers utilize carbohydrate sports drink solutions that can be consumed using a straw which is a hands-free method or they simply do not use any carbohydrate or hydration support at all due to the various challenges they face. Specifically, considerations must be made regarding the ability of a WCMer to tolerate a whole-food option when taking the tight fitting position used in this sport. Moreover, the method of ingestion needs consideration. In our study, participants were provided with potato puree by a member of the research team and while this method is conducive for determining physiological responses, the application of this approach in a real-world competition or training situation remains a limitation to the findings. For WCMers, the use of racing gloves that cover their hands compromises their ability to use their hands, likely making this method logistically unfeasible. Finally, while gastric dysmotility may result from SCI, identifying the rates by which carbohydrates are absorbed by athletes with SCI is an area that requires more research in order to better define nutrition and hydration strategies.

Therefore, it may be of interest for sports and nutrition scientists to examine the utility of whole food ingestion upon core temperature outside of specific exercises periods. For instance, perhaps utilization of a strategy like this may be of use within the pre-cooling period and/or in combination with other cooling methods.

VO$_2$ and lactate recovery kinetics

The biomechanical element of WCM contributes to the uniqueness of the sport. For example, in able-bodied running events there is a neatly ordered decrease in speed as event distance increases across each world record. However, this trend is not true in WCR. With exception of the 100m and 200m (as the time to get started off of the line significantly impedes a wheelchair racer when compared to a runner at these short distances), one will find that average speeds hold fairly constant between each wheelchair racing event (John Barrow, 2013) See **figure 3**.

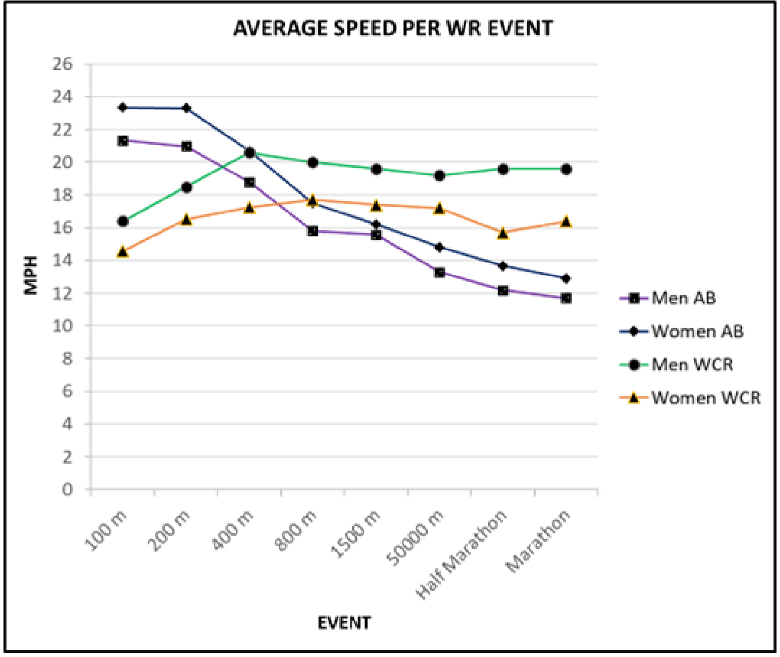

Figure 3: Average speeds (mph) per world record in outdoor athletics events. Purple square refers to able-bodied men's. Blue diamond refers to able-bodied women's events. Light green circle refers to men's wheelchair racing events. Orange triangle refers to women's wheelchair racing events.

This reality is due to the athlete's ability to quickly achieve maximal turnover rate in their cadence and subsequently maintain it over long distances. Thus, athletes are able to compete across many, and even all, of the athletics events. However, the WCM, due to its length and previously described course-induced challenges, would seem to be a priority for nutrition and technical support teams, alike. To our knowledge, no study has investigated the exact role that drafting has on metabolic responses during WCM. It should be emphasized that these average speeds are commonly maintained utilizing this strategy. Moreover, early studies demonstrate a reduction in oxygen cost by 25-40% with this method (A. E. Jeukendrup et al., 2000b) . Here, Jeukendrup et al. also calculated the energy demand of overcoming air resistance alone to be 80% when speeds are >18mph. Therefore, while drafting will significantly reduce intensity, leading athletes require the capability to produce large power outputs at intermittent moments in addition to the final burst seen at the finish line. Therefore, like team cycling races, WCMers may require maximal aerobic and anaerobic capabilities.

It is therefore important to characterize the WCM in order to develop more specific training and nutrition recommendations. It is possible that an examination of top tier WCMers may provide valuable information regarding the results of competing in such activities. Examining recovery kinetics remains an approach that is relatively simple to perform and may help understand the physiological consequences of competing in the WCM. Therefore, we conducted the first case study of such an assessment. As a case study, this project provided only a singular response of one top tier WCMer. However, the major findings were that the elite female WCMer demonstrated an early maximal lactate attainment (t=2min) and that the lactate concentration after 60-minutes of inactivity did not return to baseline levels. These results were compared to a case study of an elite male para-athlete with Cerebral Palsy. While the two athletes differed significantly (Cerebral Palsy versus spinal cord injury, male versus female, and sprinter versus WCM), the fact that the athlete with CP showed a higher spike and a more steep return to baseline could show a difference between athletes with sprinting backgrounds and the WCMer. Future directions require the addition of several other WCMers undergoing the same protocol in addition to non-WCM controls who are competitive in other types of wheelchair racing events, such as track sprinters. Furthermore, measuring recovery kinetics to 1-minute all out exercise in athletes who compete in endurance-type para-sports, like hand cycling, may also help distinguish the physiological differences, if any, that exist between WCMing and arm cranking.

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