

Carbohydrate Supplementation and Resistance Training

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ABSTRACT

There is a growing body of evidence suggesting that the performance of resistance-training exercises can elicit a significant glycogenolytic effect that potentially could result in performance decrements. These decrements may result in less than optimal physiological adaptations to training. Currently some scientific evidence suggests that carbohydrate supplementation prior to and during high-volume resistance training results in the maintenance of muscle glycogen concentration, which potentially could result in the maintenance or increase of performance during a training bout. Some researchers suggest that ingesting carbohydrate supplements prior to and during resistance training may improve resistance-training performance. Additionally, the ingestion of carbohydrates following resistance exercise enhances the resynthesis of muscle glycogen, which may result in a faster time of recovery from resistance training, thus possibly allowing for a greater training volume. On the basis of the current scientific literature, it may be advisable for athletes who are performing high-volume resistance training to ingest carbohydrate supplements before, during, and immediately after resistance training.

Key Words: resistance training, glycogen, glucose, glycogenolytic, glycogenolysis

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Introduction

Resistance training has become an integral part of the training practices of most athletes. With the increasing popularity of resistance training, many ergogenic aids and nutritional strategies have been employed in an attempt to improve performance or increase muscle growth. Many of these potential aids have not demonstrated any ergogenic effects. Carbo-

hydrate supplementation is one ergogenic aid that is not often associated with resistance-training performance and muscle growth. Traditionally, carbohydrate supplementation is associated with aerobic exercise performance. In this context, carbohydrate supplementation has been shown to increase the amount of work that can be performed (37, 61, 79) as well as increase the duration of aerobic exercise (20, 80). The elevation of blood glucose (BG) associated with supplementation is suggested to improve aerobic performance through reduction of muscle glycogen use (3, 5, 80) or through the use of BG as a predominant fuel source as glycogen becomes depleted (14, 35, 61).

Evidence presented in the scientific literature suggests that intermittent activities can stimulate significant glycogenolytic effects (6, 70, 78). Because typical resistance training is intermittent in nature, a similar effect on muscle glycogen concentration might be expected. Recently, several studies have reported that resistance-training bouts can significantly decrease muscle glycogen stores (25, 54, 67, 72, 73). These investigations suggest that muscle glycogen is an important fuel source during resistance-training activities. In fact, reductions in muscle glycogen concentration have resulted in accentuated exercise-induced muscle weakness (80), decreased isokinetic force production (40), and reduced isometric strength (36). Theoretically, the implementation of a carbohydrate supplementation regime may prevent decreases in performance and stimulate an increase in muscle glycogen resynthesis (65). This may allow athletes who are performing resistance exercises to train at higher intensities or perform more work, thus potentially enhancing the physiological adaptations that are associated with resistance training.

The purpose of this review is to explore the physiological and ergogenic effects of carbohydrate supplementation on resistance-training exercise and identify future areas of investigation.

Resistance Training and Glycogenolysis

Traditionally, it has been thought that short-duration high-intensity exercise is primarily supplied with energy from the muscular stores of phosphagens (adenosine-triphosphate phosphocreatine system), with glycogenolysis and glycolysis supplying minimal amounts of energy (55). Recently, glycogenolysis has been demonstrated to be an important energy supplier during high-intensity intermittent exercises, such as resistance training (54, 67, 72, 73). Recently, Haff et al. (26) reported that 3 sets of isokinetic leg extensions performed at $120^{\circ}\cdot\text{s}^{-1}$ can reduce the muscle glycogen content of the vastus lateralis by 17%. Additionally, in the same investigation a multiple-set resistance-training session (back squats, speed squats, 1-leg squats) performed at 65, 45, and 10% of 1 repetition maximum (1RM) back squat resulted in a 26.7% decrease in muscle glycogen of the vastus lateralis. Tesch et al. (73) have also reported a 40% reduction in muscle glycogen in response to the performance of 5 sets of 10 repetitions of concentric knee extensions performed at 60% of 1RM. A 30% decrease in the muscle glycogen content of type IIab and IIb fibers in response to this protocol was also reported (73). Muscle glycogen concentration was also reported to decrease by $\sim 20\%$ in response to the performance of 5 sets of 10 repetitions at 45% of 1RM. Similarly, Robergs et al. (67) have shown that 6 sets of 6 repetitions of leg extensions performed at 70 and 35% of 1RM can elicit a significant glycogenolytic effect resulting in 39 and 38% reductions in glycogen, respectively. Type II fibers were also demonstrated to have a greater glycogen loss when compared with type I fibers (67). Tesch et al. (72) also reported that a 26% decrease in the muscle glycogen content of the vastus lateralis can occur in response to a resistance-training regimen consisting of 5 sets of front squats, back squats, leg presses, and knee extensions. One set of 10 repetitions of biceps curls can also reduce muscle glycogen by 13%, whereas 3 sets of 10 can result in a 25% reduction in muscle glycogen (54). Pascoe et al. (65) have reported a 31% reduction in muscle glycogen content in response to leg extensions performed to muscular failure (sets: 8.0 ± 0.7). The results of these studies indicate that muscle glycogen is an important fuel source during resistance training and suggest that glycogen depletion is dependent upon the total amount of work accomplished.

Resistance-training sessions that center on higher repetition schemes (8–12 repetitions) and moderate loads such as those utilized during the hypertrophy phase of many athletes and bodybuilders may have a greater effect on muscle glycogen concentration than those of lower repetition schemes. However, very little research has been conducted examining the glycogenolytic effect of low-volume, heavy-load resistance-training protocols. Typical high-volume resistance

training, which involves moderate to heavy loads, seems to preferentially deplete type II fibers. Because type II fibers usually express higher glycolytic enzyme activity than do type I fibers, a preferential depletion of muscle glycogen may not be totally unexpected (23). The preferential depletion of type II fibers during high-intensity exercise (24, 78), such as resistance training, may compromise the performance of high-intensity exercise and ultimately lead to a decrease in performance.

Muscle Glycogen and Carbohydrate Consumption

Reduction in muscle glycogen can potentially result in reductions in performance. Decreased isokinetic force production (40), reduced isometric strength (36), and accentuated muscle weakness (80) have been reported in the scientific literature in response to reductions in muscle glycogen. The implementation of a carbohydrate supplementation regimen may reduce the muscle glycogen loss associated with resistance-training bouts. Only 1 published investigation to date has explored the effects of carbohydrate supplementation on muscle glycogen loss during a typical resistance-training bout (26). Haff et al. (26) report that the consumption of a carbohydrate beverage prior to and during an acute resistance training bout can attenuate muscle glycogen loss. In this investigation a carbohydrate beverage was ingested prior to and every 10 minutes throughout a free-weight resistance-training bout that took ~ 39 minutes. The training bout consisted of 3 sets of 10 repetitions of back squats (65% of 1RM), speed squats (45% of 1RM), and 1-leg squats (10% of 1RM) and elicited a 26.7% decrease in the muscle glycogen content of the vastus lateralis with the placebo treatment. However, the training bout only elicited a 13.7% decrease in muscle glycogen content when a carbohydrate supplementation regimen was employed. This decreased rate of glycogenolysis seen with the carbohydrate treatment may be related to an increased glycogen synthesis during the rest intervals of intermittent exercise (52). The results of the study by Haff et al. (26) suggest that carbohydrate supplementation prior to and during resistance training can maintain muscle glycogen stores. Additionally, the inclusion of a carbohydrate supplementation regimen of the type used by Haff et al. (26) may be beneficial in the maintenance of daily glycogen levels, which could potentially accentuate the benefits of training.

The daily maintenance of glycogen stores appears to be directly related to the carbohydrates in the diet (12, 13, 39). The consumption of carbohydrates during and after exercise will increase the glycogen synthesis rates following exercise. Costill et al. (13) have reported that minimal glycogen synthesis occurs after exercise when no carbohydrates are consumed. The amount of muscle glycogen synthesis in the 24-hour period postexercise is also directly correlated ($r =$

0.84) to the amount of carbohydrate ingested and the timing of that ingestion. During the 6 hours postexercise, a diet consisting primarily of simple carbohydrates appears to induce a greater glycogen resynthesis rate. In fact, relatively little glycogen resynthesis occurs when no carbohydrates are consumed after exercise (38, 39, 56). When carbohydrates are given immediately after and 1 hour after resistance exercise, the muscle glycogen content of the vastus lateralis is returned to 91% of resting values compared with 75% of pre-exercise values in 6 hours when only water is given (65). Thus, delaying the ingestion of carbohydrates after exercise by as little as 2 hours can significantly decrease the amount of glycogen resynthesis. This decrease may be of particular interest to athletes who perform multiple training sessions on one day. If the athlete can increase the amount of resynthesis between exercise bouts, an increase in performance may occur during the second bout of exercise on a given training day.

Resistance Training and Blood Glucose

A reduction in blood glucose concentration is not normally experienced during a typical resistance-training session (26, 28, 43, 58, 67, 75). Keul et al. (43) investigated the metabolic response of 15 resistance-trained subjects to a 1-hour training session consisting of the bench press, deadlift, and squats. No significant changes in blood glucose levels were noted in response to the training bout. Similarly, Haff et al. (26) have reported no significant alterations in blood glucose levels in response to a 40-minute free-weight resistance-training session. Additionally, Haff et al. (28) report no alterations in blood glucose levels in response to 57 minutes of isokinetic leg exercise.

Conversely, Vanhelder et al. (75) found that blood glucose concentration increased in response to 7 sets of full squats performed at 80% of a 10RM. Haff et al. (27) have also reported that blood glucose concentrations increase in response to a resistance-training session lasting approximately 1 hour. Robergs et al. (67) examined the metabolic effects of 8 male subjects performing 6 sets of knee extensions at 35 and 70% of their 1RM. It was determined that following the sixth set, blood glucose concentration was significantly elevated when compared with resting values. Two hours after exercise, blood glucose returned to resting values. However, blood glucose concentrations at rest, after the sixth set, and 2 hours after exercise were found to be similar when accounting for the plasma volume shift. Additionally, McMillan et al. (58) have reported that blood glucose concentrations increase as a result of a resistance-training bout. Similarly, Conley et al. (11) suggest that blood glucose concentrations were significantly ($p = 0.001$) elevated immediately after exercise, in response to a resistance-training session. The blood glucose increases found in these resistance-

training studies were similar to those reported for high-intensity aerobic exercise (80–100% $\dot{V}O_{2max}$) (19, 22) and anaerobic cycling (44).

Blood Glucose Response to Carbohydrate Supplementation

There is substantial evidence in the literature to suggest that the consumption of carbohydrate beverage before and during resistance training results in elevations in blood glucose levels during and after the training bout (11, 26, 28, 29, 51). Haff et al. (28) investigated the effects of carbohydrate ingestion on 16 sets of 10 repetitions of isokinetic leg extensions and flexions. Significantly higher blood glucose levels were seen at set 8 and immediately after the resistance-training bout when subjects consumed a carbohydrate supplement (20% maltodextrin and dextrose solution) 10 minutes before and after sets 1, 6, and 11 of exercise.

Similarly in another investigation Haff et al. (26) observed higher blood glucose levels pre-exercise and immediately after exercises when subjects consumed a carbohydrate solution (20% maltodextrin and dextrose solution) 10 minutes before and every 10 minutes during a resistance-training session. Additionally, Haff et al. (29) report significantly higher blood glucose concentrations immediately postexercise, 1 hour postexercise, and 2 hours postexercise when subjects consumed a carbohydrate solution (20% maltodextrin and dextrose solution) before and after every other set during the performance of back squats at 55% of their 1RM until voluntary failure.

Conley et al. (11) examined the effect of carbohydrate ingestion on the performance of multiple bouts of back squats at 65% of 1RM to voluntary failure. Blood glucose was found to be significantly higher during the carbohydrate supplementation (20% maltodextrin and dextrose solution) trials for the pre-exercise ($p = 0.036$), immediately after ($p = 0.031$), and 2 hours after exercise ($p = 0.026$) when compared with the placebo trials.

Lambert et al. (51) examined the effect of carbohydrate ingestion on the performance of multiple bouts of leg extensions at 80% of the subject's 10RM. Blood glucose was significantly higher ($p < 0.05$) in the carbohydrate supplemented (10% glucose polymer) trials after the seventh set and at failure, when compared with the placebo trials (51).

It is likely that the elevations in blood glucose seen with the varying supplementation protocols in the literature result in either a reduction in muscle glycogen utilization (3, 5, 80) during the exercise bout or a faster glycogen resynthesis rate after exercise. When the carbohydrate supplement is consumed prior to and during the resistance-training bout, it appears that BG plays a critical role in fueling glycolysis (51). Additionally, it is likely that elevations in blood glucose directly affect the hormonal response to resistance train-

ing, which can increase glycogen and possible protein synthesis, which could ultimately impact performance.

Hormonal Responses to Carbohydrate Ingestion

The hormonal responses that occur in response to acute and chronic resistance training are currently being investigated (7, 30–34, 50, 58). The addition of a carbohydrate supplementation regimen to a resistance-training program may result in an enhanced anabolic environment. The enhancement of the anabolic environment could potentially increase muscle hypertrophy and ultimately increase resistance-training performance.

Insulin. Insulin is a polypeptide hormone that is produced in the β -cells of the islets of Langerhans in the pancreas. This hormone functions to (a) lower blood glucose level by enhancing cellular uptake, (b) enhance the storage of glycogen, (c) enhance fat storage, (d) enhance cellular uptake of amino acids, (e) increase the synthesis of proteins, and (f) suppress the catabolism of proteins (48, 49, 66). Typically, increases in the concentration of plasma insulin occur in response to elevations in glucose, amino acids, and fatty acids (57). Thus, the consumption of a carbohydrate supplement before and during resistance exercise might be expected to significantly increase insulin concentrations. Fahey et al. (18) have demonstrated that the ingestion of a liquid meal (13 g protein, 32 g carbohydrate, and 2.6 g of fat) 30 minutes before and during exercise can significantly increase insulin levels. Chandler et al. (8) have also reported that the ingestion of a carbohydrate beverage immediately before and 2 hours after a resistance-training bout resulted in significantly higher insulin concentrations when compared with a placebo beverage. These rises in insulin theoretically should result in increases in muscle glycogen stores, protein anabolism, and muscle hypertrophy. Increases in postexercise insulin levels in response to carbohydrate ingestion may result in enhanced glycogen synthesis and an anabolic hormonal state that potentially could result in an ergogenic effect. Currently, very few studies have investigated this potential ergogenic effect, and further research is warranted.

Research exploring postexercise carbohydrate supplementation has suggested that myofibrillar protein breakdown can be decreased (69). In one investigation subjects consumed 1 g glucose per kilogram of body mass immediately after and 1 hour after exercise. The addition of the carbohydrate supplement resulted in a significant increase in plasma insulin and glucose concentrations when compared with a placebo. This finding was associated with the carbohydrate treatment eliciting significantly less 3-methylhistidine and urea nitrogen excretion, which suggests less amino acid transamination and oxidative deamination occurred. Additionally, the carbohydrate treatment resulted in a

slightly increased fractional protein synthetic rate. Increases in insulin are often associated with increases in amino acid delivery that potentially stimulate increases in fractional muscle protein synthetic rate and whole body protein synthesis rate (4). In the study by Roy et al. (69) the combination of increases in insulin concentration and fractional protein synthetic rate and decreases in 3-methylhistidine and urea nitrogen excretion suggest that carbohydrate supplementation can result in a reduction of muscle protein degradation after resistance training.

Recently, Tipton et al. (74) have reported that the timing of the consumption of a carbohydrate plus amino acid beverage (CAB) can significantly alter insulin levels and muscle protein synthesis rates. When the CAB was ingested prior to the resistance training bout, significantly greater net protein synthesis and higher insulin levels were seen when compared with post-exercise-only consumption. This suggests it is possible that limiting carbohydrate supplementation to the postexercise period slows net protein synthesis. It is possible that this effect on net protein synthesis will be magnified if carbohydrate supplementation is undertaken before and during the resistance-training bout. However, no research to date has explored this hypothesis.

On the basis of this limited research it appears that the inclusion of a carbohydrate supplementation regime may enhance protein synthesis or decrease muscle breakdown and ultimately enhance the effects of resistance training. This may be of particular importance to the strength athlete who is attempting to promote muscle growth and possibly enhance overall muscular strength. Additional research is necessary to develop a complete understanding of the effects of carbohydrate-induced insulin increases on muscle hypertrophy and resistance-training performance.

Growth Hormone. Growth hormone is a polypeptide hormone that is involved with the growth process of skeletal muscle and other tissues (49). Increases in amino acid transport and protein synthesis have been reported as being stimulated by elevations in growth hormone (46, 47). Artificial elevations of growth hormone levels coupled with heavy resistance training are often associated with increases in lean body mass and decreases in fat mass (15). Additionally, elevations in growth hormone levels can be stimulated through the induction of hypoglycemia by insulin (68). Therefore, carbohydrate-induced insulin spikes may potentially lead to increases in growth hormone that may enhance hypertrophy induced by resistance training. Chandler et al. (8) have reported that supplements that promote the greatest insulin spike postexercise lead to significantly higher growth hormone levels 5–6 hours post-exercise. These higher levels of growth hormone only occurred in carbohydrate and protein-carbohydrate treatment groups. Additionally, Kraemer et al. (50)

have also reported that growth hormone and insulin were significantly elevated after day 1 of a 3-day carbohydrate supplementation and heavy resistance-training regime. The combined data of these investigations lend some support to the concept that insulin may induce elevations in growth hormone postexercise. The elevations in growth hormone stimulated by carbohydrate supplementation may ultimately lead to increases in muscle hypertrophy and enhanced resistance-training performance. In order to fully understand these potential ergogenic effects, additional research exploring the interactions of carbohydrate supplementation, insulin, and testosterone are warranted.

Cortisol. The steroid hormone cortisol is classified as a glucocorticoid. This specific glucocorticoid is considered a catabolic hormone in skeletal muscle (49). As a catabolic hormone, cortisol stimulates muscle protein degradation and inhibits protein synthesis in both type I and type II muscle fibers (41). Cortisol appears to be highly catabolic in type II fibers and less catabolic in type I fibers (42). Chronically elevated levels of cortisol can lead to muscle atrophy and loss of contractile proteins, which ultimately could reduce strength levels (21). These negative effects on muscle fibers may predominate in athletes who perform explosive strength-training exercises (i.e., power snatch, power clean, etc.) or participate in sports that require strength, power, and speed because there is a reliance on type II fibers (71) in these activities.

Generally, it is believed that the myriad of catabolic effects stimulated by cortisol occur in order to stimulate gluconeogenesis (57). The inclusion of a carbohydrate supplementation regimen may result in a decreased demand for gluconeogenesis and a concomitant decrease in cortisol levels. Additionally, it has been demonstrated that the lowering of cortisol levels enhances the release of growth hormone in response to growth hormone-releasing hormone (17). As stated earlier, increases in growth hormone may lead to increases in muscle hypertrophy and resistance-training performance. Despite these potential benefits, very few studies have attempted to elucidate the effects of carbohydrate supplementation on postexercise cortisol levels. Several studies have demonstrated that the consumption of carbohydrates during aerobic exercise reduces postexercise cortisol levels (2, 16, 59). Similar cortisol responses to carbohydrate supplementation and resistance training may also be expected. Kraemer et al. (50) have reported suppressed cortisol levels in response to 3 days of carbohydrate supplementation and a heavy resistance-training regime. Additionally, increases in growth hormone were reported in conjunction with these suppressed cortisol levels. This suggests that insulin-mediated suppression of cortisol may result in increases in growth hormone concentration and thus lead to an ergogenic effect.

The effects of glucose ingestion during prolonged

endurance exercise on cortisol levels have also been shown to counteract negative immune changes (63). Elevations in cortisol levels stimulated by exhaustive endurance exercise appear to suppress the functioning of the immune system through a cytotoxic effect on its cells. Lymphocytes have been shown to be degraded in the presence of cortisol (10). Additionally, cortisol has been shown to decrease nucleic acid and protein synthesis in thymocytes (10). A similar effect might be expected with high-intensity resistance exercise. In fact, Nieman et al. (64) have reported that back squats performed to muscular failure can result in an immune response that is very similar to that seen with endurance exercise. Recently, Koch et al. (45) have reported that the ingestion of a carbohydrate beverage during a 20-minute resistance-training bout stimulates a minimal influence on immune response and no effect on cortisol response when compared with a placebo treatment. These authors suggest that the short duration of the training bout induced a stimulus that was insufficient to significantly elevate cortisol and thus impact the immune system's functioning. When contrasting the cortisol and immune responses of the studies by Koch et al. (45) and Nieman et al. (64), it is clear that longer-duration resistance protocols (>35 minutes), such as those that are typically undertaken in an attempt to induce hypertrophy and are marked by large training volumes, are needed to significantly affect cortisol levels and thus the immune system.

The suppression of the immune system may be a critical issue in the body's response to muscle damage. Typically, muscle damage is accentuated by exercises that have large eccentric muscle action components, such as resistance training (62). The suppression of the immune system may increase the recovery time as a result of an increased time needed to repair muscle damage. Therefore, the negative effect of cortisol on the immune system blunted by carbohydrate supplementation may reduce the time needed to recover from a typical resistance-training bout. Currently, no research exists exploring this hypothesis, and further investigation is needed to fully understand the effects of carbohydrate supplementation on cortisol and its relationship to the immune system during resistance training.

Carbohydrates and Resistance-Training Performance

Research examining the effects of carbohydrate supplementation on resistance-training performance is limited and presents conflicting results. Recently, Haff et al. (26) have reported that carbohydrate supplementation does not enhance or maintain isokinetic leg exercise performance. In this investigation, 3 sets of 10 repetitions were performed at $120^{\circ}\cdot\text{s}^{-1}$ prior to and after a free-weight resistance-training bout and were used as a marker of performance. Even though significant glycogen decreases occurred in response to the

resistance-training regime, the addition of a carbohydrate supplementation (prior to and every 10 minutes during the resistance-training bout) did not elicit an ergogenic effect. However, this result may potentially be a product of the performance test selected. Recently, Leveritt and Abernethy (53) have reported that low levels of glycogen seem to impair the performance of back squats but have no effects on isokinetic leg exercise. Thus, it is possible that the maintenance of muscle glycogen reported by Haff et al. (26) with carbohydrate supplementation would have resulted in an enhancement of performance if a different performance test had been employed.

Increases in resistance-training performance with carbohydrate supplementation have been reported in 3 investigations presented in the literature. Lambert et al. (51) have reported that carbohydrate supplementation prior to and during resistance training can enhance the performance of sets of 10 repetitions of leg extensions performed at 80% of 10RM to muscular failure. In their study each subject participated in 2 testing trials where they consumed either a placebo or carbohydrate. The carbohydrate treatment elicited an increased number of sets (+2.7) and repetitions (+20). Similarly, Haff et al. (28) have reported that carbohydrate supplementation can increase the amount of work that can be performed during 16 sets of 10 repetitions of isokinetic leg extensions performed at $120^{\circ}\cdot\text{s}^{-1}$. Additionally, it was reported that significantly greater torque was generated by the quadriceps when the carbohydrate supplement was consumed. Recently, significant increases in resistance-training performance after carbohydrates are consumed during and between multiple training sessions in one day have also been reported (29). Two treatment sessions were conducted in this investigation, in which a carbohydrate or placebo beverage was consumed. Subjects ingested these treatments during a 1-hour morning training session, 4-hour recovery period, and an afternoon performance test consisting of sets of 10 back squat repetitions performed at 55% of the 1RM to volitional failure. The carbohydrate supplementation protocol used in this investigation resulted in significantly more repetitions (+67.7) and sets (+7.4) and greater exercise duration (+31.6 minutes) during the afternoon performance test. The results of these 3 investigations seem to support the hypothesis that carbohydrate supplementation enhances resistance-training performance. However, it is important to note that all these studies required the subjects to perform a resistance-training session that required the performance of high volumes of work similar to those performed during the hypertrophy phase of a periodized program or the typical training of many body builders.

Contrarily, 2 additional investigations have reported that carbohydrate supplementation does not elicit an ergogenic effect during resistance training. The first

study, by Conley et al. (11), explored the effects of carbohydrate supplementation on the performance of sets of 10 repetitions at 65% of 1RM to volitional failure. A carbohydrate beverage was consumed 15 minutes before and after every successful set during testing. There were no significant differences in the number of sets or repetitions or total work observed between the 2 treatments. Similarly, it has been reported that carbohydrate supplementation immediately before a free-weight resistance-training session consisting of 8 exercises does not result in an enhanced performance of isokinetic leg exercise after exercise (76).

The discrepancy between these investigations is presently unclear. Several distinct possibilities exist for these differences. The most notable difference between the studies is the duration of exercise activity. The studies by Lambert et al. (51), Haff et al. (29), and Haff et al. (28) showed ergogenic effects when the exercise bout lasted 56 minutes, 77 minutes, and 57 minutes, respectively. In contrast, the studies that failed to demonstrate an ergogenic effect lasted 35 (11) and 39 minutes (26). Thus it is possible that the duration of the activity influenced the ergogenic effectiveness of the carbohydrate supplement. Anantaraman et al. (1) have reported that exercise bouts lasting less than 40 minutes primarily rely on muscle glycogen as a fuel source. Thus, as the duration of activity increased, a greater reduction in muscle glycogen and a greater reliance on exogenous blood glucose may have occurred. Secondly, the volume of work performed may be a significant factor mediating the ergogenic effect of the carbohydrate supplementation. It is possible that high volumes of work performed for a duration greater than 40 minutes stimulate a greater stress on the glycogenolytic system. The 3 studies that demonstrated an ergogenic effect of carbohydrate supplementation all lasted longer than 55 minutes and required the subjects to perform high-volume work with moderate loads over that time frame. The consumption of a carbohydrate supplement during this scenario could possibly spare muscle glycogen (3, 5, 80) or result in BG becoming the predominant fuel source as glycogen becomes depleted (14, 35, 61). Thirdly, the exercise test selected may have resulted in the lack of an ergogenic effect. Two of the studies that reported no ergogenic effect utilized an isokinetic performance test. The study by Vincent et al. (76) utilized a protocol that required the subjects to perform 3 sets of 15 repetitions of isokinetic leg exercise at $75^{\circ}\cdot\text{s}^{-1}$ before and after a free-weight training program. Similarly, Haff et al. (26) used a testing protocol that required subjects to perform 3 sets of 10 repetitions at $120^{\circ}\cdot\text{s}^{-1}$ before and after a free-weight training program. It is possible that the potential ergogenic effect of carbohydrates would have been clearer if a different testing protocol had been employed. Evidence of a lack of impairment in isokinetic leg exercise performance has been reported in

response to decreased levels of muscle glycogen (53). Impairments in exercise performance were also seen in the performance of back squats in the same study.

The only other study to employ an isokinetic testing bout did, however, exhibit an ergogenic effect (28). Therefore, the major difference between this study and those that did not demonstrate an ergogenic effect is that the study lasted ~59 minutes and employed a protocol that required ~130 more repetitions. Thus the increased duration of activity and volume of work may have mediated the occurrence of an ergogenic effect. Another explanation for the lack of an ergogenic effect during isokinetic testing bouts may be that this is a result of less work being performed during the isokinetic bout. This may occur because isokinetic devices are not really isokinetic and force is only applied during a relatively small range of motion (9, 60). This potentially could decrease the amount of work performed and result in a masking of the ergogenic benefit of carbohydrate supplementation. Additionally, large-mass exercise may stimulate a greater amount of glycogen loss in a number of muscles (not just the prime movers), allowing for an increased ergogenic benefit from carbohydrate supplementation.

There is limited research exploring the effects of carbohydrate supplementation on resistance-training performance. To our knowledge, these are the only investigations that have attempted to explore the relationship between carbohydrate supplementation and resistance-training performance. The data in the literature seem to suggest that carbohydrate supplementation has some ergogenic benefits for athletes who are using high-volume resistance-training protocols similar to those typically used in the hypertrophy phase of a periodized training program. However, due to the limited number of investigations in the literature, this relationship is still unclear. Further research is necessary to establish a clearer understanding of this relationship. Additionally, more research is needed to elucidate the effect of carbohydrate supplementation on different types of resistance exercise (i.e., large mass, small mass, isokinetic, isometric, and isoinertial).

Directions for Future Research

The present body of scientific knowledge suggests that carbohydrate supplementation can generate several potential ergogenic benefits for resistance exercise and training. At present there exist only a few empirical studies supporting the use of carbohydrate supplementation in conjunction with resistance training. There are several areas related to carbohydrate ingestion and resistance training that merit further investigation:

1. What is the effect of carbohydrate supplementation on ability to perform work at different intensities?

Under what conditions will increases in work be manifested?

2. What is the relationship between different program variables (sets, repetitions, and rest intervals) and modes of resistance training (isotonic, isokinetic, eccentric, concentric, and isometric)?
3. What are the effects of acute and chronic carbohydrate supplementation on hypertrophy, body composition, and athletic performance?
4. What is the effect of carbohydrate-induced insulin increases on muscle hypertrophy and resistance-training performance?
5. What are the relationships between carbohydrate supplementation and the anabolic hormonal environment?
6. What is the potential mechanism for the ergogenic effects of carbohydrate supplementation during resistance training?
7. What is the relationship of high-glycemic carbohydrate supplements to the occurrence of obesity and diabetes mellitus?
8. What are the effects of high-glycemic carbohydrates supplements on glucose sensitivity of athletes?

Conclusions

Current research strongly suggests that resistance training, especially using large-muscle mass free-weight exercises performed with high training volumes with moderate loads, is partially dependent upon muscle glycogen stores. The amount of glycogen used in these exercises also appears to be related to the total amount of work accomplished and the duration of the resistance-training bout. The ingestion of liquid carbohydrates prior to, during, and after exercise may serve to promote a faster recovery, which may enhance subsequent exercise and training sessions. Additionally, the implementation of carbohydrate supplementation prior to and during a resistance-training session appears to offer some ergogenic benefit, through increasing work output when the athlete is performing high-volume training with moderate loads. The ingestion of a carbohydrate beverage prior to and during a resistance-training bout may ultimately effect the overall net protein synthesis rate postexercise, which could magnify the hypertrophic response to training. These potential ergogenic effects may ultimately result in improved performance during daily training sessions, which could ultimately enhance performance in power sports such as football and weightlifting.

Practical Applications

The literature reviewed suggests that muscle glycogen plays an important role as a substrate in high-intensity anaerobic exercise bouts such as resistance training.

This role may be magnified when multiple high-volume bouts of anaerobic exercise are performed in the same training day or athletes are participating in a comprehensive conditioning program that requires intense exercise on multiple days. The daily maintenance of glycogen stores may be of crucial importance for maximizing the performance gains associated with resistance training or conditioning programs. One potential mechanism for maintaining daily glycogen stores is the implementation of a carbohydrate supplementation regimen. The consumption of a liquid carbohydrate supplement immediately prior to, during, and immediately after daily training sessions may offer some ergogenic benefits to athletes who perform resistance-training exercises or multiple anaerobic bouts in the same training day (i.e., morning resistance training and evening football practice) or over a training week. These benefits may include increases in work output during training, increases in rates of recovery between training sessions, increases in protein synthesis rates, maintenance of muscle glycogen stores, and creation of an anabolic hormonal environment. All of these benefits could ultimately result in enhanced muscular strength and hypertrophy, which are of particular importance to athletes who compete in sports that require enhanced strength and size, such as American football. Additionally, the effects of a carbohydrate supplement's ability to decrease stress on the immune system may be of additional benefit to anaerobic athletes. Therefore it may be advisable for athletes who are participating in resistance-training programs for high school, collegiate, and professional sports to implement a carbohydrate supplementation program on a daily basis in conjunction with a healthy diet. This supplementation program should center on consuming liquid carbohydrates prior to, during, and immediately after the resistance-training session, whereas the remainder of the carbohydrate consumption, from the healthy diet, should focus on low-glycemic carbohydrate sources (fruits, vegetables, and grains) (77). It is important to make sure that athletes do not consume the majority of their carbohydrates in their diet from high-glycemic sources (sugars, candy, soda, sports drinks, etc.) because this practice may have some adverse effects on health such as increased risk of obesity and diabetes mellitus (77). Ultimately, the implementation of a carbohydrate supplementation regimen in conjunction with a healthy balanced diet may result in the enhancement of competition performance as a result of daily improvements in work output during training sessions.

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