Review

Performance in sports – With specific emphasis on the effect of intensified training

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Performance in most sports is determined by the athlete's technical, tactical, physiological and psychological/social characteristics. In the present article, the physical aspect will be evaluated with a focus on what limits performance, and how training can be conducted to improve performance. Specifically how intensified training, i.e., increasing the amount of aerobic high-intensity and speed endurance training, affects physiological adaptations and performance of trained subjects. Periods of speed endurance training do improve performance in events lasting 30 s–4 min, and when combined with aerobic high-intensity sessions, also performance during longer events. Athletes in team sports involving intense exercise actions and endurance aspects, such as soccer and basketball, can also benefit from intensified training. Speed endurance training does reduce energy expenditure and increase expression of muscle Na\(^+\), K\(^+\) pump \(\alpha\) subunits, which may preserve muscle cell excitability and delay fatigue development during intense exercise. When various types of training are conducted in the same period (concurrent training), as done in a number of sports, one type of training may blunt the effect of other types of training. It is not, however, clear how various training modalities are affecting each other, and this issue should be addressed in future studies.

Bengt Saltin had a vivid interest in understanding the limitations of human performance, and how performance in sport could be optimized. He was throughout his life involved in sport being a successful ice hockey player and orienteer, helping top-athletes to perform and, among many other things, president for the International Orienteering Federation and chairman of the Danish Anti-doping Committee. Many may recall the photo found in various textbooks where Bengt Saltin is sitting on a bicycle having a local helper behind him holding a Douglas bag to collect expired air from a Swedish top-class runner to determine oxygen uptake in the preparation for the Olympic Games in Mexico in 1968. He not only wanted to help the athletes but would also like to understand why they performed so well. He thoroughly studied the world’s best Kenyan runners to understand the mechanisms underlying their superiority (Saltin et al., 1995), and conducted impressive studies with Swedish elite cross-country skiers. Thus, in a study of different skiing techniques performed on a treadmill with highly invasive measures, he convincingly demonstrated that skeletal muscle vascular conductance is restrained during whole body exercise in the upright position to avoid hypotension (Calbet et al., 2004). He even performed a study of the effect of diet on the performance of players during a soccer match, estimated from two 3-min video-clips, back in the early 1970s (Saltin, 1973).

Performance in most sports is determined by the athlete's technical, tactical, physiological, and psychological/social characteristics (Fig. 1). In some sports disciplines, such as 100-m run, marathon, and rowing, performance is closely related to the physical capacity of the athletes, whereas in other sports like ball games, high technical and tactical standards may compensate for weakness within the fitness level. Nevertheless, in most sports the athletes need a high standard of fitness to cope with the physical demands of the competition and to allow for their tactical and technical skills to be utilized throughout the competition.

Under optimal conditions, the demands in sport are closely related to the athlete’s physical capacity, which can be divided into the following categories: (a) the ability to perform prolonged exercise (endurance); (b) the ability to exercise at high-intensity for a prolonged period; (c) the ability to sprint; and (d) the ability to develop a high power output (force) in single
actions such as kicking in soccer and jumping in volleyball (Fig. 1). Not all categories are relevant in all sports, e.g., the endurance component is not important for a 100-m runner.

The capacity within these categories is based on the characteristics of the respiratory and cardiovascular system as well as the muscles with the interplay of the nervous system. The respiratory system includes the trachea, lungs, and respiratory muscles. The heart, blood, and blood vessels form the cardiovascular system, which is, among other things, important for oxygen transport to the exercising muscles and for the individual maximum oxygen uptake (VO₂max). The muscular system is constituted by a multitude of components, which have important influence on the mechanical and metabolic behavior of the muscle (Fig. 1). Muscle architecture, morphology, and myosin isoform composition play a major role in the contractile strength characteristics of the muscle evaluated as maximal isometric, concentric, and eccentric contraction force, as well as maximal rate of force development and power generation. Muscle ionic transporters and glycolytic enzyme levels affect the development of fatigue during intense exercise and anaerobic energy production, when expressed as anaerobic power, capacity, and rate of anaerobic energy production. Likewise, mitochondrial enzyme levels and capillary density exert a strong influence on aerobic metabolism and endurance performance. The respiratory, cardiovascular, muscle, and neural characteristics are determined by genetic factors and are dependent of sex, anthropometry, age, and for children also maturation, but they can also be developed by training. A number of environmental factors such as temperature, humidity, and altitude, as well as nutritional intake before

Fig. 1. A holistic model of the determinants of sports performance.
competition, and for outdoor sports, the weather and the surface of the competition ground, may also influence performance and the demands of the athletes. For example, high temperatures and altitude may lower endurance performance, but improve performance in short-lasting events like a high jump.

In this article, a brief introduction of what may limit human performance at various exercise intensities is given to provide a basic of the discussion how training can change physiological factors and improve performance. Then, the various components of fitness training are presented, and the cardiovascular and muscular adaptations with regard to change in training of already trained people are addressed. Finally, the concept of concurrent training is briefly touched upon.

Physical capacity and performance

In some sports, performance during competition is basically the result, e.g., the time to complete 2000-m rowing or a 1500-m run, whereas it is more difficult to determine performance in other sports, such as soccer and badminton, where the complexity of the activities does not allow a single measure to represent physical performance. Nevertheless, independent of the sport, the physical aspect of performance cannot be isolated as performance is also dependent on psychological, technical, and tactical factors.

To examine performance in scientific studies, a number of different exercise protocols are used. It may be peak power development which could be studied by performing 10 s of maximal exercise on a bike, or time to fatigue, defined as a decrease in exercise intensity during a constant load exercise, or time to complete a given work load, e.g., time to produce 500 kcal on a bike and a 10-km run. Under the latter conditions, performance is linked to the development of fatigue.

A number of cross-sectional studies have examined the issue of which physiological factors are determining performance or what is causing fatigue at various exercise intensities (Iaia et al., 2011). High-intensity exercise of duration longer than 10 s leads to a pronounced accumulation of H⁺ and lactate within the working muscles (Bangsbo et al., 1993, 1996). In addition, K⁺ and Na⁺ is accumulating outside and within, respectively, the muscle cells causing changes in the membrane potential and perhaps sarcolemmal inexcitability (Sejersted & Sjøgaard, 2000). Therefore, the Na⁺, K⁺ pump may play a crucial role in preserving membrane excitability and ensuring skeletal muscle function, i.e., delaying the time of fatigue during exercise at a given intensity (Clausen, 2003). Nevertheless, in a study by Iaia et al. (2011), the expression of the Na⁺, K⁺ pump β₁-subunit was found to account for only 13–34% of performance during exhaustive exercise of ~ 1–4 min, and the other Na⁺, K⁺ pump subunits were not correlated with performance. Likewise, transporters associated with lactate and H⁺ transport, such as the Na⁺/H⁺ exchanger isoform 1 (NHE1) and isoforms of the monocarboxylate cotransporters (MCT1 and MCT4), accounting for 70–80% of the proton and lactate efflux during intense exercise (Juel, 1997), were not associated with performance. This does not mean that they are not important for the capacity to perform the work, but just that they may not be crucial for maintaining the exercise intensity. Actually, in a number of studies, intensified training has shown to cause an elevated expression of NHE1, and it may play a significant role in reducing the fall in muscle pH during intense exercise, which may delay the development of fatigue (Bangsbo & Juel, 2006).

A surprising finding in the study by Iaia et al. (2011) was that the muscle capillary density was estimated to explain 50–80% of the total variance observed in exercise performances lasting ~ 30 s to 3 min, and it was correlated with cycle performance at 550 (r² = 0.60), 500 (r² = 0.78), and 395 (r² = 0.68) W (Fig. 2), as well as inversely related to the net rate of plasma K⁺ accumulation during a ~ 3-min exercise bout (r² = 0.68). The reason for these findings is unclear. The power output during the exercise periods ranged between 100% and 140% of VO₂max and the aerobic system was contributing 40–80% of the total energy production. Thus, a higher number of capillaries may have elevated the mean transit time and the distribution of oxygen in the contraction muscle, and thereby promoted oxygen uptake. In addition, more capillaries may have supported release of ions like potassium and protons from the muscle interstitium to the blood, delaying the accumulation of potassium in muscle interstitium, and lowering the concentration of H⁺ outside of the muscle cells favoring release of protons from the muscle cell and thereby reducing the fall in muscle pH. Both factors may have contributed to a slower developing of fatigue (Bangsbo & Juel, 2006; McKenna et al., 2008).

In the study by Iaia et al. (2011), over 80% of the variance in performance at exercise duration longer than 4 min was related to VO₂max, which is not surprising as there is a major aerobic contribution during such exercise bouts. Generally, endurance performance is determined by maximum oxygen uptake (VO₂max), work economy (mechanical efficiency), and the relative intensity (fractional utilization of VO₂max) that can be sustained throughout the exercise (Joyner & Coyle, 2008).

VO₂max may not be the determining factor for well-trained, as often no relationship between
VO2max and performance is observed in athletes (Coyle, 1995). Furthermore, performance in events lasting more than a few min can be improved by training without changes in VO2max, but rather work economy (Iaia et al., 2008; Bangsbo et al., 2009). Top-class athletes in endurance sports, such as a marathon, usually have a high VO2max in early years, and then through years improve their long-term performance due to better work economy. As an example, the world class runner Paula Radcliffe, current world-recorder holder in marathon, had an improvement in 3000-m performance by 8% from 1991 to 1993 despite a fall in VO2max from 73 to 66 mL/kg/min. In the same period, she improved her running economy from 53 to 48 mL/kg/min at 16.0 km/h leading to an increase in the running speed at VO2max from 19.0 km/h in 1991 to 20.4 km/h in 1995 (Jones, 1998). On the other hand, the major difference between elite female and male runners seems to be the lower VO2max observed in females due to men having less body fat, higher hemoglobin concentration, larger heart size, and muscle mass than women. The typical differences in VO2max are 10–15%, whereas running economy and fractional VO2, which can be used during running, are rather similar in women and men (Jones, 2006; Hunter et al., 2015). Thus, the difference in VO2max can to some extent explain the about 13 min difference in world record in marathon for women and men (2:15:25 vs 2:02:57 h:min:s).

It should be noted that even though the majority of energy during exercise lasting longer than 5 min is coming from the aerobic system, the anaerobic energy production may also play a significant role, not only at the start and the finishing of a race. Thus, in a number of studies with intensified training, improved 10-km performance was associated with a higher anaerobic capacity without changes in VO2max (Bangsbo et al., 2009; Skovgaard et al., 2014).

**Fitness training**

It is useful to divide fitness training into a number of components related to the purpose of the training (Fig. 3). The terms aerobic and anaerobic training are based on the energy pathway that dominates during the activity periods of the training session, and represent exercise intensities below and above the maximum oxygen uptake, respectively. Specific muscle training covers muscle strength, endurance, and flexibility training. In this section, focus will be on aerobic and anaerobic training.

Aerobic training can be divided into three overlapping areas: Aerobic low-intensity, moderate-intensity, and high-intensity training (Fig. 3). Table 1 shows heart rate targets to reach within the various categories of aerobic training, where it is taking into account that in some team sports the training is performed as a game, and thus, the heart rate of the player may frequently alternate during the training.

Anaerobic training is defined as training where the exercise is performed at supramaximal intensity and...
Table 1. Heart rate targets and range within aerobic training

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Target heart rate (%max heart rate)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerobic low-intensity training</td>
<td>65</td>
<td>50–80</td>
</tr>
<tr>
<td>Aerobic moderate-intensity training</td>
<td>80</td>
<td>65–90</td>
</tr>
<tr>
<td>Aerobic high-intensity training</td>
<td>90</td>
<td>80–100</td>
</tr>
</tbody>
</table>

Table 2. Principles of speed training (A) and speed endurance training (B)

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Rest</th>
<th>Intensity (%)</th>
<th>No. of repetitions</th>
</tr>
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<tbody>
<tr>
<td>(A) Speed training</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed training</td>
<td>2–10</td>
<td>&gt;10× exercise time</td>
<td>100</td>
</tr>
<tr>
<td>(B) Speed endurance training</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production training</td>
<td>10–40</td>
<td>&gt;5× exercise time</td>
<td>70–100</td>
</tr>
<tr>
<td>Maintenance training</td>
<td>10–90</td>
<td>&lt;3× exercise time</td>
<td>40–100</td>
</tr>
</tbody>
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where the primary aim is to stimulate the anaerobic energy production (Bangsbo, 1994). The overall aim of anaerobic training is to increase an athlete’s potential to perform high-intensity exercise. Anaerobic training can be divided into speed training and speed endurance training (Fig. 3). Anaerobic training is performed as interval training and Table 2 shows the principles of the various categories of anaerobic training.

The aim of speed training is to improve an athlete’s ability to act quickly in situations where speed is essential, to generate force rapidly, and maintain a high speed for a short period. During speed training, the athlete should perform maximally for less than 10 s and the recovery periods should be long enough for the muscles to recover to near-resting conditions, to enable the athlete to perform maximally in a subsequent exercise bout (Table 2). In ball games, speed is not merely dependent on physical factors. It also involves the ability to perceive match situations that require immediate action (perceiving), to make rapid decision and take immediate action when needed (evaluating-deciding), and rapidly produce force in a coordinated action (taking action). Therefore, in ball games, speed training should mainly be performed with a ball and drills designed to promote the player’s ability to sense and predict situations, and the ability to decide on the opponents’ responses in advance.

Speed endurance training can be separated into production and maintenance training. The primarily purpose of production training is to improve the ability to perform maximally for a relatively short period of time, whereas the main aim of maintenance training is to increase the ability to sustain exercise at a high-intensity. In production training, the exercise lasts less than 40 s and the recovery periods are >5 times the exercise duration (Table 2). In maintenance training, the duration of the exercise bouts is 10–90 s separated by short rest periods (<3 times the exercise time) resulting in a progressive accumulation of fatigue as the training goes on (Table 2). The adaptations caused by speed endurance training are mostly localized to the exercising muscles. Thus, it is important that an athlete performs movements in a manner similar to during competition, e.g., an oarsman should train in the boat or on a rowing ergometer. In ball games, this can be obtained by performing intense games or drills with a ball, which also have the advantage that technical and tactical elements are trained under physical demanding conditions, and the players have a high motivation (Bangsbo, 2007).

The effect of intensified training on performance and physiological changes in trained subjects

This section will deal with the effect of aerobic high-intensity and speed endurance training on performance and physiological changes in already trained subjects. In both types of training, intervals are conducted, and it should be emphasized that the use of interval training is not new in sport and research. Already in the early 1900 century, running coach Peter Thompson described interval training in Athletics Weekly (Thompson, 2005), and in the 1900s, a high number of studies were focusing on the physiological response to interval exercise and the adaptations to interval training with studies by Scandinavian researchers being ground breaking (Astrand et al., 1960; Christensen et al., 1960). Notably, the article by Christensen et al. (1960) was Bengt Saltin’s first publication. Later, studies were comparing the effect of aerobic moderate- and high-intensity training obtaining different results (Berger et al., 2006; Edge et al., 2006; Helgerud et al., 2007; Daussin et al., 2008). Thus, no firm conclusion about the optimal combination of aerobic moderate-intensity and high-intensity has yet been reached. Most of the studies were focusing on exercise intensities around or below the one eliciting VO_{2max} and were conducted with untrained people. In recent years, a significant number of studies have also examined the adaptations with speed endurance training of untrained subjects (Ross & Leveritt, 2001; Burgo-master et al., 2005, 2007; Mohr et al., 2007). However, as almost any type of training will improve untrained, these are of limited interest in the discus-
sion of how to train athletes, and such studies will only be included in the discussion below when they may add information to the data obtained in well-trained.

**Performance**

It is a common finding that adding aerobic high-intensity training, e.g., $4 \times 4$ min intervals at 90% of the speed corresponding to VO$_{2\text{max}}$ with rest periods of 3 min, to a training program of aerobic moderately trained subjects usually leads to improved performance with exercise durations of 1/2–5 min (Esfarjani & Laursen, 2007; Helgerud et al., 2007), i.e., relevant for athletes participating in sports like 400-, 800-, and 1500-m track events, 1000-m cycling as well as 100- to 400-m swimming. There is also consensus that a period of speed endurance training in endurance-trained subjects leads to marked performance improvements during supramaximal exercise lasting less than 10 min. For example, Daniels et al. (1978) showed a ~10% lower time over ~800 m (~2 min) when trained runners performed part of their training as 100- to 600-m sprints. Also when the speed endurance training is combined with high-intensity aerobic training improvements are obtained. Thus, Bangsbo et al. (2009) found a 23% better performance in an about 2-min run after 6–9 weeks with additional aerobic high-intensity and speed endurance training with a 30% reduction in the volume of training.

The great potential of speed endurance training also for exercises lasting more than 10 min is illustrated by the finding in a study by Iaia et al. (2008) that 10-km performance was unaltered despite the training distance was reduced by 65%, when trained runners switched from regular aerobic training to only speed endurance training. When also combined with aerobic, training improvements are observed (Stepto et al., 1999; Laursen et al., 2002; Esfarjani & Laursen, 2007; Bangsbo et al., 2009). Thus, Bangsbo et al. (2009) found that performance in 3-km (10.1 vs 10.4 min) and 10-km (36.3 vs 37.3 min) runs were better after the period with aerobic high-intensity and speed endurance training where the total amount of training was reduced by 30%. These findings clearly indicates that when combining a basic volume of training including some aerobic high-intensity exercise, with a few weekly sessions of speed endurance training, trained subjects can improve endurance performance with reduced volume of training. In accordance, in a study using the 10-20-30 training concept, i.e., 30 s of jogging, followed by 20 s at moderate speed, and a 10-s sprint, the runners reduced the training from 30 to 15 km/week, and improved in a 7-week period performance in a 1500-m and a 5-km run by 21 and 48 s, respectively (Gunnarsson & Bangsbo, 2012a). It has, however, not been examined whether the speed endurance training also can improve performance in events lasting more than an hour, such as a marathon run.

A period of speed endurance training does also improve the ability to perform repeated high-intensity work as performed in a number of sports, such as badminton, basketball, ice hockey, and soccer (Dupont et al., 2004; Bravo et al., 2008; Iaia et al., 2008). When soccer players carried out one weekly 30-min session of speed endurance training during a 5-week period in the season, they increased the Yo-Yo intermittent recovery test level 2 (YYIR2) performance by 11% (Gunnarsson et al., 2012b). In accordance, in a recent study where 13 professional soccer players completed two weekly sessions of repeated sprint training consisting of 2–3 sets of 5 s of sprinting interspersed by 10 s of recovery (repeated 6–10 times per set) during the season, the players showed an improvement in YYIR1 test performance by 12% (3127 vs 2803 m) (Nyberg et al., 2015). Adding aerobic high-intensity training does also have a positive effect on performance of soccer players (Jensen et al., 2007; Christensen et al., 2011). Thus, an extra 30 min of aerobic high-intensity training once a week for 12 weeks increased YYIR2 performance by 18% and lead to a 21% reduced decrement during a repeated sprint test in elite soccer players (Jensen et al., 2007). Apparently, speed endurance and aerobic high-intensity training are beneficial for athletes participating in team sports involving intense activities, by elevating the players’ ability to produce a high power output for a longer time and to recover faster after the intense phases of a match, and thereby it is expected that they can raise the number of high-intensity exercise period during competition.

**Physiological adaptations**

It is a common finding that aerobic high-intensity training leads to elevated VO$_{2\text{max}}$ in trained individuals (Esfarjani & Laursen, 2007; Helgerud et al., 2007; Gunnarsson & Bangsbo, 2012a). Also studies with speed endurance training with intensities slight above the intensity corresponding to VO$_{2\text{max}}$ have found improvements in VO$_{2\text{max}}$ (Tabata et al., 1996; Laursen et al., 2002; Bravo et al., 2008). However, most of the studies on well-trained individuals evaluating the effect of speed endurance production training with an intensity higher than 90% of maximal intensity have reported unchanged VO$_{2\text{max}}$ suggesting that short near-maximal efforts are not sufficient to enhance VO$_{2\text{max}}$ in well-trained.

Improved performance does not appear to be caused by a faster oxygen uptake at the initial phase
of exercise, as only few studies of well-trained individuals have shown changes in oxygen kinetics, when speed endurance training was added to aerobic moderate training (Jones et al., 2011; Christensen et al., 2015; Nyberg et al., 2015). Speed endurance training has been shown to reduce energy expenditure during submaximal exercise (Bangsbo et al., 2009; Iaia et al., 2009), which to some extent can explain the improvement in performance. It may be speculated what caused the improved running economy. It does not seem to be related to a reduced level of UCP3 as has been suggested (Gong et al., 1997; Boss et al., 2000), as in the study by Iaia et al. (2009) expression of UCP3 was not changed. Another possibility is that the improved running economy was due to adaptations in the tendons, as also improvements in running economy have been observed after periods with jump, power, and sprint training (Hoff et al., 1999, 2002; Paavolainen et al., 1999; Turner et al., 2003; Saunders et al., 2006). More studies are, however, needed to examine the cause of improvement in work economy with speed endurance training.

Changes in various muscle variables may have contributed to the better performance after a period of intensified training observed in a high number of studies. In this section, just a few of these will be considered. As fatigue development during intense exercise may be linked to accumulation of ions either within or outside the muscle cell (McKenna et al., 2008), it is worthwhile considering whether intensified training is changing ion transport proteins.

Speed endurance training of trained subjects elevates the expression of either the Na$^+$, K$^+$ pump α1 or α2 subunits, whereas no significant increases have been observed in the β1 subunit (Iaia et al., 2008; Bangsbo et al., 2009; Thomassen et al., 2011; Gunnarsson et al., 2012b). The augmented Na$^+$, K$^+$ pump α subunits may result in a high number of functional pumps and play a role for the increases in work capacity during intensive short-term performance. Indeed a higher Na$^+$, K$^+$ pump maximum activity reduces the net loss of K$^+$ from the contracting muscles preserving the cell excitability and force production (Sejersted & Sjøgaard, 2000). This is supported by the finding that in the studies showing elevated expression of the Na$^+$, K$^+$ pump α subunits after a speed endurance training period, accumulation of venous plasma K$^+$ was reduced and performance during repeated supramaximal exercise was improved. Furthermore, Gunnarsson et al. (2013) found that the decline in femoral plasma venous K$^+$ after intense cycle exercise was more rapid and that muscle interstitium K$^+$ tended to be lower after a 7-wk period with speed endurance training. However, in that study, no significant increase in the expression of Na$^+$, K$^+$ pump subunits were observed, suggesting that other factors are important for K$^+$ homeostasis. Interestingly, in that study the total expression of phospholemman (FXYD1) was larger and the non-specific phosphorylation of FXYD1 was higher both at rest and during exercise after the training period, which may have led to higher Na$^+$, K$^+$ pump activity during exercise, as FXYD1 does play a role in the regulation of the Na$^+$, K$^+$ pump activity (Unpublished data).

In contrast to what is observed in untrained people (Pilegaard et al., 1999; Juel et al., 2004; Bickham et al., 2006; Burgomaster et al., 2007; Mohr et al., 2007), speed endurance training of trained people does not seem to create a higher expression of monocarboxylate transporters (MCT) (Iaia et al., 2008; Bangsbo et al., 2009; Gunnarsson et al., 2013). Nevertheless, one study has reported higher MCT1 proteins in endurance-trained subjects after a period with sprint training (Bickham et al., 2006). In the latter study, in contrast to the other studies, the subjects maintained a high volume of training, which may have caused the difference.

Some studies have shown that the expression of the Na$^+$/H$^+$ exchanger isoform 1 (NHE1) was enhanced after a speed endurance training period (Iaia et al., 2008; Bangsbo et al., 2009). This may have facilitated the Na$^+$ uptake inside the muscle cell and, thus, possibly resulted in a higher stimulation of the Na$^+$, K$^+$ pump (Ewart & Klip, 1995) causing a hyperpolarization of the membrane potential. Furthermore, it may have led to reduced fall of intracellular pH, which may have contributed to delayed onset of fatigue and enhanced work capacity during intense exercise (Bangsbo & Juel, 2006).

A considerable number of studies on untrained people have shown improvements in glycolytic and oxidative enzymes activity after periods of training including very short maximal exercise bouts (5–30 s) interspersed with relatively long resting periods (45 s–20 min) (Costill et al., 1979; Roberts et al., 1982; Hellsten-Westling et al., 1993; Parra et al., 2000; Rodas et al., 2000; Burgomaster et al., 2005). However, the participants were not well-trained, and studies enrolling fit subjects have not been able to show changes in enzymes related to anaerobic energy production (Iaia et al., 2008; Bangsbo et al., 2009; Christensen et al., 2015). Untrained subjects doing speed endurance training do increase the level of oxidative enzymes (Burgomaster et al., 2005), whereas no changes or even decreases in expression of oxidative enzymes have been observed for well-trained with reduced amount of training (Iaia et al., 2008; Bangsbo et al., 2009; Christensen et al., 2015). Thus, a significant amount of moderate-intensity training may be needed to maintain the level of oxidative enzymes in trained subjects. Nevertheless, pronounced alterations in short-term performance
were observed despite unaltered levels of enzymes related to aerobic and anaerobic energy production (Iaia et al., 2008; Bangsbo et al., 2009; Christensen et al., 2015), suggesting that the changes in the expression and activity of these enzymes are not crucial for improvement in work capacity during exercise lasting less than 60 min.

Taken together aerobic high-intensity training and speed endurance training substituting or supplementing aerobic moderate-intensity training in trained people do lead to significant physiological changes which may have contributed to the improved performance after a period with intensified training, e.g., the higher expression of Na\(^{+}\)/K\(^{+}\) pump \(\alpha\) subunits or FXYD1 as well as larger phosphorylation of FXYD1, may have caused a higher pump activity during intense exercise and, hence, reduced the accumulation of potassium in muscle interstitium and thereby delayed the time when fatigued occurred.

**Perspectives – Concurrent training**

In many sports, the physical demands are multifactorial (Fig. 1), and the elite athlete has to conduct various type of fitness training in the same seasonal period, e.g., a soccer player may do aerobic, speed, speed endurance, and power training during a week. The question is how these types of training are influencing each other, i.e., whether the adaptation to one type of training is affected when the other types of training are conducted in the same period. The term “concurrent training” has been used to describe the incorporation of two or more divergent training modalities in a periodized program.

The issue of concurrent training was firstly addressed by Hickson (1980), who found that a group, which performed power training and aerobic training in the first 7 weeks had the same improvement in muscle strength as a group, which only performed power training, but in the following 3 weeks, in contrast to the only power training group, had a decline in muscle strength. The power and aerobic training group had the same (about 20%) increase in \(\text{VO}_{2}\text{max}\) as a group, which only performed the aerobic training. Thus, the concurrent aerobic and power training appeared after a period of time to influence the adaptations to single mode training reducing the effect of the power training. Since then, a significant number of studies have focused on the combination of aerobic and power training, and the results are diverse. Nevertheless, most studies indicate that aerobic training compromise the effect of power training on strength, power output, and muscle hypertrophy, i.e., the adaptation to power training is smaller than when power training is done alone (Kraemer et al., 1995; Bell et al., 2000; McCarthy et al., 2002; Häkkinen et al., 2003). On the other hand, it appears that endurance athletes improve endurance performance when adding power training to the aerobic training program (Aagaard & Andersen, 2010; Aagaard et al., 2011).

It has been hypothesized that the apparent negative effect of aerobic exercise on the adaptation to power training is due to cross-talk between signaling pathways, which negatively affect each other, i.e., that the signaling pathways activated by one type of training do blunt pathways stimulated by other types of training performed in the same period. For example, aerobic training may activate Ca\(^{2+}\)/calmodulin-dependent kinase (Ca2MKII) and 5’ adenosine monophosphate-activated protein kinase cascades leading to an inhibitory effect on rapamycin complex 1 (mTORC1), which is enhanced by power training and regarded as a key regulator of muscle growth (Bolster et al., 2002; Kimball, 2006; Inoki et al., 2012). Thus, muscle protein synthesis and muscle hypertrophy may be impaired when power training is performed concurrently with aerobic training (Bodine et al., 2001; Aagaard & Andersen, 2010). However, in humans it has been difficult to find evidence for such a connection. (Coffey et al., 2009; Donges et al., 2012; Lundberg et al., 2012; Apró et al., 2013), and it is unclear when aerobic training has a negative impact on the muscle hypertrophy. A key issue may be the time between the training sessions. Actually, performing aerobic training 6 h before power training enhanced the anabolic signaling compared with power training by itself (Lundberg et al., 2012). Likewise, concurrent power training may stimulate the oxidative response to training. Thus, Wang et al. (2011) observed that resistance training (six sets with \(8–14\) repetitions of leg press) carried out after aerobic training (1 h at \(65\%\) \(\text{VO}_{2}\text{max}\)) enhanced mRNA levels of PGC-1\(\alpha\), which is important for mitochondrial biogenesis (Vissing et al., 2013), compared to only aerobic training. The issue of the combination of aerobic and power training as well as the biochemical basis for the interference of the training forms has been addressed in a number of excellent reviews (Coffey & Hawley, 2007; Fyfe et al., 2014), and it will not be discussed further here.

More recently other combinations of training have been studied. The studies described under the section “The effect of intensified training on performance and physiological changes in trained subjects” may be regarded as concurrent training and apparently the high-intensity training does lead to performance improvements. These studies are characterized by having at least 24 h between the training sessions. Some studies have also looked at performing two types of training the same day or in the same session. Skovgaard et al. (2014) studied a group of recre-
 Bangsbo

ational runners, who normally performed aerobic moderate-intensity training four times a week, and in an 8-week period reduced this type of training to twice a week. In addition, they carried out two sessions with speed endurance training, consisting of repeated (6–12) 30-s all-out running bouts (separated by 3 min of recovery), followed by a 15-min break and power training consisting of three sets of eight repetitions at 15 repetition maximum (RM) in the beginning to 4 sets of four repetitions at 4RM at the end. The weekly running distance was 42% less compared to before the intervention period. They observed that performing speed endurance and power training in succession, lead to improvements in both short-term (6% in a 1500-m run) and long-term (4% in a 10-km run) performance which was associated with improved running economy as well as higher muscle strength and capacity for muscular H⁺ transport. Thus, demonstrating that performing the two types of training in the same session was efficient. However, the effect of each training modality was not studied separately, and it cannot be excluded that the effect would have been greater if any of the types of training was conducted separately. Likewise, Coffey et al. (2009) examined the effect of consecutive repeated sprint and resistance exercise bouts on acute adaptive responses in human skeletal muscle, and found that the training improved performance and the order of executing the training did not have much influence. Nevertheless, in most of these studies, the participants were not used to perform these various types of training, and it is clear that more studies are needed to address how to optimize the response to concurrent training particular the combination of speed endurance and power training in trained subjects.

Synopsis

The physical demands in most sports are complex and the key elements for success need to be identified for each athlete. In addition, the effect of various types of training to improve performance has to be understood before a training program can be made. It appears that intensified training can improve performance in trained people even with a marked reduction in the volume of training. Such changes in the training regime do lead to marked muscle adaptations which are associated with the better performance. Thus, athletes may in periods benefit from reducing the amount of training and perform sessions of aerobic high-intensity and speed endurance training. The challenge in the future is to obtain the optimal combination of the various types of training, called concurrent training, and further research should address this issue.

Key words: Physical demands, maximum oxygen uptake, enzymes, muscle, running economy.

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