2.1 Recovery and Adaptation

2.1.1 What is Recovery?

Recovery is a word that is very often used in sports. Everyone is convinced that "recovery" is important and most teams have "recovery strategies" in place. However, it is likely that if you ask 10 people for a definition of recovery you will get 10 different answers. Therefore, it is important to define recovery to avoid any misunderstandings. Also, everyone seems to have an opinion about the foods that are good for recovery. Protein is the first nutrient many people will think about… but is this indeed the most essential part of recovery?

Recovery is a broad term that refers to the restoration of performance capacity. After a hard training session, a player is fatigued and performance capacity is reduced. In the hours and days after the workout the player will "recover" and performance capacity will return to normal (and can even become better). The time course depends on many factors including how hard the workout was (intensity and duration as well as some environmental factors such as altitude and heat), but it also depends on recovery methods used including the nutrients ingested.

So, a quick definition of recovery is: complete restoration of performance capacity to pre-exercise performance capacity. However, it is important to distinguish between acute or rapid recovery and long term recovery or adaptation. "Long term adaptation refers to the improvements in the muscle and cardiovascular system that will ultimately result in improvements in performance." (Jeukendrup, 2015, https://bit.ly/2TjKY9m). The term recovery is often used for both these short-term and long term processes. In conversations, short term and long term recoveries are often mixed and "referred to as *recovery*. The two are of course linked, but they are not the same!" (Jeukendrup, 2015, https://bit.ly/2TjKY9m).

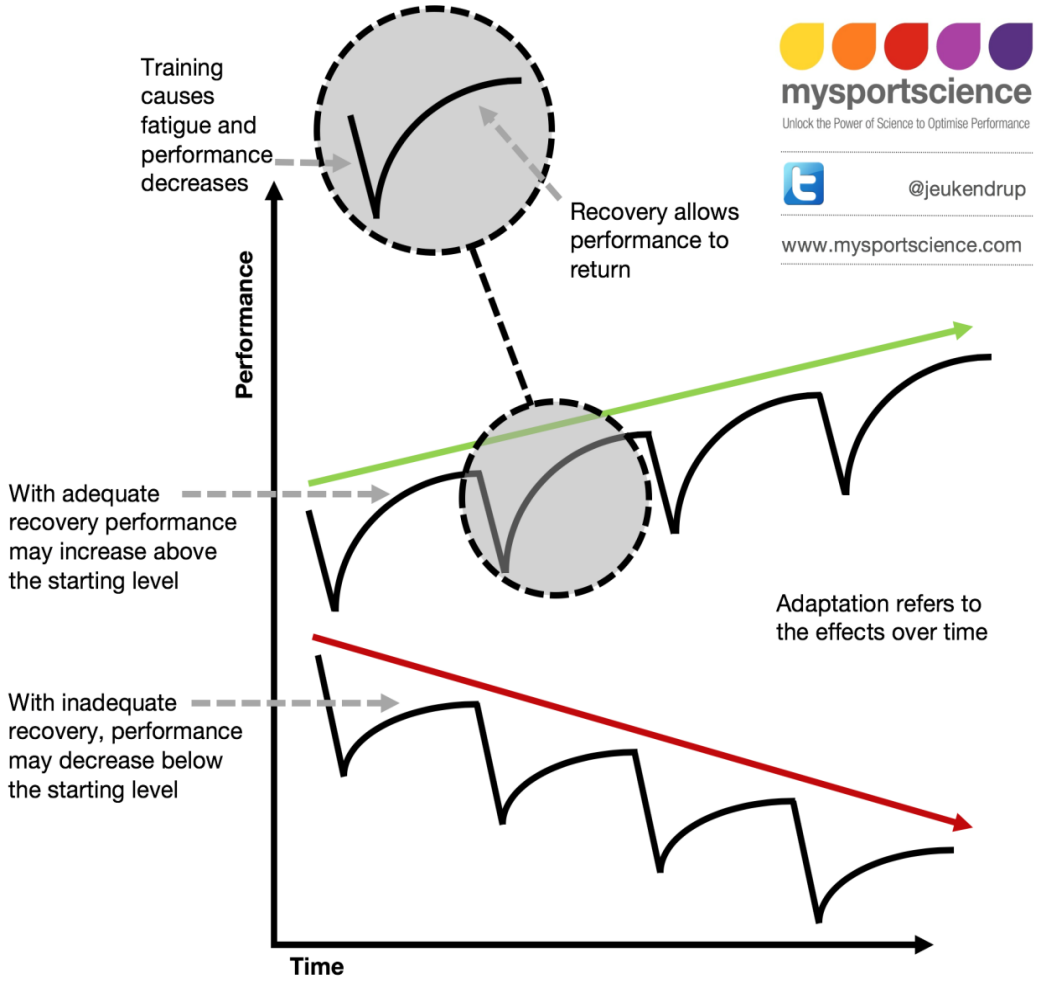
Recovery: complete restoration of performance capacity to pre-exercise performance capacity.

Adaptation: the improvements in the muscle, cardiovascular system, and other systems that over time will result in improvements of performance.

In Figure 1, acute recovery and longer term training adaptation can be seen. Recovery refers to the acute effects after an exercise bout, and adaptation refers to the longer term effects of repeated bouts of exercise and recovery. With nutrition interventions we can specifically target short term recovery

or we can enhance the long term effects which will result in improved adaptations. These nutrition interventions will be discussed in sections to follow.

Figure 1: Visualisation of Recovery and Adaptation



Source: Asker. J., 2018. Taken from: http://www.mysportscience.com/

Recovery refers to the acute process after a single bout of exercise training. Adaptation is the change that occurs over time. When recovery time is insufficient, adaptation may be negatively affected. However, sometimes optimising recovery can also impair long term adaptation.

Especially over the last few years, it has become clear that what may be good for acute recovery may not necessarily be good for long term adaptation. Here are a few examples:

- Studies have suggested that antioxidants may reduce muscle soreness and help with short term recovery, but high doses have also been linked to reduced long term training

benefits. (High doses of antioxidants may interfere with the signalling that is needed to stimulate training adaptation.)

- Reducing inflammation with non steroidal anti-inflammatory drugs (NSAIDs) such as ibuprofen may help short term recovery as well as soreness reduction. However, it may impair long term adaptation.

- Ice baths may at least help perception of short term recovery, but they may reduce long term training adaptation.

There are many more examples and in general, removing the signals of stress (which may help short term recovery), will also reduce the signals needed to adapt. So, when developing a recovery strategy, it is always important to keep the main goal in mind: Is it being able to perform again several hours later, or are the main goals further away? In competitions with several rounds and only a few hours or days between rounds, you would want to optimise all short term recovery strategies. When preparing for competition at the beginning of a season, acute recovery is not always the highest priority and it may be better to choose a strategy that enhances the adaptation to training. (Jeukendrup, 2015, https://bit.ly/2TjKY9m).

What seems a simple term (recovery) is actually a little more complex. We don't just list a number of recovery foods and methods that are used in all conditions. Instead, it is important to state the goals and develop strategies accordingly. (Jeukendrup, 2015, https://bit.ly/2TjKY9m).

This is part of the periodised nutrition approach discussed in the module **Periodised Nutrition**.

2.1.2 Training Adaptation

Exercise, regardless of the type, results in adaptation that, if repeated frequently enough, results in improved physiological function and performance. Exercise training makes use of this principle by planning and systematically applying exercise activities with the goal of optimising that adaptation. The ultimate aim is, of course, to improve performance. Adaptation occurs at all levels and in different organs of the body. This adaptation includes but is not limited to: increased capillarisation, fast-to-slow muscle fibre type conversion, increased heart size, increased mitochondrial mass, and/or increased muscle mass. Many years ago, the outcome of training programmes could only be measured by measuring performance (for which only a stopwatch was needed). As technology improved, surrogate physiological measurements were used, such as heart rate, VO_2max, and so on. To better understand these physiological changes, cellular events were then studied and eventually techniques allowed the study of the molecular mechanisms underlying training adaptations. The process of adaptation starts at a molecular level. This triggers events at cellular level, which may cause physiological changes and eventually performance changes (Jeukendrup & Gleeson, 2018) (see Figure 1). The following discussion is partly based on our recent textbook on sport nutrition (Jeukendrup & Gleeson, 2018), but those who want more detail can refer to a number of excellent recent reviews: Coffey and Hawley (2007); Hawley, Lundby, Cotter, and Burke (2018); Holloszy and Booth (1976); Holloszy and Coyle (1984); Hughes, Ellefsen, and Baar (2018); Perry & Hawley (2018). The effects of nutrition on adaptation is also discussed in other reviews, such as, Craig et al. (2015) and Hawley (2013).

Adaptations to exercise or exercise training are specific to the exercise performed. High-intensity (predominantly anaerobic) exercise will result in adaptations different from those resulting from moderate-intensity, longer-duration (aerobic) exercise. Resistance exercise typically results in a different phenotype than endurance training. With resistance exercise, hypertrophy is one of the main adaptations, whereas endurance training will not increase muscle mass and may even decrease it. Endurance training, on the other hand, will result in greater oxidative capacity, increasing the fatigue resistance of the muscle. Table 1 lists a number of adaptations to exercise (either resistance exercise or endurance exercise). (Jeukendrup & Gleeson, 2018).

Table 1: typical adaptation after endurance and after strength training.

	Endurance training	Strength training
Capillary density	++	
Muscle glycogen	++	++
Number of mitochondria	++	+
Mitochondrial density	++	+
Resting ATP	_	+
Resting PCR	_	+
Glycolytic enzymes	_	+
Phosphofructokinase	_	+
Oxidative enzymes	++	-/+
Succinate dehydrogenase	++	+
Citrate synthase	++	+
HAD	++	+
Maximum cardiac output	++	+
Maximum oxygen uptake (VO_2max)	++	+
Maximum heart rate	_	_
Plasma volume	++	
Muscle fibre size	_	++
Fat oxidation	++	+

Source: (Jeukendrup & Gleeson, 2018).

The ++ means that most studies have shown this effect, + means that some studies have shown this effect, -/+ means the results are mixed. No sign means effect is non-existent or unknown.

Strength Training

Strength training or resistance training results in a range of adaptations in muscle including hypertrophy (an increase in the muscle cross-sectional area) and altered neural recruitment patterns. (Jeukendrup & Gleeson, 2018).

"Muscle hypertrophy, can occur through two processes : an increase in the number of nuclei within each muscle fibre or an increase in the amount of contractile material supported by each nucleus." (Jeukendrup & Gleeson, 2018). Resistance exercise is a potent stimulator of muscle protein synthesis. In fact, the acute increase in muscle protein synthesis after exercise is far greater and, especially, of far longer duration, than the changes observed after feeding.

Endurance Training

> Endurance exercise training is characterized by the development of improved fatigue resistance partly because of increased mitochondrial density and thus mitochondrial protein. In addition, alterations occur in neural recruitment patterns, substrate utilization, and acid–base balance. Intramuscular glycogen stores as well as triacylglycerol stores increase after endurance training, although the amounts of both these fuel stores depend on the time since the last exercise session and the adequacy of nutrition in the postexercise period. Reliance on carbohydrate (glycogen) as a fuel decreases, and the ability to oxidize fat increases. These changes result in sparing of muscle glycogen during exercise. Endurance training does not greatly alter muscle fiber size, although an increase in the cross-sectional area of type I fibers of around 20% has been observed in some studies. Endurance training can increase the mitochondrial protein content of the muscle by 50 to 100% in 6 weeks (Hoppeler & Fluck, 2003; Hoppeler et al., 1985) (this increase in size and number of mitochondria is usually referred to as mitochondrial biogenesis). Mitochondrial density and mitochondrial enzyme activity are very good predictors of endurance performance. Training adaptations are only temporary. For example, if an endurance training stimulus is not maintained, mitochondrial proteins will be broken down again. Their half-life is only about 1 week. (Jeukendrup & Gleeson, 2018).

Adaptations will only occur if the rate of protein synthesis exceeds the rate of protein breakdown for a period of time. The type of proteins synthesized depends on the type and the intensity of the training performed. “Generally, resistance training increased muscle mass, but does not increase the oxidative capacity of the muscle much, although some studies have observed improvements in oxidative enzyme activity” (Jeukendrup & Gleeson, 2018). (citrate synthase; see Table 1).

It has been shown repeatedly that exercise increases net protein synthesis after both resistance and endurance exercise. A requirement is that dietary protein and energy intakes are adequate. Training without protein intake or training in negative energy balance has little or no effect on protein synthesis rates (Jeukendrup & Gleeson, 2018).

> When studying and interpreting the scientific literature on this topic, it is important to realize that most studies have

looked at mixed muscle protein synthesis without specifically looking at which proteins are synthesized. It is likely that with resistance exercise there is synthesis of predominantly actin and myosin, whereas endurance exercise results mostly in mitochondrial biogenesis with little or no change in the synthesis of myofibrillar proteins. (Wilkinson et al. 2008, https://bit.ly/2PMR7fS)

The increase in protein synthesis after resistance or endurance exercise may last for up to 2 to 4 days after the last training session (Jeukendrup & Gleeson, 2018).

The Triggers

The complex process of exercise-induced adaptation in skeletal muscle starts with a blend of stresses that trigger specific molecular events. These stresses are different for endurance and for strength training: with strength training stress are mostly mechanical, while during endurance exercise stresses is mainly metabolic. In all situations, cellular homeostasis is disturbed and this initiates a cascade of events that ultimately result in an adaptation. This adaptation will make sure that there is less disturbance of homeostasis the next time that the same exercise is performed.

There are generally 4 categories of stresses:

1. mechanical load
2. neuronal activation
3. hormonal adjustments and
4. metabolic disturbances.

A combination of these stresses triggers specific molecular events which in turn start an increase in protein synthesis. Certain signaling mechanisms are activated by exercise stress and these mechanisms initiate the replication of deoxyribonucleic acid (DNA) genetic sequences (genes) that enable subsequent translation of the genetic code into a series of amino acids to synthesize new proteins. The accumulation of these specific proteins ultimately results in training adaptations. There are different signaling mechanisms for different types of training. These signaling events and the resulting increases in messenger ribonucleic acid (mRNA), as well as the synthesis of specific proteins,

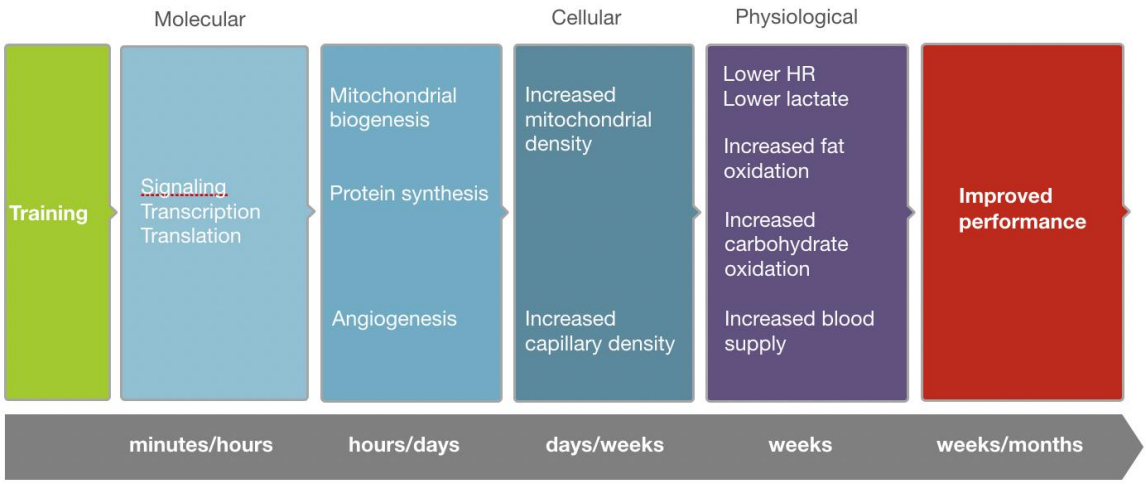
depend on the type, intensity and duration of exercise performed but also the intake of certain nutrients. Below we will first explore the molecular signaling events that underlie the training adaptations and the effects that different modes of exercise and nutrition can have on these events as well as on the outcome. (Jeukendrup & Gleeson, 2018).

In the above section we used the term net protein synthesis, meaning that protein synthesis exceeds protein breakdown. However, protein breakdown may be important, too: old and damaged proteins need to be removed so that new proteins can be build. It is therefore the protein turnover that is really important. Protein turnover refers to increasing the rate of both protein synthesis and breakdown within muscle. Increasing protein turnover is essential in order to repair muscle fibres damaged during exercise (training or competition).

“Proteins are broken down in order to replace damaged fibers and provide a stimulus for muscle repair. As a result, protein breakdown is proportional to protein synthesis” (Phillips, Tipton, Aarsland, Wolf, & Wolfe, 1997, https://bit.ly/2DF7eoC), “and trained athletes can recycle the amino acids that are released from the breakdown of damaged muscle” (Phillips et al., 1997, https://bit.ly/2DF7eoC), “resulting in larger and stronger muscles when turnover is high” (Baar & Heaton, 2015, https://bit.ly/2QuMLq1).

Training can have profound effects on protein turnover, muscle morphology and function. As discussed above different types of training have distinct effects. For example, strength training results in muscle hypertrophy, increased muscle mass, and likely maintained, or slightly increased, mitochondrial mass (Tang, Perco, Moore, Wilkinson, & Phillips, 2008). Exercise training, especially in team sports, is often a combination of strength and endurance, and the improvements in either strength or endurance depend on the relative intensity and the strength required to complete the training sessions. Whatever the adaptation, protein turnover and net protein synthesis are required and must occur in the recovery phase between training sessions (Jeukendrup & Gleeson, 2018).

Figure 2: A number of molecular and cellular events precede the physiological adaptations and changes that underpin performance.



Source: Jeukendrup & Gleeson, 2018.

Only a repeated training stimulus over prolonged periods will result in the required physiological changes.

2.1.3 The Start of Adaptation

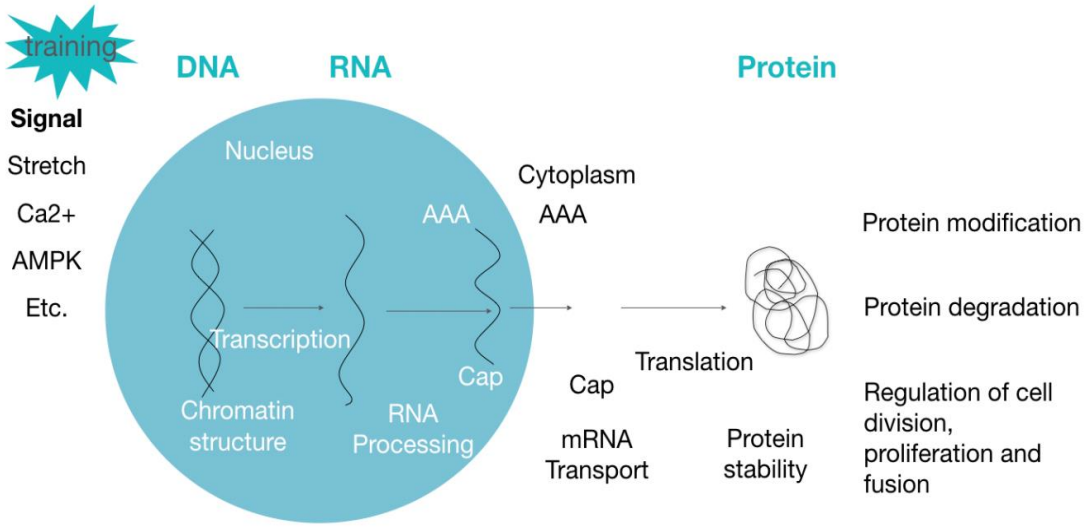
"Protein synthesis is regulated by signal transduction pathways. Local and systemic signals are sensed and computed and regulate various cellular functions" (Jeukendrup & Gleeson, 2018).

Let's use a factory as an analogy. The signals are the orders that come into a factory. There is a demand for certain products that need to be manufactured. Orders may come in by email, phone or fax (different signals). An employee will deal with these signals and pass them on to the person in charge of manufacturing. This message between the receiver of the orders and the person at manufacturing is an example of a "signalling mechanism". In the muscle, "the main signaling mechanisms are the phosphorylation of serine, threonine, and tyrosine residues by kinases and their dephosphorylation by phosphatases." (Jeukendrup & Gleeson, 2018, https://bit.ly/2Q1cbP1).

These phosphorylation processes are started by signals like nutrient availability, pH, partial pressure of oxygen, reactive oxygen species (ROS), and mechanical stimuli (the orders that came in). The endocrine and nervous systems provide further inputs. In the cells this ever-changing mix of signals is detected through specific sensor proteins. Examples of sensor proteins are cell membrane receptors and amino acid, calcium, or AMP-sensing proteins. Activation of a sensor protein will subsequently trigger a cascade of reactions. These cascades of reactions form the link between the signals and the change in cellular function. So, in the analogy with the factory: the orders come in different forms and are processed by workers who then pass the information on to the team that deals with manufacturing.

Protein kinases are typically part of a cascade of reactions that generally follows the sequence of events depicted in figure X. This model is oversimplified because many signals converge or branch off. These signal transduction pathways can then influence a number of cellular events and will ultimately result in altered function. The preceding general description of signaling pathways probably applies to most cells in most situations. The details of these signaling cascades, the triggers, the proteins, and the kinases involved are different in different tissues and different situations. To understand adaptations in muscle cells in response to exercise training, the signaling pathways in muscle have to be studied in more detail. (Jeukendrup & Gleeson, 2018).

Figure 3: Training adaptations as a result of an increased protein synthesis in response to repeated exercise sessions



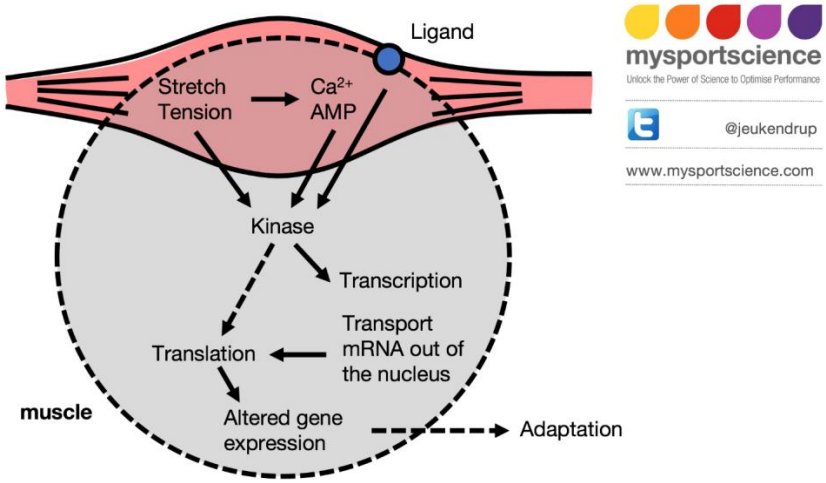
Source: Jeukendrup & Gleeson, 2018.

It is believed that an exercise session causes a signal to transcribe DNA in the nucleus into RNA, which is then transported out of the nucleus and translated into protein. The signal caused by the exercise stimulus determines which proteins are synthesized. The amount of protein formed is determined not only by the signal, the transcription, and translation but also by the RNA processing and the stability of proteins.

"Exercise results in muscle stretch or tension, changes in intracellular calcium ion (Ca^{2+}) concentrations, changes in the energy charge of the cell, and changes of the redox potential." (Jeukendrup & Gleeson, 2018) (Figure 3).

Certain hormones and other ligands that can bind to receptors on the cell surface can alter these signals. These primary messengers may then trigger a series of secondary molecular events that increase or decrease transcription or translation as described in Figure 3 and 4. The process of protein synthesis has started. The following section looks at the primary signals in detail.

Figure 4: Simplified model of signal transduction in relation to exercise



Source: Jeukendrup & Gleeson, 2018.

Muscle contraction may result in a disturbance of homeostasis. Mechanical stress (stretch, tension), Ca^{2+}, and the accumulation of AMP or metabolites are primary signals that affect the phosphorylation state of various kinases. These kinases can influence the transcription process, the transport of mRNA out of the cell, and translation. Hormones and other ligands can influence these signals. The changes in gene expression can result in different adaptations

Signal transduction pathways control the following processes:

1. Transcription of genes (specific sequences of DNA) into mRNA
2. Translation of mRNA into protein
3. Protein modification altering catalytic activity
4. Regulation of protein degradation
5. Regulation of cell division, proliferation, and fusion

(Jeukendrup & Gleeson, 2018).

2.1.4 Signals in More Detail

"The basis for any training adaptation is a disturbance of homeostasis. Metabolic or mechanical changes in the muscle start a signaling cascade that results in the relevant proteins being broken down and synthesized." (Jeukendrup & Gleeson, 2018).

Muscle Stretch and Tension

The mechanical effects of muscle contraction cause activation of a number of signalling pathways (Figure 4). "Specifically, muscle stretch or altered tension can induce activation of calcineurin, mitogen-activated protein kinase (MAPK), and insulin-like growth factor (IGF) signaling cascades." (Jeukendrup & Gleeson, 2018).

Ca^{2+}

Neural activation of skeletal muscle generates an action potential that results in Ca^{2+} release from the T-tubules of the sarcoplasmic reticulum. When the exercise is stopped the Ca^{2+} returns back from the cytoplasm to the sarcoplasmic reticulum. The fluctuations in Ca^{2+} concentration or the release and reuptake of Ca^{2+} in the sarcoplasmic reticulum are different for different types of activities, which could at least partly explain the differences in the adaptive response to exercise. Endurance exercise, for example, results in more prolonged and moderately elevated concentrations, whereas high-intensity exercise causes shorter periods of very high Ca^{2+} concentrations. Elevations of Ca^{2+} concentration in the muscle cytoplasm activate calmodulin kinase (CaMK) and calcineurin (CaN) (Jeukendrup & Gleeson, 2018).

Changes in cellular energy status

During muscle contraction, ATP is broken down to provide energy. In this process ADP and Pi are formed. ADP is then resynthesized to ATP by glycolysis or oxidative phosphorylation. Some ADP is further broken down to AMP. The ratio of metabolites ADP, AMP, and Pi relative to that of ATP is often referred to as the energy charge. If a lot of ATP is present and little of the metabolites, the energy charge is high. If the concentration of metabolites rises, the energy charge is low. These metabolites are important regulators of metabolism, but they also serve as signaling molecules. AMP

in particular can activate 5'adenosine activated protein kinase (AMPK), a potent secondary messenger. AMPK seems to play a role in the regulation of a variety of processes including glucose uptake, fatty acid oxidation, hypertrophy, and gene expression. The redox potential is another indicator of the energy status of the cell. If the ratio of the oxidized form of the coenzyme nicotinamide adenine dinucleotide (NAD+) to its reduced form (NADH) is high, poor energy status is indicated. (Jeukendrup & Gleeson, 2018).

Free radicals

The maintenance of redox potential also produces volatile free-radical oxygen molecules (reactive oxygen species, or ROS). These ROS are also thought to play a role in the exercise-induced signalling, that will ultimately be responsible for training adaptations. This signaling may work by ROS acting on transcription factors like nuclear factor kappa B (NFKB) and activator protein 1 (AP1). Although free radicals are often discussed in relation to ageing and diseases, it may thus be that they are also important to allow training adaptations. (Jeukendrup & Gleeson, 2018).

Hormones

Hormones can affect the activation of kinases as well. A hormone or other ligand binds to a receptor, which then changes the phosphorylation state of a kinase (Figure 4). For example, when thyroid hormone (tri-iodothyronine, or T3) binds to its receptor, the process induces phosphorylation of AMPK in skeletal muscle.

The primary messengers activate a series of secondary messengers. These secondary messengers are often kinases and phophatases, which are activated to pass on the exercise-induced signal. The secondary messengers often involve a complex series of reactions (cascades), which are highly regulated. Next we will discuss some of the most studied messengers.