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Fatigue during High-Intensity Intermittent Exercise

Application to Bodybuilding

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Abstract

Resistance exercise is an activity performed by individuals interested in competition, those who wish to improve muscle mass and strength for other sports, and for individuals interested in improving their strength and physical appearance. In this review we present information suggesting that phosphocreatine depletion, intramuscular acidosis and carbohydrate depletion are all potential causes of the fatigue during resistance exercise. In addition, recommendations are provided for nutritional interventions, which might delay muscle fatigue during this type of activity.

Resistance-exercise ('weightlifting') training is used by bodybuilders, powerlifters, olympic-style weightlifters and individuals involved in a wide variety of competitive sports, and has gained widespread popularity among the general population as a means of improving fitness, strength and physical appearance. It has been well established that in older adults resistance exercise can improve muscle mass, strength and physical function.[1,2] Other beneficial effects of resistance training are increased caloric expenditure as a result of the accretion of metabolically active muscle tissue[3,4] and increased bone density.[5] As such, resistance exercise has become an essential mode of exercise in combination with aerobic exercise for developing total body fitness. Despite the fact that it has been clearly established that resistance training is the best way to increase muscle strength and mass,[6] there has been little scientific inquiry into the metabolic demands of resistance training or the metabolic demands of different types of resistance training. Understanding the metabolic demands of specific resistance-exercise training types may allow for refinement of training programmes used to stimulate muscle strength gains and hypertrophy.

This review will focus on the metabolic response and associated limitations to muscle performance that occur during a resistance-training session similar to that performed by bodybuilders. Bodybuilding training sessions are very unique when compared with the regimens that powerlifters, olympic weightlifters, individuals involved in resistance training for sport, and individuals interested in improved physical fitness and appearance engage in, in that they are intense and prolonged sessions. For example, it is not uncommon for a bodybuilder to perform 15 to 20 exercise sets for a given muscle group with limited recovery between sets (~1 minute). The number of repetitions are on the average 8 to 12 with a range of 6 to 20. The goal is to fatigue the muscle with less emphasis placed on how much resistance ('weight') is being lifted. In contrast, powerlifters for example, will take prolonged rest periods (~5 minutes) between sets to ensure they are lifting the maximal amount of weight possible for each set. In addition, the number of repetitions used per set by powerlifters (~1 to 5) is usually much lower than bodybuilders. Because of the much different metabolic demands of a bodybuilding workout relative to a powerlifting workout, for example, we feel we must focus on one type of training.

Even during the course of a bodybuilding workout there are very likely different causes of fatigue at different times. For example, the fatigue mechanism during the first set of 10 repetitions to momentary muscular failure is likely different from the fatigue mechanisms that occur during the 20th exercise set of 10 repetitions. Further, because of the paucity of data regarding the specifics of muscle metabolism during a bodybuilding workout, data from other modes of high-intensity exercise which approximate the intensity, work to rest interval, and total exercise duration as bodybuilding training will be examined. In addition, the limitations of extrapolation of findings during other modes of exercise to bodybuilding exercise will be examined. The underlying premise of this review is that by reducing the effects of factors that limit muscle performance, more work can be accomplished, which should result in greater gains in muscle mass.

1. Limitations to the Extrapolation of Findings from Other Modes of Exercise to Resistance Exercise

The authors' feel that extrapolation of findings from other modes of exercise to resistance exercise is valid if the following caveats are considered. This is based on the fact that the muscle metabolic response depends greatly on exercise intensity and exercise duration. One potential limitation of extrapolating data from other modes to resistance exercise is that in cycling or running, for example, the muscle contractions are intermittent. That is, during part of the contraction of one leg, the other leg is not contracting. In contrast, during resistance exercise, typically, there is tension being generated by the muscle throughout the movement. That is,

the muscle is either contracting concentrically or eccentrically, but in general, at all times there is tension being generated by the muscle. This brings up the issue of differences in blood flow during resistance exercise versus cycling or running. It has been reported that blood flow is occluded at 15 (quadriceps femoris[7]) to ~60% (forearm muscles[8]) of maximal voluntary *isometric* contraction. However, to our knowledge, there are no data examining blood flow during resistance exercise that has both a concentric and eccentric component. Andersen and Saltin[9] reported that muscle blood flow went up linearly with power output during intense contractions of the quadriceps femoris at 1 contraction/sec. However, upon completing the concentric portion of the movement, the flywheel momentum returned the relaxed leg. Thus, there was no eccentric contraction. If blood flow is being occluded during a resistance-training set, the magnitude of the muscle lactate accumulation and phosphocreatine (PCr) degradation, would potentially be greater for a 30-second resistance-training set to muscular failure when compared with a cycling test that resulted in a drop in maintainable power output at ~30 seconds. It is well known that circulatory occlusion increases the rate of PCr degradation.[10,11] Data which may support the contention that there was more circulatory occlusion during resistance exercise than high-intensity cycling is found when you compare the PCr degradation during the studies of MacDougall et al.[12] and Medbo and Tabata.[13] In the resistance-training study of MacDougall et al.[12] participants maintained the exercise intensity for 37 seconds while in the cycle ergometer study of Medbo and Tabata,[13] participants maintained the exercise intensity for 34 seconds. The degree of PCr degradation in the study of MacDougall et al.[12] was 62% while in the study of Medbo and Tabata[13] it was 47%.

To adequately apply information from other modes of exercise to resistance training as performed by bodybuilders it is essential to differentiate the nature of fatigue during resistance exercise as compared with 'all-out' exercise bouts such as the Wingate test.[12,14] Bodybuilders typically perform repetitions to the point where they can complete a full repetition. This point of fatigue is often called 'the point of momentary muscular failure' rather than determining the amount of work (defined here as repetitions X resistance) they can attain in, for example, a 30-second period. Resistance exercise taken to the point of 'momentary muscular failure' is more like 'time to exhaustion' tests at a very high but constant power output rather than all-out cycle ergometry tests. As explained by MacDougall et al.,[12] when one performs a resistance-exercise set to muscular failure at 80% of 1 repetition maximum (RM), maximal force generating capacity has only been reduced by 20% and the muscle is fatigued, but not exhausted. In contrast to a resistance-exercise set taken to momentary muscular failure where force generating capacity is reduced by 20%, McCartney et al.[14] reported that 30 seconds of all-out isokinetic cycle ergometry resulted in decline in peak power output of ~50%. Thus, the metabolic response would likely be of lesser magnitude during a resistance-training set than during a maximal isokinetic cycle ergometer test where maximal power output declines ~50%. As a consequence, comparisons between resistance exercise to momentary muscular failure and all-out tests, even though they may be of similar duration, are not appropriate. It is therefore important to differentiate between these two types of exercise when considering the literature on high-intensity intermittent exercise other than resistance training and applying it to bodybuilding.

2. Substrate Use During Resistance Exercise

Recently, MacDougall et al.[12] published a study examining PCr and glycogen degradation and lactate accumulation in response to high-intensity resistance exercise as performed by bodybuilders. Muscle biopsies were obtained from the biceps brachii before and after one set of 12 repetitions to muscular failure at 80% of the 1RM (37 seconds). Based on their data, we have estimated the relative

contribution of stored ATP, PCr degradation, and glycolysis to meet the ATP demands of this type of exercise. The calculations assumed that the muscle lactate obtained from the biopsy is representative of all of the muscle lactate produced, and that all of the muscle lactate is derived from muscle glycogen (3 moles of ATP produced for every 1 mole of lactate) at this exercise intensity.[15] Stored ATP provided 1.6%, PCr hydrolysis provided 16.3%, while glycolysis provided 82.1% of the ATP demands. These estimates are similar to the data obtained by Medbo and Tabata[13] during 34.4 seconds of cycling to fatigue at 193% of maximal oxygen uptake ($\dot{V}O_{2max}$). We estimated (based on the assumptions above) from the study of Medbo and Tabata[13] that 0.8% of ATP production was provided by stored ATP, 16.4% was provided by PCr hydrolysis, and 82.7% was provided by glycolysis. Thus, even during intense exercise of short duration (<40 sec), glycolysis via primarily the glucose moieties from glycogenolysis provided the majority of the ATP for muscular contraction.

It has been clearly established that there is an exponential relationship between glycogen degradation in the working muscle and exercise intensity (figure 1). Therefore, it is not surprising that during intense resistance exercise, skeletal muscle relies heavily on muscle glycogen as an energy source.

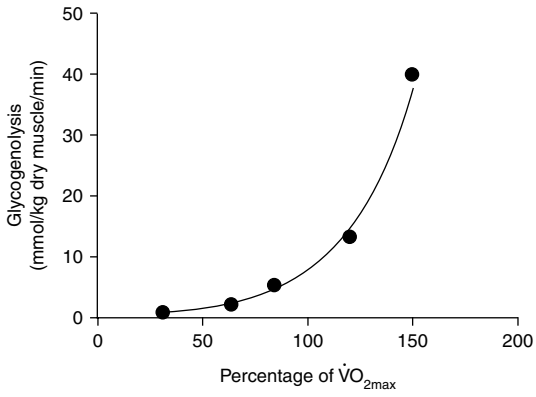

Fig. 1. Influence of exercise intensity on the rate of skeletal muscle glycogenolysis. $\dot{V}O_{2max}$ = maximal oxygen uptake.

MacDougall et al.[12] reported that one set of single arm curls at 80% of 1RM taken to the point of muscular failure (12.0 repetitions), resulted in a 12% reduction in the mixed muscle glycogen concentration. In addition, these investigators reported that three sets at 80% of 1RM taken to the point of muscular failure resulted in a 24% decrease in the mixed muscle glycogen concentration. Similarly, Robergs et al.[16] reported a 26.1% decrease in glycogen of the vastus lateralis muscle after three sets of 12 to 13 repetitions with each set approaching muscular failure. In the same investigation, Robergs et al.[16] also reported a 38% decrease in glycogen after six sets of 12 to 13 repetitions. In addition, these investigators reported a greater rate of glycogen degradation in type II fibres than type I fibres.

3. Causes of Fatigue During Resistance Exercise

It is difficult to determine the cause or causes of muscular fatigue during exercise when changes in substrates and/or metabolites believed to cause muscle fatigue are coincident with changes in other substrates or metabolites. For example, during intense contraction to fatigue there is a fall in muscle pH and an increase in ADP and inorganic phosphate (Pi).[17] Which of these is/are the cause(s) of fatigue cannot be easily determined because of a similar magnitude of changes in these substances that have been shown to cause fatigue independently. Thus, one way to determine the cause or causes of fatigue, although limited, is to increase or decrease the concentration of a substrate required for contraction or a metabolite believed to cause fatigue. Manipulations which have been used during high-intensity exercise that approximates resistance exercise are creatine ingestion to elevate intramuscular stores of PCr,[18-22] changes in extracellular hydrogen ion concentration through sodium bicarbonate,[23-25] sodium citrate supplements,[26-28] and/or ammonium chloride ingestion[29,30] and carbohydrate restriction or supplementation to alter carbohydrate availability.[31-36] Fatigue during resistance exer-

cise is likely to be multifactorial; however, PCr depletion, intramuscular acidosis, and a reduction in muscle glycogen content as causes of fatigue during multiple bout resistance exercise will be considered in sections 3.1, 3.2 and 4.2.

3.1 Studies of Creatine Ingestion

It is clearly established that 5 days of creatine ingestion (20 to 30 g/day) can elevate intramuscular creatine (>20% increase),[21] PCr stores (~5%)[21] and the rate of PCr resynthesis;[21] however, few investigations have examined the influence of creatine ingestion on resistance-training performance. Earnest et al.[19] reported that 28 days of creatine monohydrate ingestion significantly increased the bench press 1RM (6%) and the number of repetitions performed at 70% of 1RM (34.8%). However, it is difficult to determine the mechanism of the improvement with the 28 days of creatine ingestion. It is unclear whether the ergogenic effect of creatine was due to an increase in the muscle PCr and/or total creatine stores or whether it was due to muscle hypertrophy. We assume after 28 days of creatine ingestion that the concentration of total creatine and PCr would be elevated but it is also possible that muscle hypertrophy occurred and that this was the cause of the improvements in resistance-training performance. This speculation is supported by a 6% increase (significant) in bench press 1RM. It seems highly unlikely that PCr depletion would be the cause of fatigue during a 1RM, which typically would be completed in <5 seconds. It has been reported in a few studies using muscle cell cultures that the addition of creatine to the medium increases myosin synthesis.[37-39] Whether an increase in protein synthesis leading to a greater muscle mass was the cause for the improvements in the study of Earnest et al.[19] is not known.

Volek et al.[40] reported that 6 days of creatine ingestion (25 g/day) significantly improved the number of repetitions that could be performed on each of 5 sets of the bench press taken to muscular failure with 2 minutes of rest between sets. Acute creatine ingestion should elevate the intramuscular PCr stores by ~5% and total creatine by >20%.[21] Since the supplementation period was short, it would be much less likely that the improvements seen by Volek et al.[40] were due to muscular hypertrophy.

Vandenberghe et al.[41] reported that 10 weeks of progressive resistance training combined with the ingestion of 5 g/day of creatine monohydrate per day after a 4-day period of creatine loading, resulted in a 20 to 25% greater increase in maximal strength, a 10 to 25% greater increase in maximal intermittent exercise capacity of the arm flexors, and a 60% greater increase in fat-free mass when compared with the placebo condition. It is difficult to discern, however, whether these changes were caused by an elevation of intramuscular creatine and/or PCr and/or an increase in muscle size. In some of these studies,[19,41] the acute effect of creatine ingestion cannot be separated from the chronic effects, but one can conclude that the increase in intramuscular creatine concentration and PCr concentration can improve the rate of PCr resynthesis and exercise capacity during resistance exercise. Thus, it appears that depletion of the PCr concentration is a potential cause of fatigue during resistance exercise.

3.2 Effects of Changes in Acid-Base Status on Multiple-Bout High-Intensity Exercise

The ingestion or infusion of substances to make the extracellular fluid alkalotic or acidotic has been employed in an attempt to determine whether these factors alter high-intensity exercise capacity and to determine whether acidosis is a cause of fatigue during high-intensity exercise of different durations. In general, these studies lead us to suggest that acidosis is a probable cause of fatigue during high-intensity intermittent exercise.[23,26-29] However, the data are inconclusive with regard to resistance training. Costill et al.[23] had participants perform four 1-minute bouts of cycle exercise at 125% of $\dot{V}O_{2max}$ with 1 minute of recovery between bouts. The fifth and final bout was performed to fatigue. On one occasion, 1 hour before performing

the exercise, participants ingested sodium bicarbonate that induced alkalosis and on the other occasion they ingested placebo. On the fifth bout, there was a 42% increase in the time to exhaustion when participants ingested sodium bicarbonate.

McCartney et al.[42] had participants perform 30 seconds of maximal exercise on an isokinetic cycle ergometer on four different occasions: after the ingestion of ammonium chloride to induce metabolic acidosis, after the ingestion of sodium bicarbonate to induce metabolic alkalosis, after the inhalation of 5% CO_2 to induce respiratory acidosis, and after a control condition. No effect of the three experimental conditions was observed on exercise performance during the single 30-second bout.

With regard to resistance training and the effects of acid-base status, Webster et al.[25] had participants perform four standardised bouts of resistance training (12 repetitions at 70% of 1RM) which lasted ~1 minute each, followed by 90 seconds of recovery. The fifth bout was taken to the point of muscular failure. Participants ingested sodium bicarbonate on one occasion and placebo on the other occasion. Despite, a significant effect of the sodium bicarbonate ingestion in causing alkalosis, no significant difference was observed with regard to the number of repetitions performed before the point of muscular failure.

In an investigation from the same laboratory as that of Webster et al.,[25] Portington et al.[24] reported that alkalosis had no effect on the number of repetitions performed during five sets of the leg press exercise each taken to fatigue with 90 seconds of recovery between each bout. The authors suggested that the high-force but low oxygen consuming effects of resistance training minimised the reduction in pH and resulted in a reduced lactate accumulation when compared with studies in which induced alkalosis had improved exercise performance. Despite the supramaximal effort in the muscle group that was exercised, the authors suggested that the ~50% of whole body $\dot{V}O_{2max}$ required during resistance training elicited a lower whole body metabolic response than the ≥100% of $\dot{V}O_{2max}$ whole body metabolic response observed in studies[23,26-29] where induced alkalosis has been shown to have a beneficial effect on exercise performance.

Despite studies[23,26-29] in support of this idea it is difficult to discern whether intramuscular acidosis is a cause of fatigue during resistance exercise as performed by bodybuilders. Based on the data of MacDougall et al.[12] a combination of acidosis and PCr depletion were likely the causes of fatigue after one set in their study, and acidosis was the cause of fatigue after three sets (each set was performed to muscular failure at 80% of 1RM with 3 minutes of rest between bouts). PCr decreased 62% after one set and 50% after three sets (from the pre-value) and lactate increased to 91 mmol/kg dry weight (21.3 mmol/kg wet weight) after one set and 118 mmol/kg (27.4 mmol/kg wet weight) after three sets. Because, PCr decreased less after three sets and lactate was extremely high, the authors suggested that acidosis and not PCr depletion was the cause of fatigue during the three set condition.

4. Carbohydrate Availability and Multiple-Bout High-Intensity Exercise

4.1 Mechanisms for a Carbohydrate Limitation

4.1.1 Effects of Glycogen Level on Glycogenolysis, Glycolysis and ATP Production

It is fair to assume that if enough bouts are performed during multiple bout high-intensity exercise that muscle glycogen will reach a level where it is no longer able to sustain glycogenolysis, glycolysis, and therefore ATP production. Thus, fatigue resulting from glycogen depletion will ensue. Jacobs[43] has suggested that a reduction in muscle or blood lactate concentration during high-intensity exercise a few days after exhaustive exercise followed by a low carbohydrate diet is due to a reduction in glycogenolysis. However, an alternative interpretation put forth by Bangsbo et al.[44] is that in the carbohydrate-depleted state, the low substrate availability may lead to greater utilisation of lactate as a fuel source. Thus, lower lactate accumulation

may be the result of greater lactate removal and not reduced production.

It appears that a reduction of the pre-exercise glycogen to ~200 mmol/kg dry weight muscle (~50 mmol/kg wet weight muscle) is insufficient to reduce the glycogenolytic rate during high-intensity exercise, however; when the pre-exercise glycogen is ~60 mmol/kg dry weight muscle (~15 mmol/kg wet weight muscle) the glycogenolytic rate is significantly reduced.[45] These investigators,[45] however, reported that the rate of glycolysis was maintained despite a reduced rate of glycogenolysis, likely as a result of an elevation of allosteric stimulators of phosphofructokinase. Although findings of a reduction in glycolysis as a result of carbohydrate depletion has been elusive, it is logical to assume that there is a glycogen concentration reached during high-intensity intermittent exercise where glycogenolysis, glycolysis, and therefore ATP production are reduced below the needs of the contracting muscle fibres.

4.1.2 Preferential Use of Glycogen by Type II Muscle Fibres

It has been clearly established that the glycogen concentration in type II muscle fibres is significantly higher than that in type I fibres.[46,47] Greenhaff et al.[46] reported that the glycogen concentration in type II fibres was 26% higher than that in type I fibres. In addition, these investigators reported that the rate of glycogenolysis was 63.6% greater in type II fibres than in type I fibres during 30 seconds of maximal treadmill sprinting. After the 30-second bout of sprinting, the glycogen concentration was still very high in type II fibres (346 mmol/kg dry muscle; 80.5 mmol/kg wet muscle) and it did not appear that glycogen was low enough to impair performance. Vollestad et al.,[48] also reported that as a result of cycle ergometry to exhaustion at 194% of $\dot{V}O_{2max}$ (34 seconds) the glycogen use was 30 to 35% less in type I fibres than type II fibres. Thus, the glycogen concentration has been shown to be ~25% higher in type II fibres[46,47] and the glycogenolytic rate has been shown to be about ~65% greater in type II than type I fibres during 30 seconds of maximal effort exercise.[46,48] Because the rate of glycogenolysis is so much higher in type II than type I fibres (table I) it is possible that during repeated bouts of very intense exercise the glycogen concentration in type II fibres may become limiting to performance. Nicholas et al.[35] reported that muscle glycogen degradation was 48% higher and the post-exercise glycogen concentration was lower ($p < 0.01$) in type II than type I fibres after 90 minutes of high-intensity intermittent shuttle running. Balsom et al.[49] examined the effects of repeated intense 6-second sprints interspersed with 30-second rest periods on mixed muscle glycogen concentration. These authors reported that muscle glycogen concentrations (not fibre-specific glycogen concentration) were much

Table I. Glycogenolytic rates in type I and type II muscle fibres during intense exercise

Study	Exercise	Type II fibre glycogenolytic rate (mmol/kg dry mass/sec)	Type I fibre glycogenolytic rate (mmol/kg dry mass/sec)	Increase in glycogenolysis (type II relative to type I fibres) [%]
Greenhaff et al.[50]	30 sec maximal sprinting	4.2	2.6	61.5
Greenhaff et al.[46]	64 sec intermittent electrical stimulation	3.54	0.18	1867
Vollestad et al.[48]	30 sec of cycle ergometry at 194% of $\dot{V}O_{2max}$	2.18	1.47	48
Robergs et al.[16]	Leg extensions: six sets of six repetitions at 70% of 1 repetition maximum	Absolute rates not given	Absolute rates not given	89.7
Nicholas et al.[35]	90 min of intermittent maximal shuttle running	Absolute rates not given	Absolute rates not given	42.2

$\dot{V}O_{2max}$ = maximal oxygen uptake.

higher in individuals who had high initial glycogen levels (as a result of a carbohydrate loading regimen) than individuals who had low initial glycogen levels (as a result of depletion and a low carbohydrate diet) at fatigue. If we assume that glycogen depletion was a significant contributor to fatigue in both the high- and low-glycogen trials in the study of Balsom et al.,[49] it is tempting to speculate that fatigue ensued because of type II fibre depletion in both dietary conditions despite mixed muscle glycogen at fatigue being higher in the high carbohydrate condition (151 mmol/kg dry muscle; 35 mmol/kg wet muscle) than in the low carbohydrate condition (64 mmol/kg dry muscle; 14.9 mmol/kg wet muscle).

4.2 Carbohydrate Availability and High-Intensity Intermittent Exercise Including Resistance Exercise

Balsom et al.[49] reported that individuals who had high initial muscle glycogen levels were able to perform 265% more 6-second high-intensity intervals on a cycle ergometer interspersed with 30 seconds of rest than individuals who had low initial muscle glycogen levels. However, the total exercise times are long, relative to the duration of a bodybuilding workout on a given muscle group (67 minutes for low carbohydrate and 178 minutes for high carbohydrate). Thus, because of this long duration of the exercise sessions compared with the duration that bodybuilders exercise for a given muscle group, the practical implications for resistance workouts of the same muscle group is limited. Davis et al.[51] reported that when individuals performed 1-minute bouts of exercise on a cycle ergometer at 120 to 130% of $\dot{V}O_{2max}$, those who ingested a carbohydrate solution were able to perform 50% more exercise bouts (21 bouts; 87 minutes *vs* 14 bouts; 59.8 minutes) before fatigue than individuals who ingested a placebo. Lambert et al.[33] reported that the ingestion of carbohydrate during resistance exercise resulted in more sets ($p = 0.067$; 18.8% increase) and repetitions ($p = 0.056$; 15.5% increase) being performed before exhaustion than the placebo condition. It was hypothesised that the carbohydrate ingestion resulted in an increase in glycogen synthesis during the rest periods and therefore a net sparing of muscle glycogen. Furthermore, it was hypothesised by the authors that muscle glycogen was spared because during high-intensity exercise (97% of $\dot{V}O_{2max}$) it has been shown that blood glucose contributes only 1% of carbohydrate used while muscle glycogen provides the remainder.[15] A glycogen-sparing mechanism as a result of carbohydrate feedings during high-intensity intermittent exercise has been recently documented during intense intermittent running[35] and during resistance exercise.[32]

Data which support the concept of a carbohydrate limitation during resistance exercise come from Leveritt and Abernathy[34] who reported that exhaustive exercise followed by 2 days of carbohydrate restriction (1.2g carbohydrate per day; carbohydrate 19% of total energy intake) resulted in a significant 21% reduction in the number of repetitions performed during three sets of isoinertial squats.

Haff et al.[31] reported that carbohydrate feeding (compared with placebo feeding) in the hours after a morning resistance-training session (15 bouts, 10 repetitions each bout) designed to reduce muscle glycogen stores improved the number of repetitions (34%), the number of sets (39%) and the exercise duration (40.8%) during a second resistance-training session that was performed 4 hours after the first session. Thus, it appears that during high-intensity multiple bout exercise similar to a bodybuilding workout, carbohydrate availability can greatly influence exercise performance. The improved performance as a result of carbohydrate ingestion immediately before or during this type of exercise appears to be caused by a muscle glycogen-sparing effect.[22,35]

In contrast to the studies where a positive effect of carbohydrate supplementation has been used to increase resistance-exercise performance, Mitchell et al.[36] reported no effect of carbohydrate loading compared with a low carbohydrate diet on the

amount of work performed during 15 sets of quadriceps exercise (5 sets of squats, 5 sets of leg presses, and 5 sets of knee extensions) performed with the 15RM weight. The total exercise time for the study of Mitchell et al.[36] was 43 minutes (combined carbohydrate group and placebo group) which was similar to the 47.4 minutes for the placebo group in the study of Lambert et al.[33] who used only leg extensions. Thus, the difference in performance does not appear to be caused by different exercise durations. One important difference between the study of Mitchell et al.[36] and Lambert et al.[33] is that all of the sets in the study of Mitchell et al.[36] were taken to muscular failure. Only some of the sets were performed to muscular failure in the study of Lambert et al.[33] Thus, the intensity (effort per set) was greater in the study of Mitchell et al.[36] Because of the higher intensity of effort, the degree of intramuscular acidosis in the quadriceps would likely have been much greater in the study of Mitchell et al.[36] than the study of Lambert et al.[33] As a result, acidosis instead of impaired carbohydrate availability may have been the cause of fatigue in the study of Mitchell et al.,[36] while reduced muscle glycogen availability was the likely cause of fatigue in the study by Lambert et al.[33]

Evidence supporting our contention that acidosis and not carbohydrate availability was the cause of fatigue in the study of Mitchell et al.[36] has been provided by a study performed by Tesch et al.[47] Tesch and colleagues[47] had participants perform 20 sets of quadriceps exercise with each set taken to muscular failure and used a recovery period of 1 minute between sets. The muscle glycogen use in this study was 26% when 20 sets were performed. This was similar to the 24% reported by MacDougall et al.[12] after only three sets with 3 minutes of recovery between each. The fact that each set was taken to muscular failure and that there was only 1 minute of recovery between sets is likely the cause of the modest glycogen use in the study of Tesch et al.,[47] as Spriet et al.[52] have reported that intramuscular acidosis inhibits glycogen degradation. Thus, it appears that even when many bouts are performed, if each set is taken to the point of muscular failure with short recovery periods, acidosis is the probable cause of fatigue and not reduced carbohydrate availability

4.3 Other Factors that May Influence Carbohydrate Requirements

4.3.1 Influence of Muscle Damage on Glycogen Synthesis

Resistance exercise as performed by bodybuilders has an eccentric component. It is well known that unaccustomed eccentric exercise will result in muscle damage and soreness. Furthermore, eccentric exercise results in impaired glycogen storage due to an increase in insulin resistance.[53] Although bodybuilders have highly resistance-trained muscles, significant muscle damage still occurs after the previous days' workout.[54] Thus, it follows that in the hours and days after a resistance-training workout there may be impaired glycogen storage. However, it has been shown that increasing the amount of ingested carbohydrate from 4.3 g/kg bodyweight/day to 8.5 g/kg bodyweight/day results in greater glycogen storage 24 and 72 hours after eccentric exercise.[55] Thus, for this reason a moderate- to high-carbohydrate diet may be advantageous for individuals involved in high-intensity multiple set resistance exercise.

4.3.2 Aerobic Exercise

In addition to performing resistance exercise, bodybuilders also typically perform aerobic exercise during contest preparation to reduce their body fat percentage as well as during the noncontest phase to maintain a low body fat percentage. Aerobic exercise above 50% of $\dot{V}O_{2max}$ relies primarily on muscle and liver glycogen and blood glucose.[56] The more intense the exercise (above 50% of $\dot{V}O_{2max}$) the more glycogen that is used. Thus, besides the carbohydrate requirements of the resistance training, the addition of aerobic exercise will also increase the need for dietary carbohydrate.

4.3.3 Carbohydrate Requirements for Bodybuilding Training

Glycogen resynthesis with carbohydrate supplementation in the early hours after resistance exercise has been examined.[57] However, the important question for bodybuilders is: will muscle glycogen return to pre-exercise values by the time of their next workout? Only one study, to the authors' knowledge, has examined the effects of diet on long-term (≥24h) muscle glycogen resynthesis after intense intermittent exercise.[58] The equivalent of six to seventeen 1-minute bouts at 140% of $\dot{V}O_{2max}$ were performed by the participants before exhaustion. Muscle glycogen was reduced by 72%. These investigators found that the consumption of 3.15g of carbohydrate per kilogram of bodyweight restored muscle glycogen to the pre-exercise value by 24 hours post-exercise. No added benefit was observed by the ingestion of 7.71g of carbohydrate per kilogram of bodyweight. One major difference between the exercise performed in the investigation of MacDougall et al.[58] and resistance exercise was that there was no eccentric component. As reported by Gibala et al.,[54] eccentric muscle contractions induce muscle damage even in highly trained bodybuilders. As described above, muscle damage may increase the dietary carbohydrate requirement for optimal muscle glycogen resynthesis.

5. Recommendations

It appears that PCr depletion and carbohydrate depletion can cause fatigue during resistance exercise. Therefore, to increase the amount of work that can be performed during an exercise session, supplementation of the diet with creatine to increase the PCr stores and/or increase PCr resynthesis, and carbohydrate to increase carbohydrate availability is recommended. It has been shown that moderate amounts of creatine ingestion (3 g/day) over 28 days increases the intramuscular creatine concentration to a similar extent as 'creatine loading' for 6 days.[59] In addition, it has been shown in rat skeletal muscle long-term (3 to 6 months) creatine administration can down-regulate the creatine transporter.[60] Thus, because of these two findings, we recommend the ingestion of moderate amounts of creatine during normal training (3 to 5 g/day for a month followed by a 1-month wash-out period in an attempt to prevent creatine transporter down-regulation) to enhance the amount of work performed during resistance-training workouts and potentially increase the degree of muscle hypertrophy. In addition, because of the mixed results obtained with high-intensity intermittent exercise performance with buffers that alter extracellular acid-base status, we cannot endorse the use of these substances. Because it appears that: (i) glycogen use is substantial during resistance exercise;[12,16] (ii) eccentric damage results in greater carbohydrate requirements for adequate glycogen resynthesis;[55] and (iii) carbohydrate-utilising aerobic exercise is often undertaken by individuals involved in bodybuilding, it follows that consuming adequate amounts of carbohydrate is important to sustain work output during resistance-exercise sessions. We suggest that individuals involved in a bodybuilding type of resistance-exercise regimen consume 6g of carbohydrate/kg bodyweight/day or about ~55 to 60% of their total energy intake.

6. Conclusion

Fatigue during one set of resistance exercise (10 repetitions) taken to the point of 'momentary muscular failure' is likely caused by low phosphocreatine concentrations. Intramuscular acidosis appears to be the predominant reason for fatigue on the third resistance exercise set taken to momentary muscular failure when there is adequate recovery between sets (1 to 3 minutes). It is likely that when 15 to 20 resistance-exercise sets are performed for a given muscle group with 2 to 3 minutes of recovery between sets that the concentration of intramuscular glycogen may become limiting. To enhance resistance-exercise sessions, bodybuilders should consider ingesting creatine monohydrate and a relatively high-carbohydrate diet: 6 g/kg bodyweight per day or 55 to 60% of total daily energy intake.

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