THE SCIENCE OF POST-EXERCISE RECOVERY

RESEARCH FROM THE ACE SCIENTIFIC ADVISORY PANEL

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Post-exercise recovery is a vital component of the overall exercise training paradigm, and essential for high-level performance and continued improvement. If the rate of recovery is appropriate, higher training volumes and intensities are possible without the detrimental effects of overtraining. Health and fitness professionals play a critical role in helping clients identify the most appropriate training recovery program, a process that requires purposeful trial and error.

Therefore, it is essential that health and fitness professionals understand the physiological concept of recovery, and recognize that considerable individual variability exists within the recovery process due to training status (trained vs. untrained), factors of fatigue and a person's ability to deal with physical, emotional and psychological stressors. Frequency, intensity, time and type of recovery between each bout of exercise must also be considered to optimize recovery.

Much contemporary research has explored numerous tactics for augmenting the recovery process, including various nutritional strategies (e.g., when, why and how much to consume of various nutrients and combinations of nutrients), cold-water immersion, stretching and compression garments. To translate exercise, nutrition and training recovery research into practice, health and fitness professionals should program active recovery, specific recovery intensities and high-intensity interval training, and translate nutrition research into real-world consumable items for clients.

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KEY POINTS

- Recovery from exercise and competition is a vital component of the overall exercise training paradigm, and paramount for high-level performance and continued improvement.
- The underlying mechanisms that mediate post-exercise recovery include skeletal muscle damage, decreased substrates and the accumulation of metabolic by-products.
- Optimal recovery entails restoring the capacity for each of the three energy systems to function once again at maximal levels.
- Three chronic training adaptations improve post-exercise recovery: increased $\dot{V}O_2$max, increased buffering capacity and increased monocarboxylate transporters.
- Health and fitness professionals must consider the frequency, intensity, time and type of recovery between each bout of exercise in order to optimize recovery.
- Evidence-based nutritional strategies are a required aspect of recovery, including when, why and how much to consume of various nutrients and combinations of nutrients.
- Alternative methods used to augment post-exercise recovery include cold water immersion, ischemic preconditioning, massage, stretching and compression garments, though not all are equally effective.
- To translate exercise, nutrition and training recovery research into practice, health and fitness professionals should program active recovery, specific recovery intensities and high-intensity interval training, and translate nutrition research into real-world consumable items for clients.

RECOVERY FROM exercise and competition is a vital component of the overall exercise training paradigm, and paramount for high-level performance and continued improvement. If the rate of recovery is appropriate, higher training volumes and intensities are possible without the detrimental effects of overtraining. Understanding the physiological concept of recovery is essential for designing optimal training programs. Considerable individual variability exists within the recovery process due to training status (trained vs. untrained), factors of fatigue and a person's ability to deal with physical, emotional and psychological stressors. Much contemporary research has explored numerous tactics for augmenting the recovery process, including various nutritional strategies, cold-water immersion, stretching and compression garments. This review article will provide evidence-based research and practical applications on post-exercise recovery for health and fitness professionals.

THE PHYSIOLOGY OF POST-EXERCISE RECOVERY

What are the underlying mechanisms that mediate post-exercise recovery?

The capacity to recover permits a high level of performance within the next exercise bout, exercise session or competition. Yet, for the health and fitness professional to design a training program that facilitates recovery, he or she must first identify the specific conditions from which a client will be recovering. In the subsequent sections, three key areas are explored.

Skeletal Muscle Damage

High-intensity aerobic and resistance exercise can impose considerable perturbations of the skeletal muscle, including damage to the sarcolemma, contractile proteins and connective tissue.[1] These disturbances result in a diminished capacity to generate peak muscle forces that persists until repair is complete. The muscle damage impairs the ability to transport blood glucose into the skeletal muscle cell. This in turn leads to a decreased capacity to replenish glycogen stores.[2] Skeletal muscle damage also leads to soreness and pain.

Decreased Substrates

Exercise conditions that extensively tax either the phosphagen system or glycolysis will ultimately lead to depletion in the primary substrate (or fuel) for each energy pathway. The skeletal muscle concentration of phosphocreatine (CrP) is limited, and within a duration of approximately 10 seconds of high-intensity exercise, the resting CrP stores are rapidly depleted.[3] Activities that rely heavily on the phosphagen system for adenosine triphosphate (ATP) provision include sprinting, chopping wood, jumping rope and the equivalent. High-intensity exercise is frequently repeated over multiple bouts, whether the environment be a training session or athletic competition. Therefore, recovery from CrP degradation becomes critical in these instances if high-intensity exercise performance is to continue. Likewise, the primary substrate for glycolysis, glycogen, can be depleted following prolonged and vigorous endurance exercise. Unless glycogen stores are sufficiently restored prior to the next exercise session, a high level of performance will be compromised.[1]

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Accumulation of Metabolic By-products

ATP turnover rates are elevated during high-intensity exercise conditions. Concomitantly, increased glycolytic flux and ATP hydrolysis contributes to an accumulation of lactate and protons within the cells. Both of these molecules can impair continued ATP resynthesis and skeletal muscle contraction through different mechanisms.[4] Lactate has been found to hinder the electrical stimulus for muscle contraction. The accumulation of protons leads to a decreased muscle pH. Cellular acidosis impairs the recovery of CrP stores. Furthermore, the key enzymes involved in glycolysis, including phosphorylase and phosphofructokinase, are each down-regulated by an accumulation of protons. Recovery from cellular acidosis is paramount in order to restore the capacity to regenerate ATP from both the phosphagen system and glycolysis.[5]

How do the three energy systems interact with post-exercise recovery and performance?

Skeletal muscle performance, be it sprinting down the field during a soccer match or cycling 40 kilometers in the middle stage of a triathlon, requires a constant supply of energy. The molecule ATP provides the immediate source of energy for skeletal muscle contraction for these types of exercise scenarios, and is frequently referred to as the energy currency of the cell or the universal energy donor. Given that ATP is essential for repeated muscle contraction, it would seem logical that large stores of ATP exist within skeletal muscle. This is not the case. In fact, if ATP could not be rapidly regenerated, the resting stores of ATP would quickly be depleted during high-intensity exercise scenarios.

There are three main energy pathways available to regenerate ATP—the phosphagen system, glycolysis and mitochondrial respiration. These pathways differ considerably in the maximal rate of ATP regeneration, and the duration for which this maximal rate can be sustained. Peak performance of the different energy systems can be compromised following challenging exercise conditions, such as repeated high-intensity sprints or extended submaximal running. Optimal recovery entails restoring the capacity for each energy system to function once again at maximal levels. An appreciation of how the three energy pathways function provides the foundation for designing a training program that optimizes recovery.

A BRIEF PRIMER ON THE THREE ENERGY PATHWAYS

The Phosphagen System: The most rapid means for regenerating ATP is the phosphagen system (Figure 1). This pathway involves a single reaction whereby the enzyme creatine kinase is responsible for catalysing the metabolite creatine phosphate (CrP). Subsequently, free energy is made available to rephosphorylate ATP (i.e., add a P_i to ADP). The enzyme creatine kinase, which facilitates the CrP reaction, is up-regulated by an increased concentration of ADP. Creatine kinase activity is inhibited when concentrations of ATP are normal. Therefore, when ATP demand increases suddenly, as is the case with the onset of high-intensity exercise, the hydrolysis of ATP results in elevated levels of ADP, and thus the necessary biochemical signal for this pathway to regenerate ATP. This design permits an almost instantaneous capacity to match ATP demand with a swift supply.

Glycolysis: The glycolytic metabolic pathway provides ATP at a rate below that of the phosphagen system, but still nearly twice as fast as mitochondrial respiration (see Figure 1). Glycolysis comprises a series of nine enzymatically catalyzed reactions. Glycolysis involves the conversion of either a molecule of blood glucose or muscle glycogen to two molecules of pyruvate or lactate. The activity of the enzymes phosphorylase and phosphofructokinase are both swiftly up-regulated at the onset of intense exercise. There are two phases to glycolysis. Phase one is an energy investment phase, while phase two represents the energy generation phase. Phase one of glycolysis consists of four reactions and requires an investment of either one or two ATP molecules to proceed. The phosphofructokinase reaction requires an ATP. This reaction is considered the main rate-limiting reaction of glycolysis. If glucose is the substrate provided for glycolysis, an additional ATP is required for glucose transport from the blood into the muscle cell (this is facilitated by the transporter protein GLUT-4). The second phase of glycolysis involves five additional reactions from which four ATP molecules and two pyruvate molecules are produced. The phosphoglycerate kinase and pyruvate kinase reactions each produce two ATP. It is also important to note that two molecules of NAD^+ are reduced to NADH during phase two of glycolysis from the glyceraldehyde-3-phosphate dehydrogenase reaction. In summary, the reactions of the glycolytic energy system produce two pyruvate, two NADH, and either two or three ATP. The difference in net gain of ATP can be explained by the one ATP cost of bringing glucose into the muscle cell via GLUT-4 transporter protein as the substrate for glycolysis.

Mitochondrial respiration: The third pathway by which ATP is regenerated is through mitochondrial respiration (see Figure 1). In terms of overall quantity, the regeneration of ATP molecules is greatest from fuels that undergo mitochondrial respiration. However, the maximal rate of ATP regeneration from mitochondrial respiration is considerably less than either the phosphagen system or glycolysis. Pyruvate produced from glycolysis can enter into the mitochondria where it undergoes further oxidation in the Krebs cycle. The pyruvate dehydrogenase reaction facilitates the entry of pyruvate into the mitochondria. During this reaction, NADH acetyl-CoA molecules are formed. Acetyl-CoA molecules subsequently pass through a full turn of the Krebs cycle, yielding molecules of ATP, FADH and NADH. The NADH and FADH molecules produced from the Krebs cycle then move onto the electron transport chain where additional ATP is regenerated. Depending on whether or not glucose or glycogen is the initial molecule entering into glycolysis, the overall tally of ATP regenerated from mitochondrial respiration summates to 32 or 33 ATP.

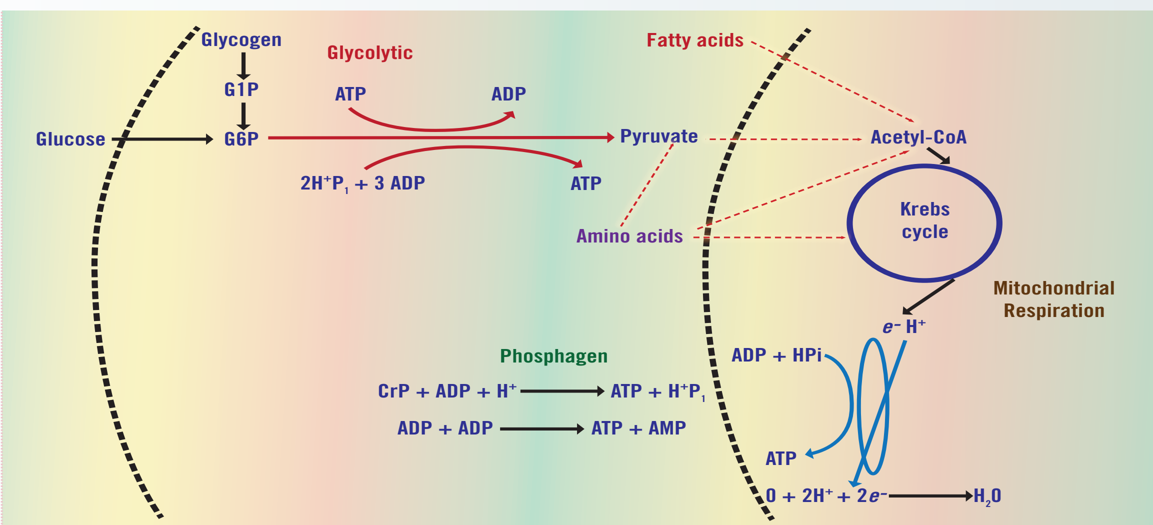

Figure 1
The Three Energy Pathways

What chronic training adaptations improve post-exercise recovery?

The principle of training specificity states that the physiological and metabolic responses and adaptations to exercise training are specific to the type of exercise and muscle groups involved. Health and fitness professionals should also recognize that the principle of training specificity extends to recovery.[6] Critically, specific training strategies should be employed to elicit specific adaptations that will expedite recovery. In the following sections, three favorable adaptations that will occur with the proper training regimen are presented.

Increased $\dot{V}O_2$max

It is well known that high levels of maximal oxygen uptake ($\dot{V}O_2$max) are linked with superior performance in endurance-related events. However, $\dot{V}O_2$max also plays an integral role in recovery. Research has shown that individuals with a greater $\dot{V}O_2$max recover more quickly between repeated sprints, and consequently have a superior performance in the later bouts of a series of sprints.[7] Individuals with high $\dot{V}O_2$max levels also more rapidly resynthesize CrP stores. Recent research has shown that high-intensity interval training (six to 12 interval bouts of two minutes each at a workload of 100% $\dot{V}O_2$max with one minute of rest) augmented $\dot{V}O_2$max levels and the capacity for CrP resynthesis.[5]

Increased Buffering Capacity

As highlighted earlier, an accumulation of proton molecules within the cell can impair skeletal muscle function. The cellular environment possesses a buffering-capacity system to help combat increased acidosis (i.e., proton accumulation); however, in untrained individuals this system is easily overwhelmed during high-intensity exercise conditions. Correct exercise training confers an increased muscle-buffering capacity, which will ultimately contribute to a more rapid recovery. Interestingly, researchers have reported that it is high cellular concentrations of protons that provide the necessary stimuli for improvements in the muscle-buffering capacity.[5] It appears that high-intensity interval training (six to 12 interval bouts of two minutes each at a workload of 90 to 100% $\dot{V}O_2$max with one minute of rest) is a successful strategy for eliciting favorable buffering-capacity adaptations.

Increased Monocarboxylate Transporters

Given the fact that increased concentrations of lactate and proton molecules within the muscle cell are detrimental to skeletal muscle performance, it should not be altogether surprising that the cell has a means for removing these fatigue-inducing products of metabolism from the cell. Monocarboxylate (MCT) transporters are proteins found on the cell membranes that facilitate the efflux of lactate and proton molecules from the intracellular environment into the blood. MCT is in fact a co-transporter in that it collectively transports a molecule each of lactate and proton out of the cell. Exercise training leads to an increased MCT concentration and therefore a concomitant greater capacity for removal of excessive lactate and protons from the cell.[8] This adaptation clearly provides a means for quicker recovery from exercise conditions that increase muscle lactate and proton concentrations. A suitable training program for improving MCT concentrations appears to be shorter interval bouts with longer 1:3–4 work-to-rest ratios [four to eight interval bouts of 30 seconds each at a workload of ~130% $\dot{V}O_2$max (equates to 150 to 200 m near all-out sprint) with 180 to 240 seconds of recovery).[4]

EXERCISE-RELATED STRATEGIES TO ENHANCE RECOVERY

What is the exercise program F.I.T.T. for accelerating recovery?

Training recovery can be optimized by correctly managing the various components surrounding the exercise program.[9] To accomplish this endeavor, health and fitness professionals are encouraged to plan an appropriate FITT for training recovery itself (Figure 2). In the following sections, different features of the training recovery aspect of the exercise program are described in more detail.

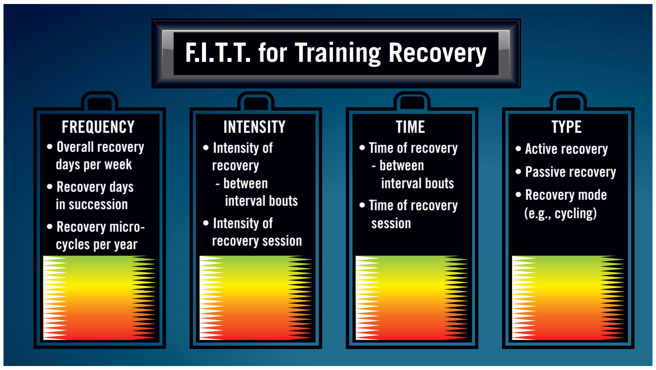

Figure 2
FIIT for Training Recovery

Frequency of Recovery

This component refers to the number of days per week devoted to recovery. If a client is simply recovering from a somewhat hard training session, the frequency of recovery may be a single day. Conversely, a client recovering from a 10 kilometer run may require several days of recovery. It should also be noted that the frequency of recovery could also extend beyond a single week. In fact, it is not uncommon for professional athletes to spend several weeks after the competition portion of their season in recovery microcycles.

Intensity of Recovery

For a client performing an interval session that consists of four repetitions of four minutes at 90 to 95% maximal heart rate interspersed with two minutes of active recovery bouts, health and fitness professionals need to program a specific intensity (e.g., 40 to 60% maximal heart rate) to be performed for the active recovery bouts. The intensity of recovery may also extend to the overall intensity of a daily session of exercise dedicated to recovery (e.g., a moderate-intensity, 60-minute bicycle ride at 65 to 75% of maximal heart rate).

Time of Recovery

This component can refer to either the recovery time between interval bouts or the duration of an entire recovery session. In the above interval-training example, the time of recovery between interval bouts was two minutes. In the second example in the "Intensity of Recovery" section, the time of an entire recovery session was 60 minutes. In terms of programming the time of recovery for a whole training session, it might not appear to be much different than setting the time of an ordinary exercise session. The critical distinction is that health and fitness professionals need to allot an appropriate time for the recovery session to accomplish the goal of recovery itself.

Type of Recovery between Each Bout

This component refers to the type of recovery, and may refer to either active or passive recovery. Active recovery comprises continued exercise at a substantially lower intensity or workload, while passive recovery consists of resting completely. The type of recovery to be performed is a consideration for both the time between interval bouts or daily recovery sessions. In terms of an active recovery, the mode of exercise to be performed is an additional variable to be contemplated. It is common for clients who normally run to cross-train; for example, an active recovery day may consist of swimming or exercising on an elliptical cross trainer.

NUTRITIONAL-RELATED STRATEGIES TO ENHANCE RECOVERY

What role does nutrition play in post-exercise recovery? Research-based strategies.

Purposeful tactics are required to ensure adequate recovery from training. In this section, four evidence-based nutritional strategies are presented. These strategies are specific to recovery and should be integrated within, not substituted for, an overall healthy eating plan.

Ingest Carbohydrate after Exercise – When, Why and How Much?

When?

A classic nutritional recommendation for recreational enthusiasts and athletes alike is that after prolonged and exhaustive endurance-related exercise the most important factor determining the timeframe to recovery is muscle glycogen replenishment.[2] Indeed, it is well established that post-exercise carbohydrate (CHO) ingestion is critical to synthesis of muscle glycogen. More recently, both the precise timing of CHO ingestion and optimal CHO dosage have become better understood.[10]

Why?

Post-exercise muscle glycogen replenishment occurs in two phases—a rapid rate that persists for 30 to 60 minutes after exercise cessation and a considerably reduced rate (60 to 90%) in the time period afterwards.

Muscle glycogen replenishment requires the entry of blood glucose into the muscle cell. This process is facilitated when GLUT-4 transporter proteins migrate from the cell cytoplasm and bind to the cell membrane. Both skeletal muscle contraction and insulin serve as signals for GLUT-4 transporter proteins to bind to the cell membrane and facilitate glucose uptake. The initial rapid rate of glucose flux into the muscle cell for glycogen resynthesis is mediated by skeletal muscle contraction–stimulated GLUT-4 transporter protein activity. This rapid phase window closes after approximately one hour. As such, CHO intake within this narrow timeframe is paramount to rapid glycogen repletion. Conversely, the second phase of glycogen synthesis is facilitated by insulin-stimulated GLUT-4 transporter protein activity. Glycogen resynthesis during this phase occurs more slowly.

How much?

There is evidence for a dose-response relationship between post-exercise dosage of CHO ingestion and the rate of muscle glycogen resynthesis. For example, it has been shown that administration of 1.2 grams per kilogram per hour (g/kg/hr) of CHO increased muscle glycogen content 150% more than 0.8 g/kg/hr of CHO. However, ingestion of 1.6 g/kg/hr of CHO provided no further increase in muscle glycogen content. Of further interest is that more frequent provision of this overall CHO dosage interspersed in smaller doses over a few hours is more effective at replenishing muscle glycogen compared to one or two large doses ingested less regularly. In summary, to optimize muscle glycogen repletion post-exercise, 1.2 g/kg/hr of CHO can be consumed at 15- to 30-minute intervals immediately upon exercise termination.[10]

Combine Protein with Carbohydrate after Exercise—When, Why and how much?

When?

Ingestion of CHO in conjunction with protein after exercise can accelerate the recovery process in two distinct areas. First, as previously highlighted, sufficient CHO intake facilitates muscle glycogen replenishment. Combining protein with CHO can attenuate this important physiological process, most notably when individuals have a difficult time ingesting the recommended 1.2 g/kg/hr of CHO. Second, and in addition to muscle glycogen synthesis, post-exercise recovery requires repair to muscle damage sustained during exercise training and skeletal muscle reconditioning. Favorable muscle adaptations (e.g., muscle hypertrophy) and repair to exercise-induced muscle damage are dependent on positive muscle protein balance. This scenario is only achieved with sufficient protein intake.

Why?

A number of studies have demonstrated that the combination of protein plus CHO is superior to CHO alone at stimulating post-exercise muscle glycogen synthesis.[10,11] The mechanism by which protein plus CHO ingestion accentuates muscle glycogen synthesis is via increased pancreatic insulin production. This is important because during the second phase of glycogen synthesis, glucose uptake is facilitated by insulin-stimulated GLUT-4 transporter protein activity. In summary, coingestion of a protein (0.4 g/kg/hr) plus CHO (~1.0 g/kg/hr) mix in frequent intervals of 15 to 30 minutes can promote optimal muscle glycogen repletion.

How much?

Positive muscle protein balance will also be achieved with ingestion of protein in conjunction with CHO. However, there remains considerable debate in the scientific literature on the precise type of protein required to maximize post-exercise muscle protein synthesis. Nevertheless, the above-recommended protein amount (0.4 g/kg/hr) has been shown to be effective when it consists of milk proteins and their isolated forms of whey and casein.[10]

Combine Caffeine with Carbohydrate after Exercise

An additional strategy that can promote increased post-exercise muscle glycogen synthesis is combing caffeine with CHO intake. Two studies have shown this approach to be successful. In the first study, researchers reported that coingestion of 2 mg/kg/hr of caffeine with 1.0 g/kg/hr of CHO resulted in a 66% greater increase in muscle glycogen synthesis rates over four hours of post-exercise recovery.[12] More recently, a separate study showed combined CHO plus caffeine intake resulted in improved high-intensity interval-running capacity.[13] Participants initially completed a maximal exercise test to exhaustion. Throughout a four-hour recovery period, participants ingested 8 mg/kg/hr of caffeine combined with 1.2 g/kg/hr of CHO. Subsequent high-intensity interval-running performance was enhanced with this nutritional intake strategy compared to a condition where a similar CHO intake was combined with water. The mechanisms by which CHO + caffeine ingestion accelerate muscle glycogen synthesis have yet to be fully elucidated. In summary, a combination of CHO (~1.2 g/kg/hr) and caffeine (2 mg/kg/hr for two hours) will facilitate muscle glycogen replenishment, and likely yield improvements in subsequent high-intensity exercise performance.

Ingest Sodium Bicarbonate before Intense Exercise to Improve Repeated Sprint Performance

As previously highlighted, the recovery from cellular acidosis is paramount in order to restore the capacity to regenerate ATP from both the phosphagen system and glycolysis. It was noted that correct exercise training confers an increased muscle-buffering capacity, which will ultimately contribute to a more rapid recovery from metabolic acidosis. Muscle-buffering capacity can also be augmented by nutritional strategies. Alkalizing agents have been studied extensively for their potential to enhance performance by attenuating the extent to which metabolic acidosis contributes to fatigue during high-intensity exercise performance.[14] One such alkalizing substance that has been found to improve recovery by increasing the muscle-buffering capacity is sodium bicarbonate. The mechanism by which sodium bicarbonate ingestion mediates an ergogenic effect is by promoting removal of protons from the skeletal muscle. Given the fact that increased concentrations of proton molecules within the muscle cell are detrimental to skeletal-muscle performance, it should be recognized that an increased rate of removal from the skeletal-muscle environment will result in a more rapid recovery. This in turn will permit a better performance of subsequent high-intensity exercise bouts. The main drawback to the use of sodium bicarbonate is that some individuals experience gastrointestinal distress with its ingestion. Accordingly, the recommended dosage and timeframe for sodium bicarbonate ingestion is 0.2 to 0.4 g/kg with 1 liter of fluids at 60 to 120 minutes pre-exercise.[14] Sodium bicarbonate can be ingested in either capsule form or in a flavored beverage such as water.

ALTERNATIVE METHODS FOR AUGMENTING POST-EXERCISE RECOVERY

What alternative methods are available for enhancing post-exercise recovery?

In recent years there has been considerable research focused on numerous alternative recovery strategies, including cold water immersion, ischemic preconditioning, massage, stretching and compression garments. In the following sections, the effectiveness of these various recovery techniques is discussed.

Cold Water Immersion

The use of cold water immersion (CWI) has been adopted as a viable method to recover from an exercise training session or competitive performance because it is believed to aid in lessening muscle fatigue and soreness[15] and, ultimately, reduce the overall time needed for recovery. The exact mechanisms involved in aiding in recovery are not well understood, since the use of CWI in investigations is a relatively newer topic of concern. However, in a recent review to outline the possible physiological mechanisms associated with CWI, it was found that the major factors are the effects from the *cold* water and the added hydrostatic pressure.[16] The coolness of the water helps to decrease the core and skin temperature, which increases the heat-storage capacity, causes peripheral vasoconstriction and increases central blood volume. The increased vasoconstriction may also aid in mitigating the inflammatory response in the tissue affected by the training bout or performance. The added hydrostatic pressure to the body is thought to aid in increasing the osmotic gradient and allows for a better "flushing" of metabolic by-products.

Currently, there are no set guidelines for implementing CWI. For example, temperatures of CWI in the literature vary from 5 to 20° C (40 to 68° F) with immersion times reported as five to 20 minutes and shorter repeated times (one to five minutes) with one- to 2.5-minute breaks outside of the water.[15] However, implementing CWI appears to provide a small, but potentially important improvement in overall recovery time.[17] Three key studies investigating CWI effects on delayed-onset muscle soreness (DOMS), soccer tournament play and improvements in performance in a non-traditional sport (rock climbing) are presented here:

1. Vaile and colleagues[18] investigated the effects of CWI [15° C (59° F)], hot water immersion [38°C (100° F)], and contrast water therapy [15° C (59° F) for one minute and 38° C (100° F) for one minute] compared to passive recovery after a muscle-damaging protocol (seven sets of 10 eccentric repetitions on a leg press machine). All hydrotherapy sessions occurred for 14 minutes. It was found that both CWI and contrast water therapy were successful in mitigating the physiological and functional factors associated with DOMS, with improvements in recovery of isometric and dynamic power and lessened edema.

2. In order to understand the effects of CWI on the physical performance of soccer players during tournament play, Rowsell et al.[19] had high-performing male soccer players utilize CWI [10° C (50° F)] or immerse themselves in thermoneutral water for five sessions of one minute in the water and one minute out of the water. The hydrotherapy sessions took place 20 minutes after each

of the four matches on four consecutive days. Roughly 90 minutes before each match and 22 hours after the final match, measurements of physical performance testing, intracellular proteins and inflammatory markers were noted. Perceptual recovery measurements were also recorded 22 hours after each match. It was concluded that there was no evidence of enhanced physical performance between matches when using CWI compared to thermoneutral water, but CWI did help to reduce the perception of fatigue and leg soreness between subsequent matches. While this study did not find any physiological markers of improvement, there was considerable psychological improvement toward recovery when CWI was implemented.

3. A group of Belgian researchers[20] investigated the effects of passive recovery, active recovery, electromyostimulation and CWI of the arms (three sessions of five minutes in the water [15° C (59° F)] and two minutes out of the water) after a rock climbing test (completion of a 6b route, on the French grading system, at an indoor climbing gym) to volitional exhaustion. Once the recovery methods were implemented, the athletes completed the same rock climbing test to volitional fatigue. Indeed, it was found that CWI allowed for the climbing performance to be preserved, indicating CWI may be effective for recovery when repeating intense exercises. The authors suggested that CWI was successful in helping to maintain performance due to an analgesic effect and reduced inflammation in the forearms.

Ischemic Preconditioning

Ischemic preconditioning (IPC) consists of repeated cycles of vascular occlusion via a high pressure cuff on either the upper or lower limbs, followed by reperfusion in which pressure in the cuff is released. The IPC technique initiates a series of protective mechanisms that synergistically function to alleviate future cell injury. Administration of IPC is known to improve vasodilation, oxygen utilization and muscle function, and has been demonstrated to enhance exercise performance. Overall, the scientific evidence as it pertains specifically to IPC and improved post-exercise recovery are mixed. Here are three key studies:

1. A group of international researchers[21] showed that IPC (two x three minutes of each leg at 220 mmHg) relative to control (two x three minutes of each leg at 15 mmHg) improved recovery from lower-body strength and power tests and repeated sprint performance in a cohort of healthy men and women. The beneficial effects on recovery of power production and sprint performance were observed both immediately and 24 hours after the IPC treatment.

2. American researchers[22] showed that recovery was enhanced between multiple Wingate trials in a group of 43 recreationally active men and women after bilateral remote IPC (four x four minutes at 200 mmHg in each arm). Specifically, it was reported that total power output across four x 30-sec Wingate tests was 1.3 percent greater when remote IPC was administered relative to the control condition.

3. More recently, a group of Scottish researchers[23] investigated whether administration of IPC benefited repeated sprint performance in a cohort of 16 trained men and women. The participants underwent an IPC and placebo treatment involving three periods of five-minute occlusion applied unilaterally (three, five-minute occlusion treatments to each leg) at either 220 mmHg or 50 mmHg. Each period of occlusion was followed by five minutes of reperfusion. The main outcome measures included peak power, total power, percentage decrement, post-exercise blood lactate and ratings of perceived exertion. No significant differences were reported between IPC and placebo treatment conditions and the researchers concluded that there was no benefit in utilizing IPC as a modality for enhancing recovery and repeated sprint performance.

Stretching, Massage, and Compression Garments

In everyday practice, there is widespread anecdotal use of various stretching, massage and compression garment modalities as a means to accelerate the recovery process.[24] Nevertheless, the majority of research findings are unsupportive of these specific methods as effective strategies for enhancing post-exercise recovery. Indeed, results from numerous review articles show no beneficial effect toward post-exercise recovery from either stretching,[25] massage[26] or compression garments.[24] There is some evidence that these techniques may provide a psychological benefit. Additionally, research also shows no negative effects in using these recovery modalities. Taken together, stretching, massage and compression garments may confer a psychological advantage; however, the direct physiological benefit to post-exercise recovery from these modalities is likely to be negligible.

CURRENT MISUNDERSTANDINGS IN POST-EXERCISE RECOVERY

Do acute vs. chronic recovery strategies elicit different physiological responses?

A comprehensive and successful approach to post-exercise recovery entails both a short-term (i.e., acute) and long-term perspective (i.e., chronic). Moreover, it is critical for health and fitness professionals to appreciate that an effective acute post-exercise recovery modality may be, paradoxically, an ineffective chronic post-exercise strategy. Indeed, as highlighted earlier in this report, acute CWI post-exercise lessens DOMS and reduces perceptual fatigue. In contrast, chronic CWI has been demonstrated to be an antagonist to favorable training adaptions. Likewise, acute and chronic elevations in oxidative stress elicit significantly different responses. It is well established that chronically elevated oxidative stress contributes to the pathophysiology of numerous diseases, including cancer, cardiovascular disease and diabetes.[27] As such, it is not altogether surprising that free radicals have gained such a widespread negative reputation. Nevertheless, it would be exceptionally misleading to characterize any increase whatsoever in free radical concentration as an adverse threat to other cells within the biological system. In this section, the acute vs. chronic issue is discussed in more detail, specifically as it pertains to the post-exercise recovery strategies of CWI and nutritional supplementation with antioxidants.

Acute vs. Chronic: Cold Water Immersion

Even though there have been a plethora of studies indicating the effectiveness of CWI, there are just as many indicating CWI may have no effect or a negative effect on performance. In particular, emerging evidence is finding that chronic CWI may be counterproductive to long-term performance adaptations. For instance, Fröhlich and colleagues[28] examined the long-term effects of CWI after resistance training. In this study, the researchers investigated five weeks of the leg curl exercise with one leg undergoing CWI after training bouts. At the end of the study, it was found that the cooled leg exhibited a 1 to 2 percent reduction in training effects compared to the non-cooled leg. While these effects may be small, this could play a critical role in decreasing adaptations in a high-performance setting. Similarly, Roberts et al.[29] found that after a 12-week strength training program, participants that utilized CWI had less strength and muscle mass gains than those who participated in active recovery. A subset of this study also found that CWI reduced the acute anabolic signaling pathways that regulate muscle hypertrophy. Therefore, if CWI immersion is used chronically, there may be smaller muscle strength and hypertrophy adaptations after strength training. Based on the current literature, it appears the acute bouts of CWI to facilitate a quicker recovery may be feasible, but chronic use of CWI should be reconsidered to avoid lessening of training adaptations.

Acute vs. Chronic: Free Radicals and Antioxidants

Interestingly, as early as 1971, it was shown that antioxidant supplementation (400 IU/day of vitamin E supplementation for six weeks) caused unfavorable effects on endurance performance in swimmers.[30] Overall, the authors concluded: "There is no evidence here to suggest that vitamin E has any beneficial effect on endurance performance. Indeed, the evidence, if anything, suggests that the vitamin has an unfavorable effect." More recently, throughout the past five to 10 years, there have been numerous studies that have shown that the exercise-induced increase in free radicals serves as an important signaling molecule ultimately leading to favorable training adaptations.[31,32] Could an increase in free radicals actually be a necessary evil required for favorable training adaptations? A growing body of evidence suggests that this may indeed be the case. Here are three keys studies:

1. Spanish researchers[33] showed that improvements in $\dot{V}O_2$max were 11% lower following eight weeks of endurance training in a group that supplemented with antioxidants (vitamin C) when compared to a group that was not supplemented. The authors identified that the underlying reason why vitamin C supplementation decreased endurance training efficiency was that it prevented crucial cellular adaptations to exercise.

2. German researchers[31] evaluated the effects of a combination of antioxidants (vitamin C and vitamin E) on insulin sensitivity in both previously untrained and pretrained healthy young men both before and after a four-week exercise intervention. It was found that exercise-induced reactive oxygen species (ROS) production improved insulin resistance and caused a beneficial adaptive response promoting natural antioxidant defense capacity. They also noted that by blocking exercise-dependent formation of ROS due to ingestion of antioxidant supplements that the health-promoting effects of exercise were abolished. Exercise increased parameters of insulin sensitivity only in the absence of antioxidants in both previously untrained and pretrained participants. The authors concluded that exercise-induced oxidative stress helps to improve insulin resistance; however, antioxidants supplementation negates these health-promoting effects of exercise in humans.

3. American researchers[34] investigated the effects of both antioxidant supplementation and chronic exercise training on blood pressure in a cohort of older, hypertensive men. Blood pressure was measured at rest and during exercise with and without antioxidant supplementation (vitamins C and E, and α–lipoic acid). It was found that following six weeks of exercise training that systolic and diastolic blood pressure were each reduced by 12 mmHg. However, it was also reported that antioxidant supplementation administered following exercise training completely blunted these favorable training adaptations. It was concluded that an exogenous supply of antioxidants was counterproductive and interfered with the important signaling role that ROS played in arterial vasodilation.

In summary, it appears that an acute, transient exercise-induced increase in free radicals is a positive and much needed metabolic event required to induce favorable physiological adaptations.[31,32] Accordingly, it is long overdue that the one-sided thinking that free radicals only cause harm to the body should be dismissed. Furthermore, the nutritional post-exercise recovery strategy of antioxidant consumption to counter the acute exercise-induced increase in free radicals is unsupported by the literature, and therefore unadvisable.

PRACTICAL APPLICATIONS FOR THE HEALTH AND FITNESS PROFESSIONAL

How can health and fitness professionals translate exercise, nutrition and training recovery research into practice to help clients achieve optimal training and performance outcomes?

Underpinning all physiological phenomena, including the relationship between exercise, nutrition and post-exercise training recovery, are causal mechanisms. The purpose of science as it relates to human physiology is to better understand these mechanisms. With each study, new knowledge is acquired that should ultimately improve practice. However, for health and fitness professionals the process of translating research findings into real-world practical applications that can be applied to daily practice with clientele can often be a frustrating process. This section provides health and fitness professionals with four practical applications supported by the scientific literature aimed at augmenting post-exercise recovery.

Program Active Recovery

Whether it is between interval bouts, immediately after an interval session or the day following strenuous exercise, there is compelling evidence that an active recovery is superior to passive recovery.[35] Logically, from a physiological perspective, this practice should make sense. Continued blood flow to the skeletal muscle bed promotes the resynthesis of CrP and glycogen stores; it also facilitates the removal of protons. Collectively, these factors aid in recovery.

Program Specific Recovery Intensities

Regrettably, it is common for many clients and athletes to exercise too hard during periods of recovery, be it between interval bouts, following an interval workout or the day after competition. Health and fitness professionals can assist clients to avoid or minimize this error by establishing specific target intensities for recovery scenarios. Research has reported that active recovery bouts of very light intensity (<50 percent of maximal heart rate) are optimal for decreasing lactate and proton levels.[35] In terms of coupling the very light recovery intensity with a proper cool-down, research has identified ~10 minutes as an ideal duration. In terms of an exercise intensity for recovery sessions, research has generally reported moderate-intensity (65 to 75 percent of maximal heart rate) exercise to be sufficient.[1]

Program High-intensity Interval Training

Research shows high-intensity interval training elicits several physiological adaptations that aid in recovery, including improved $\dot{V}O_2max$, increased buffering capacity and a greater concentration of MCT.[4,5,8] However, to elicit these improvements, there are several important considerations for the exercise program. The intensity of intervals should be high (~90 to 95 percent of maximal heart rate), but not maximal. The duration of interval bouts should equate to two minutes with a shorter recovery period (e.g., one minute). The number of interval bouts can range from three to 12 per session; and the number of high-intensity interval training sessions per week can range from one to three with at least 48 hours between sessions.

Translating Research into Practice for Clients

An important first step to better understanding nutrition and training recovery research is to appreciate the terms with which scientists perform their research, and then to subsequently put those into a context that will work for you and your clients. Science uses the metric system. Thus, nutritional intake will be in units of either milligrams (mg) or grams (g). Commonly, the nutritional intake that is provided to a participant in a study will be referred to as the dose administered. For instance, a participant may be provided a dose of 1 g of carbohydrate (CHO). Usually the dose provided is relative to the body weight of a participant [kilograms (kg)]. To covert from pounds (lb) to kg, simply divide body weight by 2.2046 (e.g., 155 lb ÷ 2.2.046

= ~70 kg). If a participant is to be provided with a dose of CHO equivalent to 1 g/kg, it simply means his or her body weight is multiplied by 1 g CHO. For instance, a 70 kg individual would ingest 70 g CHO (i.e., 1 g/kg CHO x 70 kg). Lastly, nutritional interventions for training recovery are typically time-sensitive, meaning that the dose of nutritional intake is provided over a very specific timeframe. This is usually after exercise training stops; however, for some nutritional strategies to be successful the dose of nutrition is provided before exercise. A simple example would be for 1 g/kg CHO to be provided for one hour (hr) post-exercise. This would be reflected as 1 g/kg/hr CHO.

As highlighted earlier in this report, a principal aim of nutrition and training recovery research is to identify the optimal dose (e.g., g/kg/hr CHO) that will provide the best result. For instance, to optimize muscle glycogen repletion post-exercise, 1.2 g/kg/hr CHO should be consumed at 15- to 30-minute intervals immediately upon exercise termination.[10] Apart from understanding the nuances of the metric system, another key challenge for health and fitness professionals is to translate a specific dose of nutrition, identified in the scientific literature as beneficial, to a real-world item that clients can actually eat or drink. Put simply, the clients of health and fitness professionals will eat bananas and bagels, not g/kg/hr. An example of how nutrition and training recovery research can be translated into a specific post-exercise meal is presented in Table 1.

CONCLUSION

Health and fitness professionals should recognize that current and future clients will spend more time throughout the week in training recovery compared to actual exercise training. This fact necessitates a purposeful approach to the overall training recovery paradigm. Despite the research-based recommendations put forth in this report, the reality is that recovery remains an under-researched topic and therefore is still not well understood compared to other areas of training.[8] Moreover, there is evidence to show considerable variability among individuals in the time course of training recovery.[6] Collectively, these factors point to the critical role that health and fitness professionals play in working with clients to identify the most appropriate training recovery program. This process will require purposeful trial-and-error. What does this mean? Health and fitness professionals are encouraged to recommend research-substantiated recovery strategies. This is the purposeful component. Numerous evidence-based recovery strategies have been presented in this report. It is up to the health and fitness professional to systematically implement and evaluate these various strategies to ultimately pinpoint the recovery strategies that best suits each client. This is the trial-and-error component. In conclusion, an evidence-based and purposeful trial-and-error approach is required for health and fitness professionals to master post-exercise recovery.

Table 1

Translating Nutrition and Training Recovery Research into a Post-exercise Meal

Angela (65 kg) is primarily an endurance enthusiast and regularly completes moderate-to-vigorous workouts in excess of an hour. In order to replenish muscle glycogen stores, her target CHO intake for the first two hours post-exercise is calculated to be approximately 160 g (65 kg x 1.2 g/kg/hr CHO x two hours). Below is a sample menu of beverages/foods that can be consumed every 30 minutes to achieve her CHO goal.

Immediately post-exercise	8 oz sports drink (e.g., Gatorade) + 1 medium banana	42 g CHO
30-minutes post-exercise	8 oz sports drink + 1 medium bagel	53 g CHO
1-hr post-exercise	1 cup yogurt	42 g CHO
90-minutes post-exercise	1 cup chocolate milk (low fat)	26 g CHO
	Total	**160 g CHO**

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