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# Post-exercise ingestion of a unique, high molecular weight glucose polymer solution improves performance during a subsequent bout of cycling exercise

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# Post-exercise ingestion of a unique, high molecular weight glucose polymer solution improves performance during a subsequent bout of cycling exercise

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**Abstract**
The aim of the present study was to determine the effect of post-exercise ingestion of a unique, high molecular weight glucose polymer solution, known to augment gastric emptying and post-exercise muscle glycogen re-synthesis, on performance during a subsequent bout of intense exercise. On three randomized visits, eight healthy men cycled to exhaustion at 73.0% ($s = 1.3$) maximal oxygen uptake (90 min, $s = 15$). Immediately after this, participants consumed a one-litre solution containing sugar-free flavoured water (control), 100 g of a low molecular weight glucose polymer or 100 g of a very high molecular weight glucose polymer, and rested on a bed for 2 h. After recovery, a 15-min time-trial was performed on a cycle ergometer, during which work output was determined. Post-exercise ingestion of the very high molecular weight glucose polymer solution resulted in faster and greater increases in blood glucose ($P < 0.001$) and serum insulin ($P < 0.01$) concentrations than the low molecular weight glucose polymer solution, and greater work output during the 15-min time-trial (164.1 kJ, $s = 21.1$) than both the sugar-free flavoured water (137.5 kJ, $s = 24.2$; $P < 0.05$) and the low molecular weight glucose polymer (149.4 kJ, $s = 21.8$; $P < 0.05$) solutions. These findings could be of practical importance for athletes wishing to optimize performance by facilitating rapid re-synthesis of the muscle glycogen store during recovery following prolonged sub-maximal exercise.

**Keywords:** *Gastric emptying, skeletal muscle glycogen, sub-maximal exercise*

## Introduction

Muscle glycogen is recognized as the major fuel supporting adenosine triphosphate (ATP) homeostasis during sustained moderate-to-intense exercise, with the rate of glycogen utilization increasing with the intensity of exercise performed (Bergstrom, Hermansen, Hultman, & Saltin, 1967; Bergstrom & Hultman, 1966, 1967a; Hultman, Bergstrom, & Anderson, 1967). The depletion of muscle glycogen during exercise is associated with an accelerated rate of muscle phosphocreatine degradation, adenine nucleotide loss (Broberg & Sahlin, 1989), and muscle fatigue (Bergstrom & Hultman, 1966; Hultman *et al*., 1967), most probably due to the inability of muscle to maintain ATP production at the required rate. Thus, high pre-exercise muscle (and liver) glycogen concentrations are believed to be essential for optimal endurance exercise performance (Bergstrom *et al*., 1967), and the rapid re-synthesis of the muscle glycogen store is, therefore, of crucial importance during recovery for individuals who take part in training sessions or competitions where prolonged sub-maximal exercise or several periods of sub-maximal or intense exercise are performed in a single day.

Limiting factors to post-exercise muscle glycogen re-synthesis following carbohydrate feeding include the amount, timing, and form of carbohydrate administered, the rate of gastric emptying and intestinal absorption of the ingested carbohydrate, glucose storage and output by the liver, and muscle glucose transport and oxidation (for a review, see Jentjens & Jeukendrup, 2003). Studies in which glucose has been intravenously infused immediately following glycogen-depleting exercise have reported two- to three-fold greater rates of glycogen re-synthesis compared with post-exercise carbohydrate feeding [30 – 40 vs.

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85–130 mmol·kg dry muscle$^{-1}$·h$^{-1}$ (Bergstrom & Hultman, 1967b; Hansen, Asp, Kiens, Richter, 1999; Jentjens & Jeukendrup, 2003; Piehl-Aulin, Soderlund, & Hultman, 2000; Roch-Norlund, Bergstrom, & Hultman, 1972). This suggests that the rate of gastric emptying and intestinal absorption of the ingested carbohydrate, and glucose storage and output into the circulation by the liver, rather than muscle glucose uptake, is limiting to post-exercise muscle glycogen re-synthesis following carbohydrate feeding. Indeed, by using a unique, high molecular weight, low osmolality glucose polymer solution [the lower the osmolality of a carbohydrate polymer solution, the faster its rate of gastric emptying (Hunt, Smith, & Jiang, 1985; Vist & Maughan, 1995)], Piehl-Aulin and colleagues (2000) achieved muscle glycogen synthesis rates following glycogen-depleting exercise that were 70% greater over 2 h (50 vs. 30 mmol·kg dry muscle$^{-1}$·h$^{-1}$) compared with a commercially available solution of monomeric and short-chain oligomeric glucose with a lower molecular weight (500,000–700,000 vs. ~500 g·mol$^{-1}$) and higher osmolality (60–84 vs. ~300 mOsmol·kg$^{-1}$). Using the same carbohydrate solutions, Leiper and colleagues (Leiper, Aulin, & Soderlund, 2000) confirmed that this observation was likely to be due to a two-fold greater rate of gastric emptying in the first 10 min after carbohydrate administration.

Taking these observations together, we predicted that achieving a greater re-synthesis of muscle glycogen following glycogen-depleting exercise would result in the enhancement of performance during a subsequent bout of exercise. Therefore, the aim of the present study was to determine the effect of a unique, high molecular weight glucose polymer solution, ingested immediately after exhaustive exercise, on performance during a subsequent cycling time-trial, compared with an isoenergetic, commercially available, low molecular weight glucose polymer solution, in healthy, recreationally active young males.

## Materials and methods

### *Participants*

Eight healthy, recreationally active young men (mean age 23.0 years, $s = 4.5$; body mass 78.7 kg, $s = 7.6$; body mass index 24.3 kg·m$^{-2}$, $s = 2.4$), recruited from the student population at the University of Nottingham, participated in the present study, which was approved by the University of Nottingham Medical School Ethics Committee in accordance with the Declaration of Helsinki. Before taking part in the study, all participants underwent routine medical screening and completed a general health questionnaire. All participants provided their informed consent to take part in the study and were aware that they were free to withdraw from the experiment at any point. Upon entry to the study each participant performed a continuous, incremental exercise test to exhaustion on an electrically braked cycle ergometer (Lode Excalibur, Lode, Groningen, The Netherlands) to determine their maximal oxygen uptake ($\dot{V}O_{2max}$), which was confirmed no less than 3 days later. The mean $\dot{V}O_{2max}$ for the group was 47.8 ml·min$^{-1}$·kg$^{-1}$ ($s = 4.4$). Each participant was then familiarized with prolonged cycling exercise at least 1 week before the start of the experiment.

### *Experimental protocol*

Each participant reported to the laboratory at 09.00 h on three randomized occasions, separated by at least 1 week, and voided their bladder. The visits were randomized to eliminate any training effect of the prolonged exercise protocol. All participants were instructed to maintain the same dietary intake in the previous 24 h, and to abstain from alcohol and strenuous exercise in the previous 48 h. On arrival at the laboratory, participants were asked to rest in a supine position on a bed for 20 min while a cannula was inserted retrogradely into a superficial vein on the dorsal surface of the non-dominant hand for subsequent venous blood sampling. A 0.9% saline drip (Baxter Healthcare, Northampton, UK) was attached to keep the cannula patent. Participants then performed two-legged cycling exercise on an electrically braked cycle ergometer (Lode Excalibur, Lode, Groningen, The Netherlands) to the point of exhaustion at a predetermined workload equivalent to 75% $\dot{V}O_{2max}$ (217 W, $s = 13$), while maintaining a pedalling frequency of 70 rev·min$^{-1}$. Participants were allowed to stop exercising at any time, but after a short rest of up to 5 min were required to resume exercise. In an attempt to maximize depletion of muscle glycogen stores, this work–rest protocol was repeated until participants were no longer able to maintain a pedal frequency of 70 rev·min$^{-1}$ for more than 2 min. We have previously demonstrated that this protocol results in almost complete muscle glycogen depletion in the exercised leg (Casey *et al.*, 1995). To eliminate the effect of volume on gastric emptying, consumption of water was allowed *ad libitum* throughout exercise on the first visit, with the pattern of consumption then repeated for the following visits.

Immediately after exercise, participants rested in a semi-supine position on a bed for 2 h with their hand in a hand-warming unit (air temperature 50–55°C) to arterialize the venous drainage of the hand

(Gallen & MacDonald, 1990). Thereafter, participants ingested a one-litre solution containing sugar-free flavoured water (control), 100 g of a low molecular weight (approximately 900 $g \cdot mol^{-1}$) glucose polymer derived from hydrolysed corn starch (Maxijul, SHS International, Liverpool, UK), or 100 g of a very high molecular weight (approximately 500,000 – 700,000 $g \cdot mol^{-1}$) glucose polymer, also derived from corn starch (Vitargo, Swecarb AB, Kalmar, Sweden). The carbohydrate solutions were isoenergetic ($\sim$1600 kJ), with osmolalties of 124 and 34 $mOsmol \cdot kg^{-1}$ for the low and very high molecular weight drinks, respectively. The low molecular weight drink was chosen as we believe it is representative of the standard ''recovery'' carbohydrate (maltodextrin) drink on the market (e.g. Science in Sport PSP22, High5 EnergySource). Two hours after the consumption of the drink, participants were asked to perform as much work as possible in 15 min of cycling exercise on an electrically braked cycle ergometer (Lode Excalibur, Lode, Groningen, The Netherlands). This endurance performance time-trial, which has been shown to be reproducible in trained athletes [coefficient of variation of 3.5% (Jeukendrup, Saris, Brouns, & Kester, 1996)] and recreationally active participants similar to the present cohort (coefficient of variation of 1.6%), consisted of pedalling at the highest intensity sustainable on the cycle ergometer for 15 min. The ergometer was programmed to a pedalling-dependent mode such that with an increase in pedalling rate, the work rate was also increased. During the test, participants were only made aware of the time remaining so that they could pace themselves to maximize work output. The total amount of work performed in 15 min, recorded every second on a computer attached to the ergometer, was taken as a measure of endurance performance.

### *Sample collection and analysis*

During the recovery period of each experimental visit, 3 ml of arterialized venous blood were obtained every 10 min and used immediately for measurement of blood glucose concentration (YSI 2300 STATplus, Yellow Springs Instruments, OH, USA). The remaining blood was allowed to clot and, after centrifugation, the serum was stored frozen at $-80^{\circ}C$. Insulin was measured in these samples at a later date with a radioimmunoassy kit (Coat-a-Count Insulin, DPC, CA, USA).

### *Statistical analysis*

A two-way repeated-measures analysis of variance (time and treatment effects; GraphPad Prism 4.02, GraphPad Software Inc, CA) was performed to locate differences in blood glucose and serum insulin concentration during the recovery period. When a significant main effect was detected, the data were analysed further with a Student's paired *t*-test using the Bonferroni correction. A one-way analysis of variance with Tukey's *post-hoc* test was used to locate any differences in exercise performance. Statistical significance was set at $P < 0.05$, and all the values presented in the text and figures are reported as means and standard deviations (*s*).

## Results

### *Glycogen-depleting exercise*

Mean time to exhaustion for the sugar-free flavoured water (control), low molecular weight solution, and high molecular weight solution was 91 min ($s = 12$), 90 min ($s = 15$), and 88 min ($s = 9$), respectively, while cycling at an exercise intensity of 73.4% ($s = 0.8$), 72.5% ($s = 1.9$), and 73.1% ($s = 1.3$) of $\dot{V}O_{2max}$, respectively.

### *Blood glucose*

Blood glucose concentration was the same following the bout of exhaustive exercise during the sugar-free flavoured water (3.9 $mmol \cdot l^{-1}$, $s = 0.3$), low molecular weight solution (3.7 $mmol \cdot l^{-1}$, $s = 0.2$), and high molecular weight solution (3.9 $mmol \cdot l^{-1}$, $s = 0.4$) trials (Figure 1). After consumption of the sugar-free flavoured water, blood glucose concentration remained at 3.9 $mmol \cdot l^{-1}$ for 2 h. Following consumption of the low and high molecular weight solutions, blood glucose concentration increased to a peak of 7.3 $mmol \cdot l^{-1}$ ($s = 0.8$) and 8.1 $mmol \cdot l^{-1}$

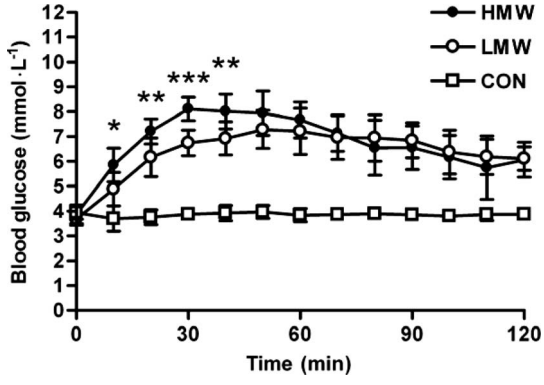


Figure 1. Blood glucose concentration during a 2-h period of recovery from glycogen-depleting exercise and following the ingestion of a one-litre solution containing sugar-free flavoured water (CON), 100 g of a low molecular weight glucose polymer (LMW) or 100 g of a very high molecular weight glucose polymer (HMW). $*P < 0.05$, $**P < 0.01$, $***P < 0.01$, HMW significantly greater than LMW. Values are means $\pm$ standard deviations.

($s = 0.5$) after 50 and 30 min, respectively, and then declined to similar values of 6.1 mmol·l$^{-1}$ ($s = 0.5$) and 6.1 mmol·l$^{-1}$ ($s = 0.7$), respectively, after 2 h. This increase in blood glucose concentration occurred at a faster rate following consumption of the high than the low molecular solution (0.14 vs. 0.07 mmol·l$^{-1}$·min$^{-1}$), such that blood glucose concentration was higher at 10 ($P < 0.05$), 20 ($P < 0.01$), 30 ($P < 0.001$), and 40 ($P < 0.01$) min following ingestion.

*Serum insulin*

Serum insulin concentration was the same following the bout of exhaustive exercise during the sugar-free flavoured water (5.4 mU·l$^{-1}$, $s = 2.9$), low molecular weight solution (5.2 mU·l$^{-1}$, $s = 3.0$), and high molecular weight solution trials (6.1 mU·l$^{-1}$, $s = 2.7$), respectively (Figure 2). Following consumption of the sugar-free flavoured water, serum insulin concentration remained around 6.0 mU·l$^{-1}$ for 2 h. Following consumption of the low and high molecular weight solutions, serum insulin concentration increased to a peak of 68.7 mU·l$^{-1}$ ($s = 33.2$) and 80.6 mU·l$^{-1}$ ($s = 52.8$) after 40 and 70 min, respectively, and then declined to similar values of 45.7 mU·l$^{-1}$ ($s = 18.7$) and 48.0 mU·l$^{-1}$ ($s = 20.4$), respectively, after 2 h. Serum insulin concentration was greater following consumption of the high than the low molecular weight solution at 20 ($P < 0.05$), 30 ($P < 0.01$), and 40 ($P < 0.01$) min following ingestion.

*Work output*

Work output during the 15-min endurance performance time-trial test, performed 2 h after the ingestion of the sugar-free flavoured water, low molecular weight solution, and high molecular weight solution, was 137.5 kJ ($s = 24.2$), 149.4 kJ ($s = 21.8$), and 164.1 kJ ($s = 21.1$), respectively. Work output following the consumption of the low and high molecular weight solutions was greater than that following the consumption of the sugar-free flavoured water ($P < 0.01$ and $P < 0.001$, respectively). Furthermore, work output was 10% greater ($P < 0.01$) following ingestion of the high than the low molecular weight solution. Importantly, this increase in work output was observed in all participants studied (range 3.4–23.3%; Figure 3).

## Discussion

The main aim of the present study was to determine the effect of a unique, high molecular weight glucose polymer solution (known to increase the rate of gastric emptying and post-exercise muscle glycogen re-synthesis, compared with a low molecular weight glucose polymer solution) on performance during a subsequent cycling time-trial. In this respect, work output 2 h after glycogen-depleting exercise and the ingestion of the high molecular weight solution was 20% greater ($P < 0.001$) than with the sugar-free flavoured water and, more importantly, 10% greater ($P < 0.01$) than with the low molecular weight solution. Furthermore, this positive performance effect of the high molecular weight solution was observed in all eight participants (Figure 3).

Previous studies have shown that the high molecular weight solution used in the present study emptied from the stomach twice as fast, and resulted in a 70% greater increase in muscle glycogen content

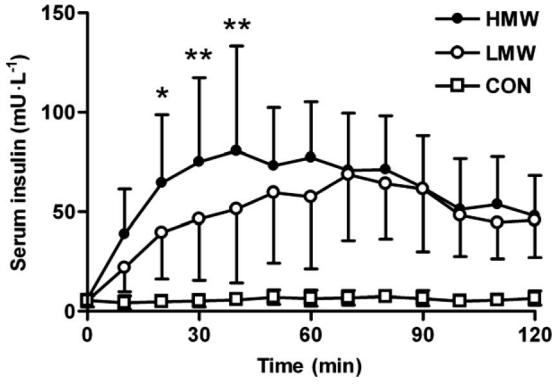


Figure 2. Serum insulin concentration during a 2-h period of recovery from glycogen-depleting exercise and following the ingestion of a one-litre solution containing sugar-free flavoured water (CON), 100 g of a low molecular weight glucose polymer (LMW) or 100 g of a very high molecular weight glucose polymer (HMW). *$P < 0.05$, **$P < 0.01$, HMW significantly greater than LMW. Values are means ± standard deviations.

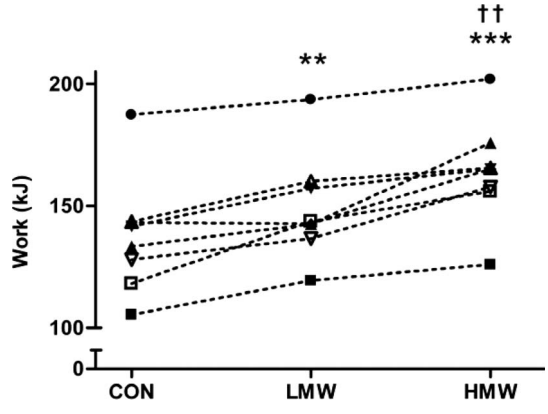


Figure 3. Work output for each individual participant during a 15-min ''all-out'' cycling time-trial that was performed 2 h after glycogen-depleting exercise and the ingestion of a one-litre solution containing sugar-free flavoured water (CON), 100 g of a low molecular weight glucose polymer (LMW) or 100 g of a very high molecular weight glucose polymer (HMW). **$P < 0.01$, ***$P < 0.001$, LMW and HMW significantly greater than CON, respectively. $^{\dagger\dagger}P < 0.01$, HMW significantly greater than LMW.

2 h after glycogen-depleting exercise, compared with a low molecular weight solution (Leiper *et al*., 2000; Piehl-Aulin *et al*., 2000). In accordance with this, peak blood glucose concentration following ingestion of the high molecular weight solution in the present study was 10% greater, and occurred 20 min earlier, than with the low molecular weight solution (Figure 1). Furthermore, the rate of increase in blood glucose concentration was two-fold greater over the first 30 min following ingestion, which is in line with the two-fold greater rate of gastric emptying observed during the initial 10 min following ingestion of the high molecular weight solution by Leiper and colleagues (2000). The rapid increase in blood glucose concentration following ingestion of the high molecular weight solution also resulted in a significantly higher serum insulin concentration during the first hour of recovery (Figure 2). In the present study, there were no differences between visits in exercise time to exhaustion in the ''glycogen-depleting'' phase of the study, suggesting that post-exercise muscle glycogen content was similar across treatments at exhaustion. Furthermore, blood glucose values before the cycling time-trial were the same for the high and low molecular weight trials. It is reasonable to speculate, therefore, that the improvement in exercise performance observed after ingestion of the high molecular weight solution in the present study was the result of greater re-synthesis of the skeletal muscle glycogen store during the 2 h of recovery following exhaustive exercise compared with after ingestion of the low molecular weight solution, particularly as the ingestion of carbohydrate *per se* resulted in an increase in performance compared with ingestion of the sugar-free flavoured water.

It should be noted, however, that in the study of Piehl-Aulin and colleagues (2000), there were no differences in blood glucose or serum insulin concentration between the high molecular weight and control drink. The reasons for the discrepancy between the findings of the present study and those of Piehl-Aulin *et al*. (2000) are unclear, but could be because a mixture of monomeric and short-chain oligomeric glucose, with a lower molecular weight than the low molecular weight drink used in the present study ($\sim$500 vs. $\sim$900 g $\cdot$ mol$^{-1}$), was used in the control drink by Piehl-Aulin and colleagues. Additionally, any potential differences in blood glucose or serum insulin concentration during recovery in Piehl-Aulin and colleagues' study could have been missed because of the use of venous blood sampling (as opposed to arterialized-venous sampling in the present study), the relatively large time interval in blood sampling (30 min), the large inter-individual variation in blood glucose and serum insulin, or the repeated ingestion of carbohydrate every 30 min of recovery. Also, Piehl-Aulin *et al*. (2000) speculated that if a faster delivery of glucose to the intestine is combined with a faster glucose uptake by the muscle cell immediately after exercise, this may mask an increase in delivery of glucose to the blood from the intestine and result only in minor changes in blood glucose concentration.

Since the pioneering work of Bergstrom and Hultman in the 1960s (Bergstrom & Hultman, 1966, 1967a, 1967b; Bergstrom *et al*., 1967), it has been recognized that a clear relationship exists between pre-exercise muscle glycogen concentration and prolonged exercise performance. In the present study, a 15-min high-intensity sub-maximal time-trial was used to measure exercise performance and it is unquestionable that, assuming a normal pre-exercise muscle glycogen content of 350–450 mmol $\cdot$ kg dry muscle$^{-1}$, muscle glycogen availability will not limit performance in this test. However, given that the participants performed prolonged exhaustive exercise before the time-trial, it is clear that muscle glycogen content would have been markedly reduced. Indeed, we have previously shown that this exercise model reduces muscle glycogen content to $\sim$25 mmol $\cdot$ kg dry muscle$^{-1}$ (Casey, Short, Hultman, & Greenhaff, 1995). Thus, we propose that muscle glycogen content would not have been restored during the 2 h of recovery that preceded the 15-min time-trial, particularly in the control condition where only water was ingested, such that its availability would have limited exercise performance during the 15-min time-trial (particularly in the control trial). By way of example, in the study by Piehl-Aulin *et al*. (2000), muscle glycogen content increased from 60 to 118 and 153 mmol $\cdot$ kg dry muscle$^{-1}$ during the 2 h of recovery following glycogen-depleting exercise in the low and high molecular weight trials, respectively. Furthermore, 300 g of carbohydrate was administered in Piehl-Aulin and colleagues' study compared with only 100 g in the present study. It is plausible, therefore, that post-exercise re-synthesis of muscle glycogen following the ingestion of the high molecular weight solution in the present study could well account for the increase in performance observed in all participants compared with the low molecular weight solution and certainly the sugar-free flavoured water. This is particularly the case when one considers that untrained individuals (normal pre-exercise muscle glycogen content of $\sim$300 mmol $\cdot$ kg dry muscle$^{-1}$) will utilize around 150 mmol $\cdot$ kg dry muscle$^{-1}$ of glycogen during 15 min of cycling exercise at 85% $\dot{V}O_{2max}$ (Dyck *et al*., 1993), which, based on heart rate responses, approximates the workload achieved in the present time-trial (170–180 beats $\cdot$ min$^{-1}$; data not shown).

The degree of glycogen re-synthesis in the liver may have also contributed to the difference in 15-min time-trial performance following post-exercise ingestion of the high molecular weight solution in the present study, particularly as liver-biopsy studies in healthy human volunteers have clearly demonstrated that the liver is extremely sensitive to changes in dietary carbohydrate intake (Nilsson & Hultman, 1973). Indeed, magnetic resonance spectroscopy studies have demonstrated that following exhaustive exercise liver glycogen is depleted to a considerable extent and, if the post-exercise carbohydrate load is inadequate, glycogen re-synthesis can impair glucose release from the liver and subsequent exercise capacity (Casey *et al*., 2000).

## Conclusion

The ingestion of a unique, hign molecular weight glucose polymer solution (known to increase post-exercise muscle glucose delivery and glycogen re-synthesis compared with a standard, low molecular weight glucose polymer solution) increased work output during a subsequent highly reproducible, high-intensity sub-maximal time-trial cycling test. Furthermore, this effect was observed in all participants studied. These findings could be of practical importance for athletes who partake in training sessions, or indeed competitions, where rapid re-synthesis of the muscle glycogen store is required and performance must be maintained during a second period of exercise. It is noteworthy, however, that ingestion of this high molecular weight glucose polymer solution immediately before exercise does not appear to increase carbohydrate oxidation during exercise compared with a low molecular weight solution (Rowlands *et al*., 2005), most likely because carbohydrate oxidation during exercise is not limited by gastric emptying or muscle carbohydrate delivery following pre-exercise carbohydrate feeding. Thus, it would appear that the high molecular weight solution should be ingested immediately following exhaustive exercise when a significant period of recovery is anticipated before a subsequent bout of exercise.

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