Potato ingestion is as effective as carbohydrate gels to support prolonged cycling performance

Amadeo F. Salvador[1], Colleen F. McKenna[2], Rafael A. Alamilla[1], Ryan M. T. Cloud[1], Alexander R. Keeble[1], Adriana Miltko[1], Susannah E. Scaroni[2], Joseph W. Beals[2], Alexander V. Ulanov[3], Ryan N. Dilger[2,4,5], Laura L. Bauer[4], Elizabeth M. Broad[6], and Nicholas A. Burd[1,2]

[1]Department of Kinesiology and Community Health, [2]Division of Nutritional Sciences, [3]Roy J. Carver Biotechnology Center, [4]Department of Animal Sciences, [5]Beckman Institute for Advanced Science and Technology, University of Illinois, Urbana, IL, USA; [6]US Olympic & Paralympic Committee, Chula Vista, CA, USA.

Running head: Potato ingestion and exercise performance

Corresponding author: Nicholas A. Burd, PhD, Department of Kinesiology and Community Health, University of Illinois at Urbana-Champaign, 352 Louise Freer Hall, 906 S. Goodwin Avenue, Urbana, IL 61801, USA, Email : naburd@illinois.edu, Phone : +1 (217) 244-0970

Key words: carbohydrate, exercise, sports nutrition, endurance

ABSTRACT

Carbohydrate (CHO) ingestion is an established strategy to improve endurance performance. Race fuels should not only sustain performance, but also be readily digested and absorbed. Potatoes are a whole-food based option that fulfills these criteria yet their impact on performance remains unexamined. We investigated the effects of potato purée ingestion during prolonged cycling on subsequent performance versus commercial CHO gel or a water-only condition. Twelve cyclists (70.7 ± 7.7 kg, 173 ± 8 cm, 31± 9 years, 22 ± 5.1 % body fat; mean ± SD) with average peak oxygen consumption (VO_{2PEAK}) of 60.7 ± 9.0 mL/kg/min performed a 2 h cycling challenge (60-85%VO_{2PEAK}) followed by a time trial (TT, 6kJ/kg body mass) while consuming potato, gel, or water in a randomized-crossover design. The race fuels were administered with U-[$^{13}C_6$]glucose for an indirect estimate of gastric emptying rate. Blood samples were collected throughout the trials. Blood glucose concentrations were higher (P<0.001) in potato and gel conditions when compared to water condition. Blood lactate concentrations were higher (P=0.001) after the TT completion in both CHO conditions when compared to water condition. TT performance was improved (P=0.032) in both potato (33.0 ± 4.5 min) and gel (33.0 ± 4.2 min) conditions when compared to the water condition (39.5 ± 7.9 min). Moreover, no difference was observed in TT performance between CHO conditions (P=1.00). In conclusion, potato and gel ingestion equally sustained blood glucose concentrations and TT performance. Our results support the effective use of potatoes to support race performance for trained cyclists.

New & Noteworthy: The ingestion of concentrated carbohydrate gels during prolonged exercise has been shown to promote carbohydrate availability and improve exercise performance. Our study aim was to expand and diversify race fueling menus for athletes by providing an evidence based whole food alternative to the routine ingestion of gels during training and competition. Our work shows that russet potato ingestion during prolonged cycling is as effective as carbohydrate gels to support exercise performance in trained athletes.

INTRODUCTION

Carbohydrate (CHO) ingestion during prolonged endurance exercise (>2 h) is a proven dietary strategy to sustain exercise performance (31). The factors that contribute to the increased exercise performance with CHO ingestion include maintenance of blood glucose concentrations, high exogenous CHO oxidation rates during the late stages of a race, and attenuation in the decline of liver glycogen during prolonged exercise (18). Indeed, the amount of ingested CHO required to support exercise performance is closely connected to the intensity and duration of the exercise bout, but recommendations generally range from 30-60 g/h with some recommendations as high as 90 g/h depending on the type of CHO consumed and duration of exercise (24).

Specifically formulated sports foods, such as concentrated CHO gels, are commonly used by endurance athletes to enhance CHO availability during training and competition (19). The form (e.g., liquid vs. solid) in which the CHO is ingested does not appear to modulate its delivery and oxidation during exercise (32, 35). Hence, optimal race feeding is somewhat personalized and race fuel selection will depend on a variety of factors including taste, cost, and the risk of gastrointestinal (GI) distress. The latter is pertinent as the prevalence of exercise-induced GI distress has been reported by 30-70% of endurance athletes (6, 12), and this GI distress may negatively impact their performance (12). As such, the gut has been increasingly recognized as an athletic organ (25); therefore, the most appropriate race fuel should facilitate gastric emptying, intestinal absorption, and deliver targeted amounts of exogenous carbohydrates without exacerbating GI symptoms (e.g., cramping, bloating, vomiting, etc) during competition (23).

While commercially-available sports foods have been shown to effectively increase exercise performance (7), it is relevant to identify other high performance foods to provide diet (CHO) diversity for an athlete. Therefore, the purpose of the present study was to assess the effectiveness of potato ingestion as a fueling strategy to support cycling time trial (TT) performance when compared to CHO gel or water in trained cyclists. Potatoes are a promising alternative for athletes because they represent a cost effective, nutrient dense, and whole food source of CHO; furthermore, they serve as a savory race fuel option when compared to the high sweetness of CHO gels. We examined other relevant variables that may 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-$^{13}C_6$]glucose was orally administered to provide (indirect) insight into the appearance rate of ingested glucose into 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 only consuming water in trained cyclists.

METHODS

Participants and Ethical Approval

Twelve cyclists (n = 9 male, n = 3 female; 70.7 ± 7.7 kg, 173 ± 8 cm, 30.6 ± 8.7 years, 21.6 ± 5.1% body fat) volunteered to participate in this study. Participants cycled on average 267 km/week (range 120 to 480 km/week) and had been training an average of 7 years (range 3 to 20 years). Based on peak oxygen consumption (VO_{2PEAK}, 60.7 ± 9.0 mL/kg/min), peak workload (W_{PEAK}, 350 ± 63 W), and W_{PEAK}/kg (4.9 ± 0.7 W/kg), the participants were classified as endurance trained and competitive (13). Experimental trials were completed during the mid-follicular phase of the menstrual cycle for the female participants. All participants were considered healthy based on a self-reported medical screening questionnaire. Each participant was informed of the purpose of the study, the experimental procedures, and all of the potential risks prior to 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*. This trial is registered at clinicaltrials.gov as NCT03294642.

Pre-testing

All participants underwent pre-testing procedures on two separate occasions. On the first visit, body weight, height, and body composition by dual-energy X-ray absorptiometry (QDR 4500A; Hologic, Marlborough, MA, USA) were measured. Subsequently, participants performed an incremental cycling test on an electronically-braked cycle ergometer (Lode Excalibur Sport, Groningen, Netherlands) with the initial power set at 2 W/kg body weight and increased by 30 W for males and 20 W for females every 1 min until exhaustion. VO_{2PEAK} was determined as the highest recorded 20 s VO_2 value when ≥3 criteria were satisfied: (1) a plateau in oxygen consumption despite an increase in work rate; (2) respiratory exchange ratio ≥1.10; (3) Heart rate peak within 10 bpm of age-predicted maximum (i.e., 220-age); or (4) ratings of perceived of exertion (RPE, Borg scale 6-20) ≥ 17. The VO_{2PEAK} workload (VO_{2PPEAK}) and peak workload (W_{PEAK}) were defined as the intensity related to the VO_{2PEAK} and the final intensity achieved at the end of the test, respectively. Inclusion criteria was set at a minimum VO_{2PEAK} of 50 mL/kg/min for males and 45 mL/kg/min for females. During the screening phase, 4 participants were excluded for not meeting this threshold; however, the 12 participants enrolled achieved a VO_{2PEAK} above the minimum threshold. The participant's preferred cadence was also determined during incremental test, with first and last stages excluded from the calculation to avoid ergometer adaptation and fatigue effect, respectively. The seat position was recorded and replicated for all the subsequent tests.

On the second visit to the laboratory, participants performed a familiarization ride consisting of a 120 min cycling challenge followed by a TT. The prescribed cycling challenge intensities were predicted based on the incremental test and confirmed based on respiratory gases collected during the first hour of the familiarization ride. During this trial, the participants used their own preferred fueling strategy. Participants were excluded if they were not able to complete the cycling challenge or the TT. During the screening phase, 2 participants were excluded because they could not complete the familiarization trial. The 12 participants studied successfully completed the familiarization trial. Afterwards, participants were randomized with the trial order counterbalanced to consume either: *(1)* baked white potato flesh purée (60 g CHO/h); *(2)* commercially-available energy gel (60 g CHO/h); or *(3)* water.

Dietary and Activity Control

Exercise and nutritional status were controlled prior to each experimental trial. Specifically, participants consumed standardized meals provided by the research team for 24 h prior to each experimental trial. The meal plans were designed by a registered dietitian to mimic recommended nutritional practices for endurance sport. Specifically, each meal had an energy content of 9 kcal/kg body mass and composed of 60% CHO [1.4 g/kg/meal (7 g/kg/day)], 20% protein (0.4 g/kg/meal), and 20% fat (0.2 g/kg/meal) with breakfast, lunch, dinner, and two snacks being the meal times emphasized. Consumed meals were recorded and replicated for the next trials. In addition, the participants were requested to abstain from drinking alcohol for 48 h and ingesting caffeine and/or NSAIDs (non-steroidal anti-inflammatory drugs) the morning of their experimental trials. Participants were also provided with an ingestible thermistor capsule (HQ Inc., Palmetto, FL) to be consumed 8-12 h prior to the experimental trials. Diet and training diaries were used to assess compliance and returned to allow the participant to repeat identical habits prior to each trial. In addition, the participants were requested to avoid any type of exercise 48 h before the trials.

Experimental Protocol

Each participant arrived at the laboratory at the same time in the morning after an overnight fast. On arrival, an intravenous (IV) 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 prior to the commencement of the cycling challenge. Prior to 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, USA) and were towel-dried prior to 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%VO_{2PEAK} followed by steady-state exercise at 60%VO_{2PEAK}, with four intermittent, high intensity bursts (each 3 min at 85%VO_{2PEAK}) to simulate hill climbs. Each burst was immediately followed by a low intensity period (1 min at

$35\%VO_{2PEAK}$) to simulate descents. “Hills” and “descents” were performed once every 30 minutes. On two of the trials, participants were administered supplemental CHO (15 g CHO administered every 15 min) in the form of baked russet potato flesh purée (128.5 g per bolus) or CHO gels (PowerBar; 23 g per bolus). All treatments were supplemented with 2% enriched (0.3 g) U-[$^{13}C_6$]glucose to provide a proxy for gastric emptying rates and the subsequent appearance of exogenous glucose into circulation (3). Blood sampling, heart rate, core temperature, RPE (Borg scale 6-20) and GI symptoms were assessed throughout the cycling challenge according to **Figure 1.** For the TT, the ergometer was set in linear mode with the linear factor based on their personal 70% P_{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 TT and no information about performance was provided. After completion of the TT, participants were towel-dried, 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 (16). This calculation accounts for the Borg scale’s ceiling effect (4). The GI symptoms (i.e., overall symptoms, abdominal pain, abdominal bloating, gut rumbling, flatulence, abdominal discomfort) were rated against a standardized 0–100 millimeters visual analogue scale (VAS) questionnaire. Blood samples were collected in EDTA-containing tubes and centrifuged at 3000 × *g*, 4ºC for 10 min. Aliquots of plasma were frozen and stored at -80ºC until subsequent analysis.

Race Fuel Preparation and Analysis

Russet potatoes were purchased fresh before each trial. Potatoes were microwaved, peeled, blended in a food processor, and then both processed potatoes and gel were analyzed for total nonstructural carbohydrate content (gross measure of the proportion of CHO that could be digested by mammalian enzymes) (38) in order to determine appropriate serving size for goal CHO dose. 548 g of potato flesh (~1.1 kg raw potatoes), baked in skin, yielded 120 g CHO for the 2 h cycling challenge. The baked-in-skin potato flesh was blended with 478.5 mL H_2O and 2.4 g table salt (NaCl) to achieve a consistency and salinity similar to the CHO gels. 184 g (120 g CHO) of sport gels (PowerBar®, Power Gel®, vanilla; Premier Nutrition, Emeryville, CA) were consumed during the respective cycling challenge. Both the potato purée and gels were aliquoted into 8 servings (15 g CHO), and refrigerated (4ºC) until trial-day time of ingestion. CHO conditions were administered in 30 mL disposable syringes to standardize method of delivery. The gels did not contain caffeine or any stimulants.

An additional aliquot of CHO conditions (potato and gel) from each trial was frozen at -20°C for future CHO compositional analysis. Samples were freeze-dried, ground, and a subsample was heated to 105°C to determine dry matter content—all subsequent extractions were calculated on a dry matter basis. Crude protein, ash, and total dietary fiber (along with an insoluble/soluble split) were extracted by α-amylase and amyloglucosidase as previously described (36). Free monosaccharides, oligosaccharides, and fructooligosaccharides were isolated by high-performance liquid chromatography (HPLC) analysis (8, 37). No quantifiable amount of fructo- and galacto- oligosaccharides were detected in either potato or gel samples. Monosaccharides and sugar alcohols were extracted by sulfuric acid hydrolysis with added 2-deoxyglucose as an internal standard. Composition was determined by HPLC analysis and quantified against known standards of various monosaccharides and sugar alcohols (21). The nutrient composition and estimated energy yield (44) of the treatments is shown in **Table 1**.

Fluid intake was also controlled during all three trials. Experimental trial 1, irrespective of condition, served to identify each participants' 'usual' water intake by allowing water *ad* *libitum*. This amount was recorded and replicated throughout all subsequent trials. Water used for potato purée preparation was accounted for total water allowance. We used this approach as fluid intake guidelines are varied and highly individualized in trained athletes due to differential sweat rates. Hydration status was assessed from pre- to post-exercise based on changes in body mass, urine osmolality, and USG.

Blood Analysis

Glucose and lactate were analyzed in whole blood using an automated biochemical analyzer (YSI 2300 Stat Plus; YSI, Yellow Springs, OH, USA). Plasma insulin concentrations were determined by a commercially-available enzyme-linked immunosorbent assay (ELISA) (ALPCO Diagnostics, Salem, NH, USA) and expressed as area under the curve (AUC) during the cycling challenge. Plasma I-FABP concentrations were assessed by an ELISA according to manufacturer's instructions (Hycult Biotechnology, Uden, NL) and it was expressed as fold change from baseline. Plasma [U-$^{13}C_6$]glucose enrichments were determined by gas chromatography–mass spectrometry (GC-MS) analysis (7890A GC/5975C MSD; Agilent). Briefly, plasma samples were deproteinized and converted into their tert-butyldimethylsilyl derivatives and enrichments were determined using electron ionization by ion monitoring at *m/z* of 319 (*m*+0), 321 (*m*+2), and 323 (*m*+4). Plasma glucose enrichments for each labeled ion were expressed relative to 319 (*m*+0, tracee) and enrichment was expressed as tracer-to-tracee-ratio (TTR). All blood metabolites were analyzed blindly.

Expired Gas Analysis

Oxygen consumption (VO_2), carbon dioxide production (VCO_2), and ventilation per minute (VE) were measured breath-by-breath using an automated open-circuit gas analysis system (TrueOne

2400 Parvo Medics, Inc., Salt Lake City, UT, USA) throughout each test. During the cycling challenge, the last 15 min of expired gas was collected, and 30 second-averages between 111.5 and 116 min of the cycling challenge was used to calculate fat and CHO oxidation rates during exercise in a blinded-fashion according to the equations below (17):

$$Fat\ oxidation = (1.695 \cdot VO2) - (1.701 \cdot VCO2)$$

$$Carbohydrate\ oxidation = (4.21 \cdot VCO2) - (2.962 \cdot VO2)$$

with VO_2 and VCO_2 in liters per min (L/min) and oxidation rates in grams per min (g/min).

Statistics

Based on *a priori* power analysis, twelve participants exceeded the minimum sample size required to detect difference in time trial performance with a power of 0.80. This power calculation was based on a 2-tailed alpha level of 0.05 and past efforts that used a similar time trial approach (42). The effect of nutritional strategy on outcomes was estimated via a linear mixed model analyses of variance using the software SPSS version 20. For analysis of plasma U-[$^{13}C_6$]glucose enrichments, glucose, lactate, insulin, I-FABP, CHO and fat oxidation, RPE, GI symptoms, workload, total work, and heart rate, the fixed factors were time and condition (water, potatoes, or gel) and the random factor was subject. For analysis of TT performance, weight loss, USG, and urine osmolality, condition was the only fixed factor. The TT was divided in four quartiles for performance, RPE, and HR analyzes. Bonferroni's post hoc tests were performed to determine differences between means for all significant main effects and interactions. To evaluate the relationship between TT performance and I-FABP or glucose concentrations at 120 min (onset of TT), the repeated-measures correlation analysis was performed using the rmcorr R package developed by Bakdash and Marusich (https://cran.rproject.org/web/packages/rmcorr/) (2). The level of statistical significance was set at P<0.05 for all analysis. The data are expressed as mean and standard deviation (SD).

RESULTS

Challenge and Time Trial

The average difference between experimental trial start time for cycling challenge and TT was 11 ± 10 and 9 ± 9 min, respectively. Total weight loss did not differ (P=0.824) between water (-2.04 ± 0.89 kg), potato (-1.84 ± 0.74 kg), or gel conditions (-1.87 ± 0.59 kg). Similarly, USG was not different (P=0.605) between the water (PRE: 1.008 ± 0.005 and POST: 1.010 ± 0.004), potato (PRE: 1.011 ± 0.009 and POST: 1.009 ± 0.004) and gel conditions (PRE: 1.011 ± 0.007 and POST: 1.010 ± 0.004). Before the start of the cycling challenge, urine osmolality was 323 ± 189, 380 ± 275, 374 ± 260 mOsm/kg for water, potato and gel conditions, respectively. After completion of the TT, urine osmolality was 351 ± 158, 316 ± 150, 341 ± 150 mOsm/kg for water, potato and gel conditions, respectively. No time (P=0.875) or condition (P=0.740) effects were observed in urine osmolality.

The average absolute challenge intensities were 150 ± 32, 180 ± 30, 278 ± 50, 93 ± 21 W for 50%, 60%, 85%, and 35 $\%VO_{2PPEAK}$, respectively. These intensities represent 43 ± 4, 52 ± 2, 80 ± 5 and 27 ± 3% W_{PEAK}, respectively. Average total work performed during the entire challenge was 1332 ± 232 kJ, and specifically 45 ± 9, 778 ± 133, 200 ± 36 and 28 ± 6 kJ at the intensities 50%, 60%, 85%, 35$\%VO_{2PPEAK}$, respectively. Heart rate responses during the cycling challenge were not different between conditions (P=0.962). The heart rate average values at the first, second, third, and fourth hills were 167 ± 8, 166 ± 8, 167 ± 9 and 169 ± 8 bpm for the water condition, 167 ± 7, 168 ± 8, 167 ± 8 and 168 ± 8 bpm for the potato condition and, 167 ± 8, 168

± 8, 168 ± 7 and 169 ± 8 bpm for the gel condition, respectively. During the TT, CHO ingestion, irrespective of condition, resulted in a higher percentages of peak heart rate obtained when compared with water condition (P<0.01). Peak heart rate was obtained during the incremental test. The percentage values for each condition were: 86 ± 11%, 86 ± 11% and 85 ± 10% (water); 91 ± 8%, 90 ± 8% and 92 ± 8% (potato); and 91 ± 9%, 91 ± 9% and 93 ± 7% (gel) during the second, third, and fourth quartile of the TT, respectively.

Whole Body Substrate Oxidation

A main effect of condition was observed in CHO and fat oxidation (P<0.001) with no effect of time (P=1.00). Gel (1.79 ± 0.59 g/min; P<0.001) and potato (1.69 ± 0.40 g/min; P<0.001) conditions showed higher CHO oxidation when compared to the water condition (1.42 ± 0.54 g/min). Similarly, fat oxidation was higher in water (0.75 ± 0.28 g/min) when compared to potato (0.65 ± 0.25 g/min; P=0.017) and gel conditions (0.59 ± 0.26 g/min; P<0.001). There was no difference between gel and potato conditions in CHO (P=0.556) and fat oxidation (P=0.437).

Rating of Perceived Exertion

RPE values at 60 min (water: 14.9 ± 2.1, potato: 14.6 ± 1.9, gel: 14.4 ± 2.5) and at the cessation of the cycling challenge (water: 17.5 ± 2.3, potato: 16.5 ± 2.4, gel: 17 ± 2) were different (P<0.001) from baseline (water: 7.5 ± 1.7, potato: 7.0 ± 1.4, gel: 7.7 ± 1.9). No differences (P=0.106) between conditions were observed in raw and fold-change controlled by the baseline value. However, significant differences were observed in RPE relative to load performed between potato (P=0.005) and gel (P=0.008) conditions versus water condition during the TT (**Figure 2**).

Core Temperature

There was no difference in core temperature (P=0.779) between 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) condition at 24, 17, 19 min, respectively. In addition, even with no differences (P=0.685) in the baseline value between water (36.9 ± 0.3°C), potato (36.8 ± 0.3°C), and gel condition (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) when compared to gel (38.3 ± 0.5°C) condition, with no differences when compared to the water (37.9 ± 0.5°C) condition.

Blood Analysis

No differences were observed in baseline measurements for blood glucose concentrations (P=1.00). Blood glucose concentrations (P<0.001) were elevated in both CHO conditions when compared to the water condition during the cycling challenge (**Figure 3a**). The plasma [$U^{13}C$]glucose enrichments were not different between CHO conditions. However, a difference (P<0.001) was observed between CHO conditions and the water condition after 45 min of the cycling challenge until the end of the experimental trial (**Figure 3b**). No differences were observed in blood lactate concentrations (**Figure 3c**) between conditions during the cycling challenge; however, a higher lactate concentration (P=0.001) was found after TT completion in both CHO conditions (potato: 4.0 ± 2.3 and gel: 4.7 ± 1.3 mmol/L) when compared to water condition (2.4 ± 1.0 mmol/L). Plasma insulin concentrations were higher in the gel when compared to the water condition (main effect of condition: P=0.003). There were no differences in plasma insulin concentrations between the potato and water conditions (P=0.253). CHO ingestion reduced (P=0.011) exercise-induced intestinal damage, as indicated by lower plasma I-

FABP concentrations (**Figure 3e**), in CHO conditions at 75 min of the cycling challenge, which remained lower until the end of the TT.

Gastrointestinal Symptoms

GI symptoms are shown in **Figure 4**. The overall GI symptoms were higher for potatoes when compared to the other conditions after the cycling challenge (120 min). Specifically, there was higher level of abdominal pain, bloating, and discomfort during the late phases of the cycling challenge. No correlations between plasma I-FABP concentration and GI symptoms were observed.

Performances Measurements

TT performance (**Figure 5a**) was significantly faster (P=0.032) in potato (33.0 ± 4.5 min) and gel (33.0 ± 4.2 min) conditions when compared to the water condition (39.5 ± 7.9 min). However, no difference was observed between the potato and gel conditions (P=1.00). When power output was analyzed in quartiles (**Figure 5b**), time to completion of each quartile of the TT was statistically different (P=0.02) for CHO conditions when compared to water across all quartiles, indicating no difference in pace or race strategy selected by the athlete. In addition, TT performance was inversely correlated to blood glucose concentration (r=-0.72; P<0.001; 95% confidence interval (CI) =-0.88 to -0.42), and positively correlated with plasma I-FABP concentration (r= 0.65; P=0.001; 95% CI= 0.28 to 0.85) at 120 min, before the TT start.

DISCUSSION

CHO ingestion to sustain exercise performance has been extensively studied (11, 31). However, most research has used manufactured CHO products, limiting evidence-based confirmation of whole food sources as an effective race fuel alternative. To our knowledge, our investigation is the first to provide such a comparison of a whole food CHO source (i.e., russet potato) to a commercially-available sport food such as concentrated CHO gel in a performance specific setting. We demonstrated that potato ingestion during exercise exhibited similar performance improvements over water when compared to the ingestion of gels during prolonged cycling in trained athletes.

The end-state vision for coaches, dietitians, and athletes is to translate research outputs into practical applications and ultimate implementation into training for more successful competition (10). The cyclists tested in this study are classified as endurance trained (13). This categorization is relevant for interpretation of results since a significant change in exercise performance is only observed when the intervention effect is highly pronounced. In other words, the more trained the athlete, the less susceptible they are to improvement in exercise performance outcomes than a non-trained individual (22). Even with no difference in heart rate during the cycling challenge between conditions in the present study, the self-paced timed trial altered the heart rate response. Specifically, the potato and gel conditions resulted in an increased heart rate during the TT. This was likely due to a higher exercise intensity selection and tolerance with CHO ingestion when compared to water alone. Moreover, there were no differences observed between the potato and gel conditions in heart rate, showing the ability of these treatments to reach a higher cardiovascular stimulus when 60g of CHO/h is ingested versus the consumption of only water.

The RPE responses were consistent with previous studies (33), confirming the potential of exogenous carbohydrate in attenuating exertional perceptions during long endurance cycling (1, 33). RPE relative to watts was lower in both CHO conditions (**Figure 2**), which can not only be attributed to the effectiveness of exogenous CHO in generating more power, but may also be associated with the reward value of CHO intake (43). RPE is an important marker in models of fatigue and is regularly used to dictate intensities in training sessions (16), and the similarity the RPE/W between CHO conditions highlights the feasibility of potatoes as an alternative training or race fuel.

Proper GI function (i.e., sufficient gastric emptying rates and intestinal absorption of nutrients) is relevant to ensure the adequate delivery of fluid and carbohydrates during training and competition. Here, we showed that plasma glucose concentrations were increased to a similar extent between the potato and gel conditions versus the water condition throughout the exercise protocol (**Figure 3a**). Moreover, plasma [U-$^{13}C_6$]glucose enrichments did not differ between the potato and gel conditions, which suggests that gastric emptying rates were similar between the CHO conditions (**Figure 3c**). Similarly, substrate utilization during the late phase of the cycling challenge demonstrated that whole body CHO oxidation rates were higher as well as fat oxidation rates were lower with the ingestion of exogenous CHO. Unfortunately, our experimental approach does not allow us to interpret the influence of food source preference on exogenous versus endogenous CHO oxidation rates. Moreover, it has been established that the ingestion of multiple transportable CHO allows for higher amounts (90 g/h) of CHO to be consumed, thereby allowing for higher CHO oxidation rates to be achieved during prolonged exercise (23). Hence, our findings may only be relevant for ingested CHO doses of 60 g/h.

Plasma I-FABP concentrations are often used as a biomarker for gut damage in exercise studies (27, 39). I-FABP are cytosolic proteins present in enterocytes, which are rapidly released into the bloodstream upon intestinal cell damage. We have previously demonstrated an exercise-induced increase in plasma I-FABP concentrations when compared to a rested-state (29). Importantly, previous studies have shown the potential of nutritional supplements to 'protect' the gut from exercise-induced damage during prolonged exercise (26, 45), albeit inconsistent (30).

Potato ingestion reduced gut damage, as indicated by similar reductions in plasma I-FABP concentrations between gel and potato versus the water condition, throughout the exercise protocol (**Figure 3e**). As such, more research is needed to determine optimal feeding strategies that reduce GI distress and improve gut resilience while maximizing glucose availability. Nevertheless, the present study is the first to report a correlation between exercise performance and plasma I-FABP concentrations. This highlights the importance of protecting (45) and 'training your gut' (25) to reduce intestinal damage and sustain performance.

It is important to recognize that the increase in plasma I-FABP concentrations in our study was not accompanied with an increase in GI symptoms. However, the lack of correlation between GI symptoms and I-FABP is consistent with other studies (27, 39). GI symptom responses vary based on exercise mode, intensity, duration, and nutritional strategy adopted, which makes comparisons between studies challenging (34). Here, potato ingestion resulted in higher GI symptoms when compared to the gel or water conditions (**Figure 4**). We speculate that the higher volume of potato needed to reach the same quantity of CHO/dose of gel (i.e., 128g/145 mL potato purée versus 23g/24mL gel per dose) the retrogradation (i.e., formation of resistant starch) process during cooling which increases the indigestible proportion, could cumulatively cause higher GI symptoms in this condition. Nevertheless, average GI symptoms (**Figure 4**) were lower than previous studies (34) indicating that both CHO conditions were well tolerated by majority of the study's cyclists. It is worthwhile to mention that only two participants had previously chosen potatoes as their personal race fuel, but all participants regularly ingest CHO gels during races and training, and according to the gut training theory (6, 25) frequency of ingestion could also alter digestibility and perceptions of fullness. Thus, the regular use of potato purée as a race feeding strategy may reduce GI symptoms over time; however, future work would be required to confirm this assertion.

Although the higher GI distress noted in the potato condition may be explained by the higher overall volume of potatoes (~8 medium sized potatoes) and resistant starch formation, these factors may have also influenced the significantly lower core temperature that was observed in the potato condition versus the gel condition. The gel and potato treatments were administered at the same temperature, and there were no differences in core temperature at baseline, yet potato ingestion facilitated 0.5°C decrease in core temperature. Indeed, our trials were conducted in ambient temperature, which differs from the majority of thermoregulation studies that use heat and humid conditions (40), so we advise caution when interpreting core temperature observations of chilled potato purée as a cooling strategy.

Ultimately, the identification of an optimal race feeding strategy for the competition day is complex, with direct considerations like exercise mode, intensity, and duration playing a role in an athlete's nutrition requirements (e.g., timing and dose). Furthermore, indirect considerations like taste preference, cost, and overall convenience will also influence race fuel source. Indeed, carrying and ingesting ~1 kg of potato purée would be somewhat burdensome on an athlete; however, our approach allowed us to standardize CHO content and food consistency so that we may appropriately evaluate our study outcomes. Overall, our work simply provides a proof-of-principle for a whole food source of CHO to serve as a viable sport food to be included in race feeding strategies to provide an alternative to the routine ingestion of gels during training and competition. Our outcomes can be utilized by coaches, sport dietitians, and race event organizations to incorporate potatoes as an effective performance nutrition option, with recipes being tailored to an athlete's preference throughout training and/or a race. This will help reduce the risk of flavor fatigue (i.e., viable savory option) (28), offset financial burden, and increase diet diversity. Importantly, the nutrient matrix of a potato-sourced race fuel also contains other micronutrients that may be beneficial to improve diet quality of an athlete (5, 20).

It is worth noting that there are other investigations of peri-exercise food source on exercise performance. Specifically, Thomas et al (41) observed that pre-exercise meals consisting of glucose, water, and lentils potentiated exercise performance in comparison to potatoes. Results comparison is limited however, as the respective study measured performance by time to exhaustion—an impractical method with low reliability (15). Alternatively, our exercise protocol seeks to improve race-day applicability, incorporating high intensity hills during the first two hours of exercise followed by a long cycling TT, with the total exercise duration over 150 minutes. Consequently, such practicality limits the comparisons between other findings. Nevertheless, the performance increase in CHO over control (i.e., water) in the present study is higher when compared to use of other whole food sources (i.e., honey) (14), CHO mouth rinse (9), and caffeine supplementation (7).

In conclusion, we demonstrated that the ingestion of potato purée represents a viable race feeding strategy by maintaining blood glucose concentration, facilitating gastric emptying, and supporting cycling performance similar to concentrated CHO gel products. Our results have implications for the inclusion of a whole-food based option as a component of a race feeding strategy to support prolonged exercise performance. Future studies that investigate potato processing (e.g., baked, pureed, freeze-dried, etc.) for GI acceptance (i.e., reduced GI symptoms and intestinal permeability) would certainly optimize evidence-based performance nutrition for endurance athletes.

Acknowledgements

We are thankful to the participants who volunteered for this study.

Grants

Funding for this research was provided by Alliance for Potato Research & Education. A. F. Salvador is supported by Coordination for the Improvement of Higher Education Personnel (CAPES).

Disclosures

No conflicts of interest, financial or otherwise, to declare by the authors.

REFERENCES

1. **Backhouse SH, Bishop NC, Biddle SJ, and Williams C**. Effect of carbohydrate and prolonged exercise on affect and perceived exertion. *Medicine and science in sports and exercise* 37: 1768-1773, 2005.
2. **Bakdash JZ, and Marusich LR**. Repeated Measures Correlation. *Front Psychol* 8: 456, 2017.
3. **Beelen M, Kranenburg J, Senden JM, Kuipers H, and Loon LJ**. Impact of caffeine and protein on postexercise muscle glycogen synthesis. *Medicine and science in sports and exercise* 44: 692-700, 2012.
4. **Borg GA**. Psychophysical bases of perceived exertion. *Medicine and science in sports and exercise* 14: 377-381, 1982.
5. **Brisswalter J, and Louis J**. Vitamin supplementation benefits in master athletes. *Sports medicine* 44: 311-318, 2014.
6. **Brouns F, and Beckers E**. Is the gut an athletic organ? Digestion, absorption and exercise. *Sports medicine* 15: 242-257, 1993.
7. **Burke LM, and Read RS**. Dietary supplements in sport. *Sports medicine* 15: 43-65, 1993.
8. **Campbell JM, Bauer LL, Fahey GC, Hogarth A, Wolf BW, and Hunter DE**. Selected fructooligosaccharide (1-kestose, nystose, and 1F-β-fructofuranosylnystose) composition of foods and feeds. *Journal of agricultural and food chemistry* 45: 3076-3082, 1997.

9. **Carter JM, Jeukendrup AE, and Jones DA**. The effect of carbohydrate mouth rinse on 1-h cycle time trial performance. *Medicine and science in sports and exercise* 36: 2107-2111, 2004.
10. **Close GL, Kasper AM, and Morton JP**. From Paper to Podium: Quantifying the Translational Potential of Performance Nutrition Research. *Sports medicine* 49: 25-37, 2019.
11. **Coyle EF, Hagberg JM, Hurley BF, Martin WH, Ehsani AA, and Holloszy JO**. Carbohydrate feeding during prolonged strenuous exercise can delay fatigue. *Journal of applied physiology: respiratory, environmental and exercise physiology* 55: 230-235, 1983.
12. **de Oliveira EP, and Burini RC**. Carbohydrate-dependent, exercise-induced gastrointestinal distress. *Nutrients* 6: 4191-4199, 2014.
13. **De Pauw K, Roelands B, Cheung SS, de Geus B, Rietjens G, and Meeusen R**. Guidelines to classify subject groups in sport-science research. *Int J Sports Physiol Perform* 8: 111-122, 2013.
14. **Earnest CP, Lancaster SL, Rasmussen CJ, Kerksick CM, Lucia A, Greenwood MC, Almada AL, Cowan PA, and Kreider RB**. Low vs. high glycemic index carbohydrate gel ingestion during simulated 64-km cycling time trial performance. *Journal of strength and conditioning research* 18: 466-472, 2004.
15. **Faude O, Hecksteden A, Hammes D, Schumacher F, Besenius E, Sperlich B, and Meyer T**. Reliability of time-to-exhaustion and selected psycho-physiological variables during constant-load cycling at the maximal lactate steady-state. *Applied physiology, nutrition, and metabolism = Physiologie appliquee, nutrition et metabolisme* 42: 142-147, 2017.
16. **Fontes EB, Smirmaul BP, Nakamura FY, Pereira G, Okano AH, Altimari LR, Dantas JL, and de Moraes AC**. The relationship between rating of perceived exertion and muscle activity during exhaustive constant-load cycling. *International journal of sports medicine* 31: 683-688, 2010.
17. **Frayn KN**. Calculation of substrate oxidation rates in vivo from gaseous exchange. *Journal of applied physiology: respiratory, environmental and exercise physiology* 55: 628-634, 1983.
18. **Gonzalez JT, Fuchs CJ, Smith FE, Thelwall PE, Taylor R, Stevenson EJ, Trenell MI, Cermak NM, and van Loon LJ**. Ingestion of glucose or sucrose prevents liver but not muscle glycogen depletion during prolonged endurance-type exercise in trained cyclists. *American journal of physiology Endocrinology and metabolism* 309: E1032-1039, 2015.
19. **Havemann L, and Goedecke JH**. Nutritional practices of male cyclists before and during an ultraendurance event. *International journal of sport nutrition and exercise metabolism* 18: 551-566, 2008.
20. **Heffernan SM, Horner K, De Vito G, and Conway GE**. The Role of Mineral and Trace Element Supplementation in Exercise and Athletic Performance: A Systematic Review. *Nutrients* 11: 2019.
21. **Hoebler C, Barry JL, David A, and Delort-Laval J**. Rapid acid hydrolysis of plant cell wall polysaccharides and simplified quantitative determination of their neutral monosaccharides by gas-liquid chromatography. *Journal of Agricultural and Food Chemistry* 37: 360-367, 1989.
22. **Hopkins WG**. Measures of reliability in sports medicine and science. *Sports medicine* 30: 1-15, 2000.
23. **Jentjens RL, Moseley L, Waring RH, Harding LK, and Jeukendrup AE**. Oxidation of combined ingestion of glucose and fructose during exercise. *Journal of applied physiology* 96: 1277-1284, 2004.

24. **Jeukendrup A**. A step towards personalized sports nutrition: carbohydrate intake during exercise. *Sports medicine* 44 Suppl 1: S25-33, 2014.
25. **Jeukendrup AE**. Training the Gut for Athletes. *Sports medicine* 47: 101-110, 2017.
26. **Jonvik KL, Lenaerts K, Smeets JSJ, Kolkman JJ, LJC VANL, and Verdijk LB**. Sucrose but Not Nitrate Ingestion Reduces Strenuous Cycling-induced Intestinal Injury. *Medicine and science in sports and exercise* 51: 436-444, 2019.
27. **Karhu E, Forsgard RA, Alanko L, Alfthan H, Pussinen P, Hamalainen E, and Korpela R**. Exercise and gastrointestinal symptoms: running-induced changes in intestinal permeability and markers of gastrointestinal function in asymptomatic and symptomatic runners. *European journal of applied physiology* 117: 2519-2526, 2017.
28. **Maga JAJFRI**. Potato flavor. 10: 1-48, 1994.
29. **Mazzulla M, Parel JT, Beals JW, S VANV, Abou Sawan S, West DWD, Paluska SA, Ulanov AV, Moore DR, and Burd NA**. Endurance Exercise Attenuates Postprandial Whole-Body Leucine Balance in Trained Men. *Medicine and science in sports and exercise* 49: 2585-2592, 2017.
30. **McKenna Z, Berkemeier Q, Naylor A, Kleint A, Gorini F, Ng J, Kim JK, Sullivan S, and Gillum T**. Bovine colostrum supplementation does not affect plasma I-FABP concentrations following exercise in a hot and humid environment. *European journal of applied physiology* 117: 2561-2567, 2017.
31. **Murray R, Paul GL, Seifert JG, Eddy DE, and Halaby GA**. The effects of glucose, fructose, and sucrose ingestion during exercise. *Medicine and science in sports and exercise* 21: 275-282, 1989.
32. **Neufer PD, Costill DL, Fink WJ, Kirwan JP, Fielding RA, and Flynn MG**. Effects of exercise and carbohydrate composition on gastric emptying. *Medicine and science in sports and exercise* 18: 658-662, 1986.
33. **Nybo L**. CNS fatigue and prolonged exercise: effect of glucose supplementation. *Medicine and science in sports and exercise* 35: 589-594, 2003.
34. **Peters HP, Bos M, Seebregts L, Akkermans LM, van Berge Henegouwen GP, Bol E, Mosterd WL, and de Vries WR**. Gastrointestinal symptoms in long-distance runners, cyclists, and triathletes: prevalence, medication, and etiology. *The American journal of gastroenterology* 94: 1570-1581, 1999.
35. **Pfeiffer B, Stellingwerff T, Zaltas E, and Jeukendrup AE**. CHO oxidation from a CHO gel compared with a drink during exercise. *Medicine and science in sports and exercise* 42: 2038-2045, 2010.
36. **Prosky L, Asp NG, Furda I, DeVries JW, Schweizer TF, and Harland BF**. Determination of total dietary fiber in foods and food products: collaborative study. *Journal - Association of Official Analytical Chemists* 68: 677-679, 1985.
37. **Smiricky MR, Grieshop CM, Albin DM, Wubben JE, Gabert VM, and Fahey GC, Jr.** The influence of soy oligosaccharides on apparent and true ileal amino acid digestibilities and fecal consistency in growing pigs. *Journal of animal science* 80: 2433-2441, 2002.
38. **Smith D**. Removing and analyzing total nonstructural carbohydrates from plant tissue. *Research Reports Wisconsin Coll Agric Life Sci* 41: 1969.
39. **Snipe RMJ, Khoo A, Kitic CM, Gibson PR, and Costa RJS**. Carbohydrate and protein intake during exertional heat stress ameliorates intestinal epithelial injury and small intestine permeability. *Applied physiology, nutrition, and metabolism = Physiologie appliquee, nutrition et metabolisme* 42: 1283-1292, 2017.

40. **Stevens CJ, Dascombe B, Boyko A, Sculley D, and Callister R**. Ice slurry ingestion during cycling improves Olympic distance triathlon performance in the heat. *Journal of sports sciences* 31: 1271-1279, 2013.
41. **Thomas DE, Brotherhood JR, and Brand JC**. Carbohydrate feeding before exercise: effect of glycemic index. *International journal of sports medicine* 12: 180-186, 1991.
42. **Thomas K, Stone MR, Thompson KG, St Clair Gibson A, and Ansley L**. Reproducibility of pacing strategy during simulated 20-km cycling time trials in well-trained cyclists. *European journal of applied physiology* 112: 223-229, 2012.
43. **Turner CE, Byblow WD, Stinear CM, and Gant N**. Carbohydrate in the mouth enhances activation of brain circuitry involved in motor performance and sensory perception. *Appetite* 80: 212-219, 2014.
44. **USDA**. USDA Food Composition Databases Washington DC: United States Department of Agriculture Agricultural Research Service, 2019.
45. **van Wijck K, Wijnands KA, Meesters DM, Boonen B, van Loon LJ, Buurman WA, Dejong CH, Lenaerts K, and Poeze M**. L-citrulline improves splanchnic perfusion and reduces gut injury during exercise. *Medicine and science in sports and exercise* 46: 2039-2046, 2014.

Figure Legends

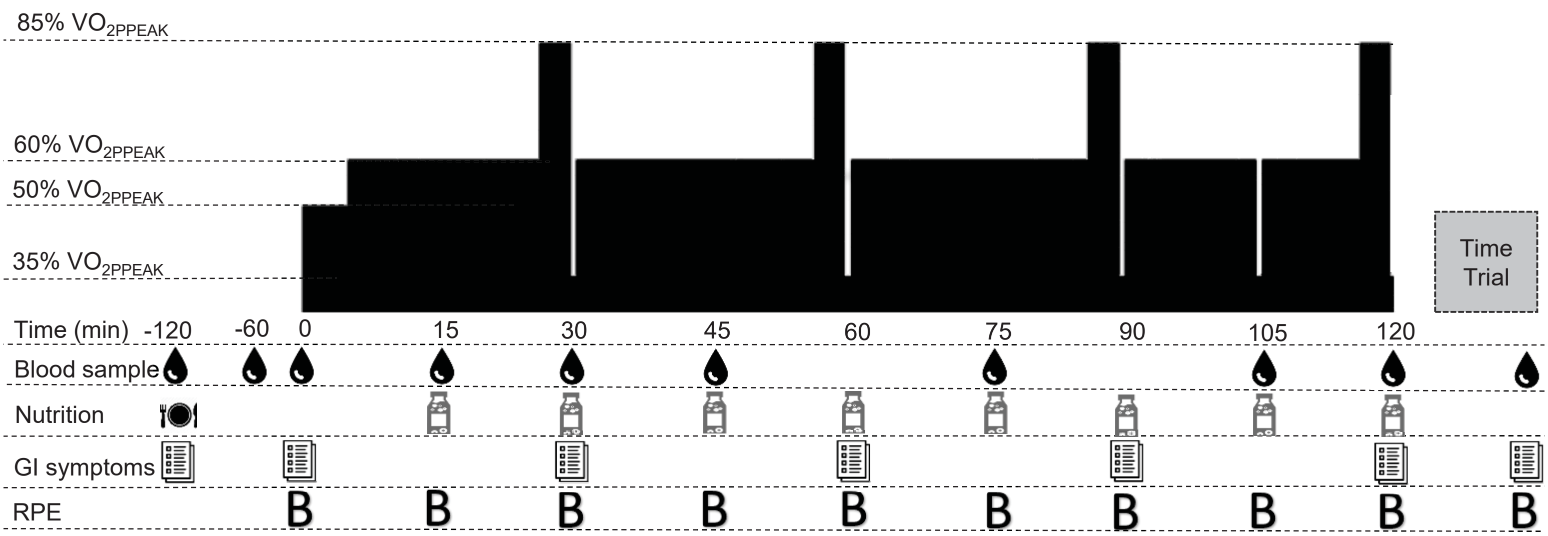
Figure 1. Overview of experimental design. A post-absorptive blood sample was obtained before the ingestion of a standardized breakfast (-120 min). The cycling challenge (0-120 min, 60% VO_{2PPEAK}) initiated with a 5 min warm-up (50% VO_{2PPEAK}), with hills (85% VO_{2PPEAK}/3 min) followed by downhills (35% VO_{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. $VO_{2PPEAK,}$ VO_{2PEAK} workload; GI, gastrointestinal; RPE, rate of perceived exertion (Borg scale, 6-20).

Figure 2. Ratings of perceived exertion (RPE) during the time trial relative to load. Water (circle), potato (square), and gel (triangle) conditions. All values are presented in mean ± SD (*n*=12). * Significant difference from water condition ($p<0.01$). [a]Significant difference from 25% within condition ($P<0.01$).

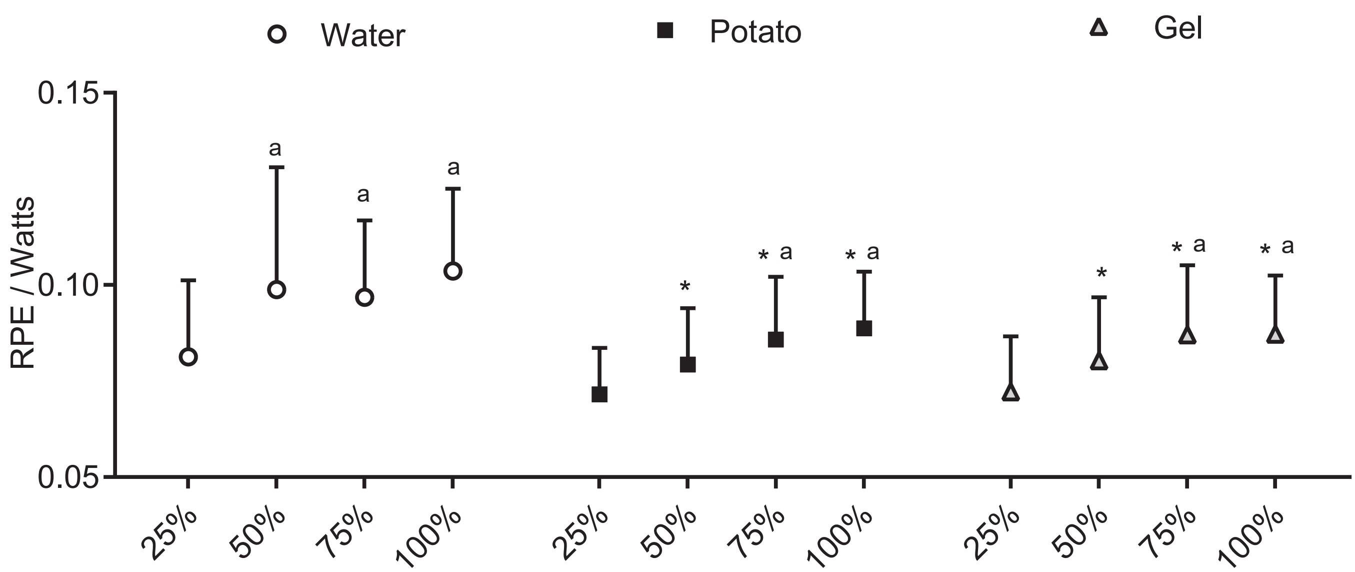
Figure 3. (A) Blood glucose, (B) blood lactate, (C) plasma [U-^{13}C] glucose enrichment, (D) plasma insulin concentrations, and (E) Fold change from baseline of plasma intestinal fatty acid binding protein (I-FABP) concentrations during the experimental trial. All values are presented in mean ± SD (*n*=12). Water (circle), potato (square), and gel (triangle) conditions. A standardized breakfast was consumed at -120 min. TTR, tracer ([U-^{13}C] glucose) to tracee (glucose) ratio. *Significant difference between water and gel (P<0.05). #Significant difference between water and potato (P<0.05). †Tendency for difference between water and gel (P<0.10). $ Tendency for difference between water and potato (P<0.10).

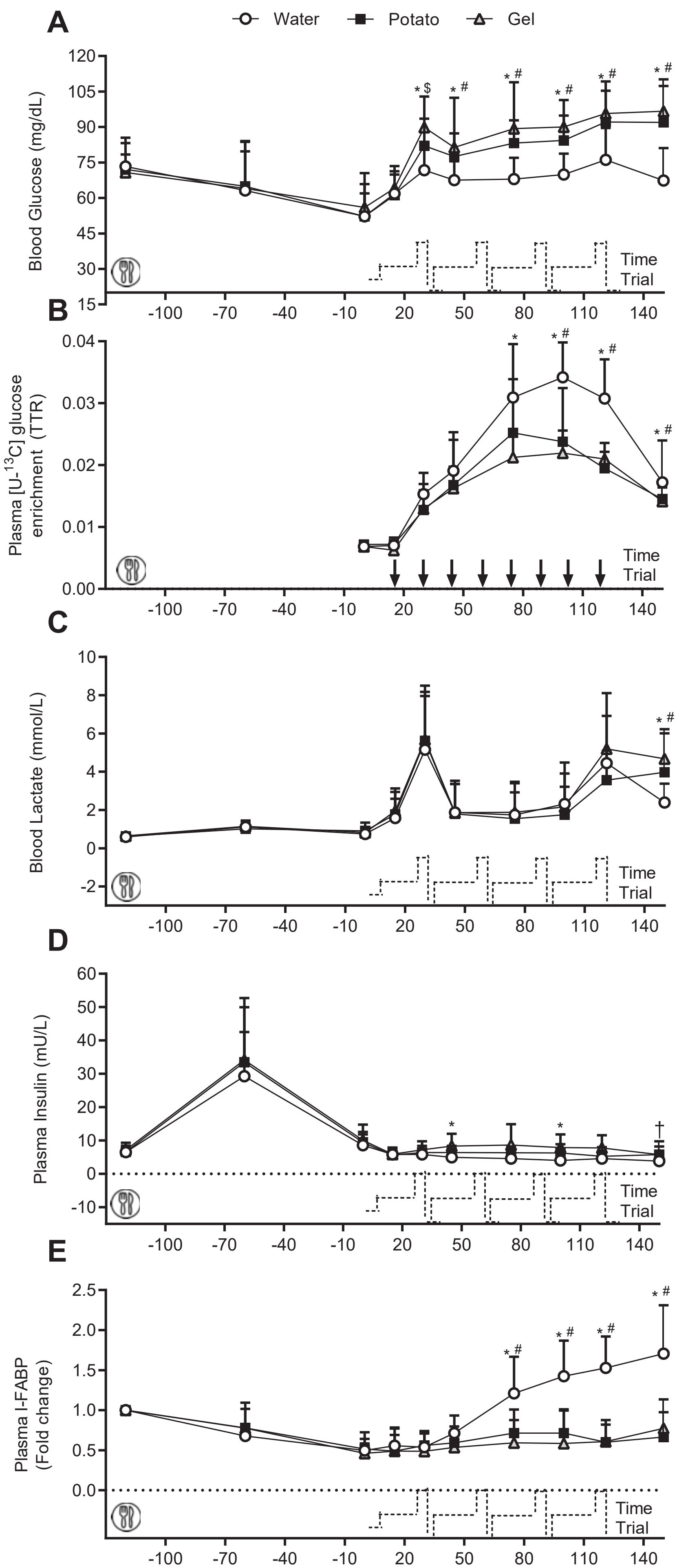
Figure 4. Gastrointestinal (GI) symptoms (mm) during the experimental trial. All values are presented in mean ± SD (*n*=12). Water (white), potato (black), and gel (gray) conditions. *Significant difference from potatoes (P<0.05).

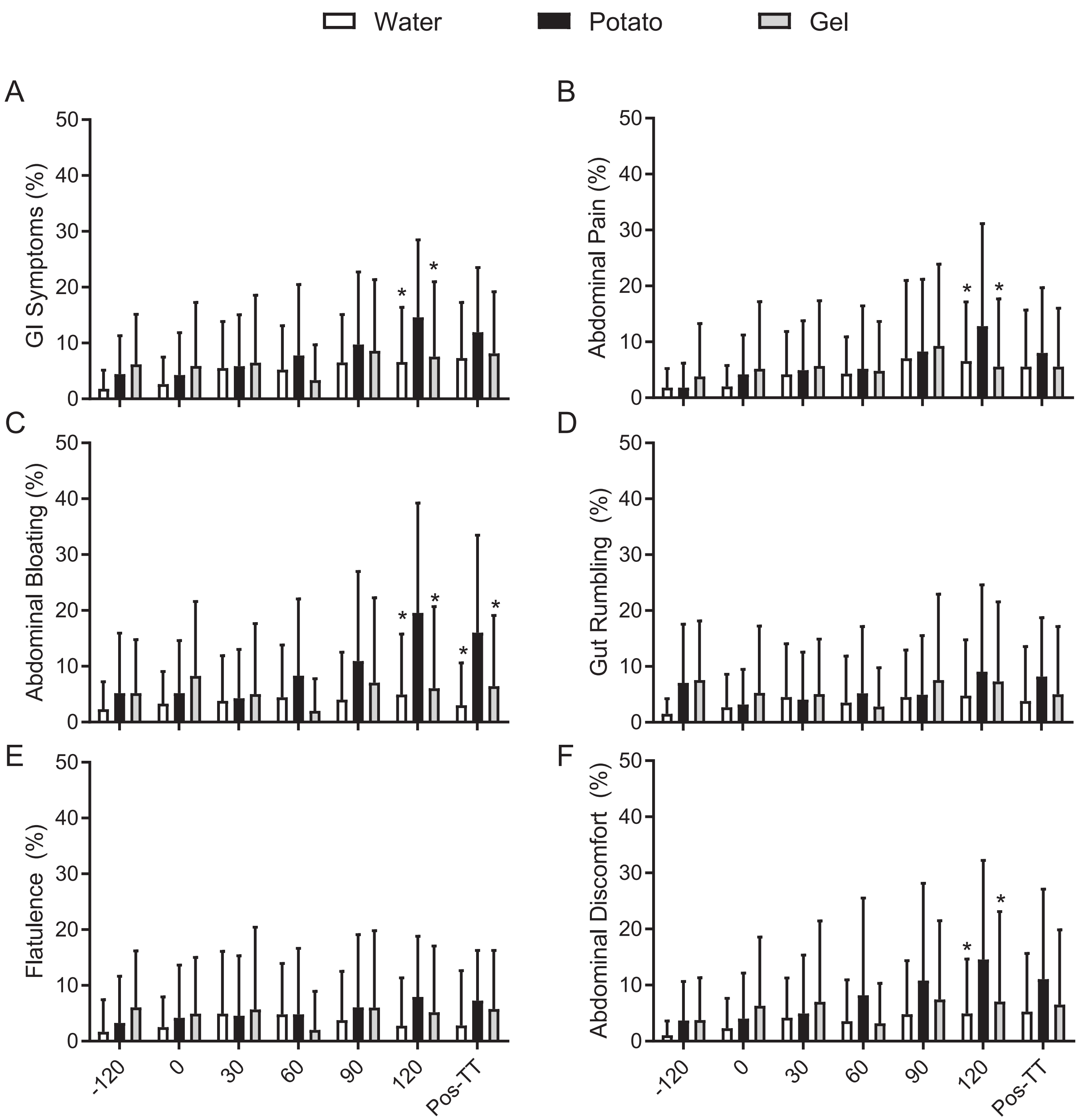
Figure 5. Time trial performance (A) as total time (min) for completion and (B) power output during each quartile of completeness. Mean ± SD (bars) and individual responses (lines) (n=12). * Significantly different from water (P=0.03). #Significantly different from water (P< 0.02).



85% VO_{2PPEAK}
60% VO_{2PPEAK}
50% VO_{2PPEAK}
35% VO_{2PPEAK}
Time Trial
Time (min) -120 -60 0 15 30 45 60 75 90 105 120
Blood sample
Nutrition
GI symptoms
RPE


Water
Potato
Gel
0.15
0.10
0.05
RPE / Watts
a
a
a
*
* a
* a
*
* a
* a
25%
50%
75%
100%
25%
50%
75%
100%
25%
50%
75%
100%


A
Water
Potato
Gel
Blood Glucose (mg/dL)
Time Trial
B
Plasma [U-13C] glucose enrichment (TTR)
C
Blood Lactate (mmol/L)
D
Plasma Insulin (mU/L)
E
Plasma I-FABP (Fold change)
-100
-70
-40
-10
20
50
80
110
140



Water
Potato
Gel
A
B
C
D
E
F
GI Symptoms (%)
Abdominal Pain (%)
Abdominal Bloating (%)
Gut Rumbling (%)
Flatulence (%)
Abdominal Discomfort (%)
50
40
30
20
10
0
*
-120
0
30
60
90
120
Pos-TT
Time

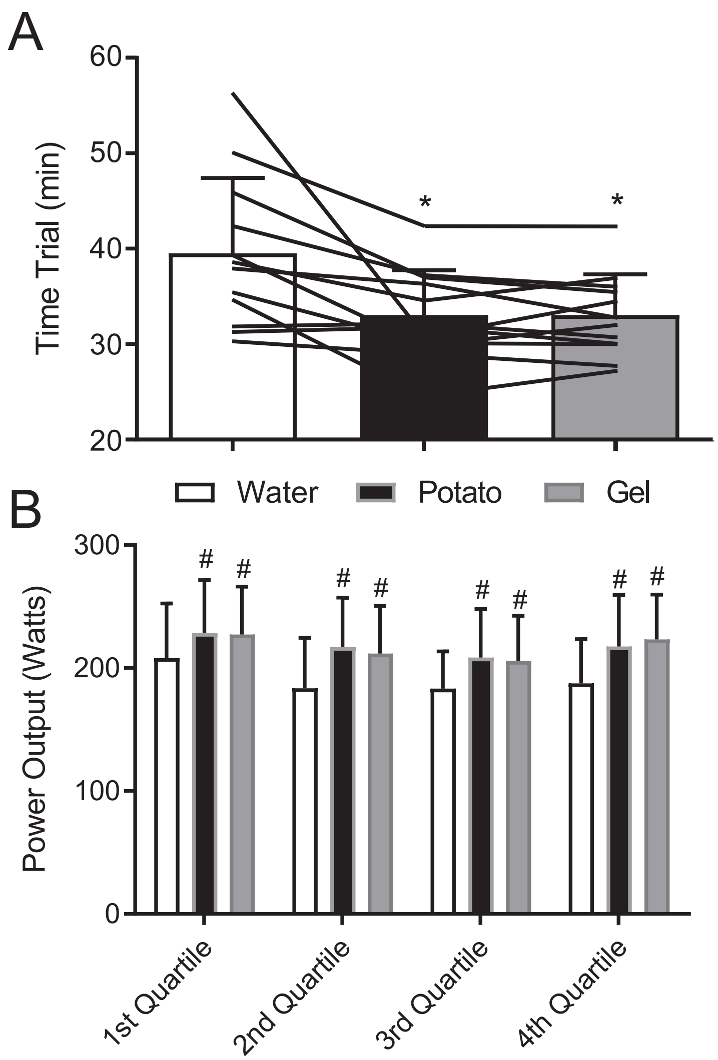

A
Time Trial (min)
60
50
40
30
20
*
*
Water
Potato
Gel
B
Power Output (Watts)
300
200
100
0
#
1st Quartile
2nd Quartile
3rd Quartile
4th Quartile

Table 1. Nutrient composition of treatment conditions.

Nutrient	**Potato**	**Gel**
Carbohydrate dose (g)	15.2	15.5
Total serving size (g)	1,028	184
Moisture content (%)	86	32
Energy (kcal)	548	494
Crude protein (g)	13.9	0.1
Total Carbohydrate (g)	121.3	123.7
Total dietary fiber	11.2	2.3
Soluble fiber	6.6	2.3
Insoluble fiber	4.6	0.0
Hydrolyzed monosaccharides	129.8	129.4
Total glucose	120.5	90.4
Total galactose	3.9	0.0
Total fructose	4.3	39.0

Carbohydrate dose administered every 15 min for 2 h. Total serving size expressed on an as-is basis. Sample aliquots were dried to completion at 105°C to determine dry matter content (i.e., non-water portion of the original sample). All nutrients were analyzed and their composition values were calculated and expressed on a dry matter basis (DMB) to ensure an equal comparison between potato and gel samples. Energy estimated from USDA Database, based on the Atwater system (44). Total carbohydrate calculated by difference (organic matter - crude protein in DMB).