

## **4. Introduction**

The following paragraphs are from the Industrial PhD guidelines (2015) and provide insight into the work tasks and the overall strategical aim of a public sector Industrial PhD (Team Danmark is a public sector company).

A public sector Industrial PhD is an industrially focused research project and PhD education, conducted jointly by a public sector company, an Industrial PhD candidate and a university. The Industrial PhD candidate is employed by the public sector company and at the same time enrolled at the university, and works on the same project at both places. The candidate spends all his working time on the project and education, and divides the working time between the company and university. The project length corresponds to the length of the education, which is three years in Denmark and the candidate has a supervisor at both the university and the company, in addition to a co-supervisor at the company (Innovation Fund Denmark 2015).

Industrial PhD is part of the Industrial Researcher Programme. The Industrial Researcher Programme has the purpose of educating and developing research talents into industrial researchers specialised in creating growth and employment in Denmark's business sector through research, development and innovation (Innovation Fund Denmark 2015).

### **4.1. Project purpose**

#### **4.1.1. What is the problem?**

Usually, elite endurance athletes perform a lot of moderate-intensity training resulting in an enormous amount of weekly training hours. Several studies on trained endurance subjects have found improved endurance performance as a result of up to 9 weeks of intense training (i.e. repeated bouts of maximal or near-maximal exercise intensity) in combination with a reduced amount of weekly training hours (Laursen et al. 2002; Bangsbo et al. 2009; Skovgaard et al. 2014; Iaia & Bangsbo 2010).

While a plethora of studies have documented the beneficial effect of intense training on performance, movement economy and muscular adaptations in trained subjects (Iaia & Bangsbo 2010; Hostrup & Bangsbo 2016; Bangsbo 2015), knowledge in certain areas are lacking. Specifically, e.g. how performance develops when intense training is performed for a prolonged period, how performance develops when intense training is performed very frequently, how training in the weeks before an important competition should be structured to gain the most from

an intense period of training, and how performance is affected when a period of intense training is repeated.

In order to better qualify and guide the Danish federations at the highest possible level, Team Danmark, the Danish elite sports organization, is in a constant need of knowledge in areas such as intense training.

#### **4.1.2. Why is it a problem?**

Competition in international elite sports is fierce, but many national elite sports organizations, such as the Australian and English Institute of Sport, are much better funded than the Danish (Australian Sports Commission 2016; UK Sport 2017a; Storm et al. 2016), which makes them capable of heavy investments in knowledge. Such investments are nowadays providing the cutting edge and if insufficient investment in research, dissemination and implementation in the Danish federations is the case, then there is a risk of getting left behind in the race for future medals. Getting left behind makes Denmark and the Danish society unable to achieve what UK sport aims for:

*"Inspiring the nation through world class success"*

(UK Sport 2017b)

Hence, the Danish federations should constantly be exposed to research-results guiding them on training structure, training load, technology, newest trends etc.

#### **4.1.3. Value to Danish elite sport**

This PhD project is useful to Team Danmark as it adds significantly to the existing knowledge in the area of intense training and how to apply this kind of training to optimize performance of the elite athlete. More substantial knowledge in this area will benefit many sports ranging from endurance to team sports and through Team Danmark new knowledge will be spread to the 25 federations that Team Danmark is expected to support in 2017 (Team Danmark n.d.).

The partnership and the bridging between elite sports (Team Danmark) and science (University of Copenhagen) is especially important with the Olympics in Tokyo in 2020 in mind. With the findings of this PhD project, Team Danmark has gained important knowledge that can be investigated further by relevant federations. Due to the open window (in Olympic terms), these federations now have a chance to gain their own valuable experience based on the findings of the present PhD project, which may increase the chances of winning medals and inspire the Danish society as done so well in Rio 2016.

#### **4.1.4. Value to society**

This PhD project can lead to public recommendations on how to optimize the structure of intense training in recreational athletes. Accordingly, a large number of Danes are engaged in both endurance (e.g. running, cycling and triathlon) and interval sports (e.g. football and handball) and train several times a week often to achieve a certain goal (e.g. run 10-km below 40 min) (Pilgaard & Rask 2016). Thus, despite the individual studies of the present PhD study are designed to optimize the training structure of elite athletes, it is believed that the results can provide recreational athletes and coaches with important knowledge on how to structure intense training most optimal thereby helping the recreational athlete to achieve their goals as well.

#### **4.1.5. Value to myself**

With this industrial PhD project I get the chance to combine research with relevant work experience. It lets me combine theory and practice, and propels me on par with foreign colleagues, which usually have a greater experience with the combination of theory and practice, than we have in Denmark. With this unique combination I will be aiming for a job in academia or in the world of elite sports.

### **4.2. Background**

Many sports, e.g. handball, football, ice-hockey, rowing, running and cycling require a high level of endurance. Endurance is an important parameter for success in team sports, but the influence of tactical and technical elements, that creates dynamic and unpredictable movement patterns, will be dictating the level of endurance needed. In some sports, such as rowing, running and track-cycling, performance during competition is essentially the result, and success is closely related to the level of endurance. Furthermore, these sports can be performed on ergometers, and the effect of a given period of training can therefore be determined with high accuracy. For these reasons, running and cycling was chosen as the sports investigated in the present PhD study.

For endurance events, such as distance running, the rate of adenosine triphosphate (ATP) generation is dependent on the oxygen uptake ( $\text{VO}_2$ ; mL/kg/min) that can be maintained throughout a race. This is determined by the subject's maximal oxygen uptake ( $\text{VO}_{2\text{-max}}$ ) and the fraction of  $\text{VO}_{2\text{-max}}$  ( $F\text{VO}_{2\text{-max}}$ ) at which the subject can run at (typically about 80–85% of  $\text{VO}_{2\text{-max}}$ ). Running economy is used to express the oxygen uptake needed to run at a given velocity (i.e. how much speed or power can be generated for a given level of oxygen consumption). This can be shown by plotting oxygen uptake (mL/kg/min) versus running velocity (m/min) or by expressing economy as the energy required per unit mass to cover a

horizontal distance (mL O<sub>2</sub>/kg/km) (Bassett & Howley 2000). Anaerobic energy provision in a distance run is particularly important at the start, if a sudden increase in (steady state) pace is required, when running uphill and during the final sprint.

Thus, as shown on fig. 1, endurance performance is determined by four factors: (1) VO<sub>2</sub>-max, (2) the FVO<sub>2</sub>-max that can be sustained during a given distance, (3) the mechanical efficiency (i.e. the ratio of work done to energy expended) also termed running economy and (4) the anaerobic contribution. As such, improved endurance performance can be ascribed to changes in any of these variables.

Generally, *VO<sub>2</sub>-max* is determined by the pulmonary diffusing capacity, maximal cardiac output, oxygen carrying capacity of the blood, and skeletal muscle characteristics. The first three factors can be classified as “central” factors; the fourth is termed a “peripheral” factor (Bassett & Howley 2000). Adaptations to training covers increased cardiac stroke volume, increased blood volume, increased capillary density and mitochondrial density.

*FVO<sub>2</sub>-max* is related to the VO<sub>2</sub> at which lactate begins to accumulate in the blood (Farrell et al. 1979), which in turn is affected by aerobic enzymatic activity, capillary density, muscle fibre type composition, distribution of power (amount of muscle mass and/or numbers of muscle fibres recruited) and movement technique (Bassett & Howley 2000; Coyle 1999). As exercise extends beyond about 2 h the problem becomes one of fuel availability as the glycogen content in skeletal muscle becomes depleted and the ability of active muscle to take up glucose from blood (via either the liver or from feeding) can limit the rate of oxidative ATP generation and thus the pace that can be sustained.

*Running economy* is influenced by a lot of factors, such as anthropometry (tendon length, muscle stiffness, body mass and body composition), biomechanics (flexibility, elastic energy stored), environment (altitude, heat), training mode (plyometric, resistance) and physiology (VO<sub>2</sub>-max, metabolic factors) (Saunders et al. 2004) as well as the interaction of muscle morphology, elastic elements and joint mechanics in the efficient transfer of ATP to running speed. However, although there has been long-standing interest in identifying the factors that allow one person compared with another to expend 30–40% less energy per kilogram of body to move at a given velocity, the cause of differences in running economy remains somewhat illusive, and biomechanical descriptions of running are not good predictors of running economy (Joyner & Coyle 2008).

*Anaerobic capacity* is determined by the total amount of energy that can be obtained from anaerobic sources (ATP-creatine phosphate (CrP) breakdown and anaerobic glycolysis). According to Joyner & Coyle (2008), the relative amount of anaerobic metabolism may contribute 10–20% of total ATP turnover during 10-km running. However, the rate at which this energy might be generated and consumed is difficult to estimate in a definitive way. An important adaptation might be the development of fatigue resistance at intensities that stimulate significant anaerobic metabolism.

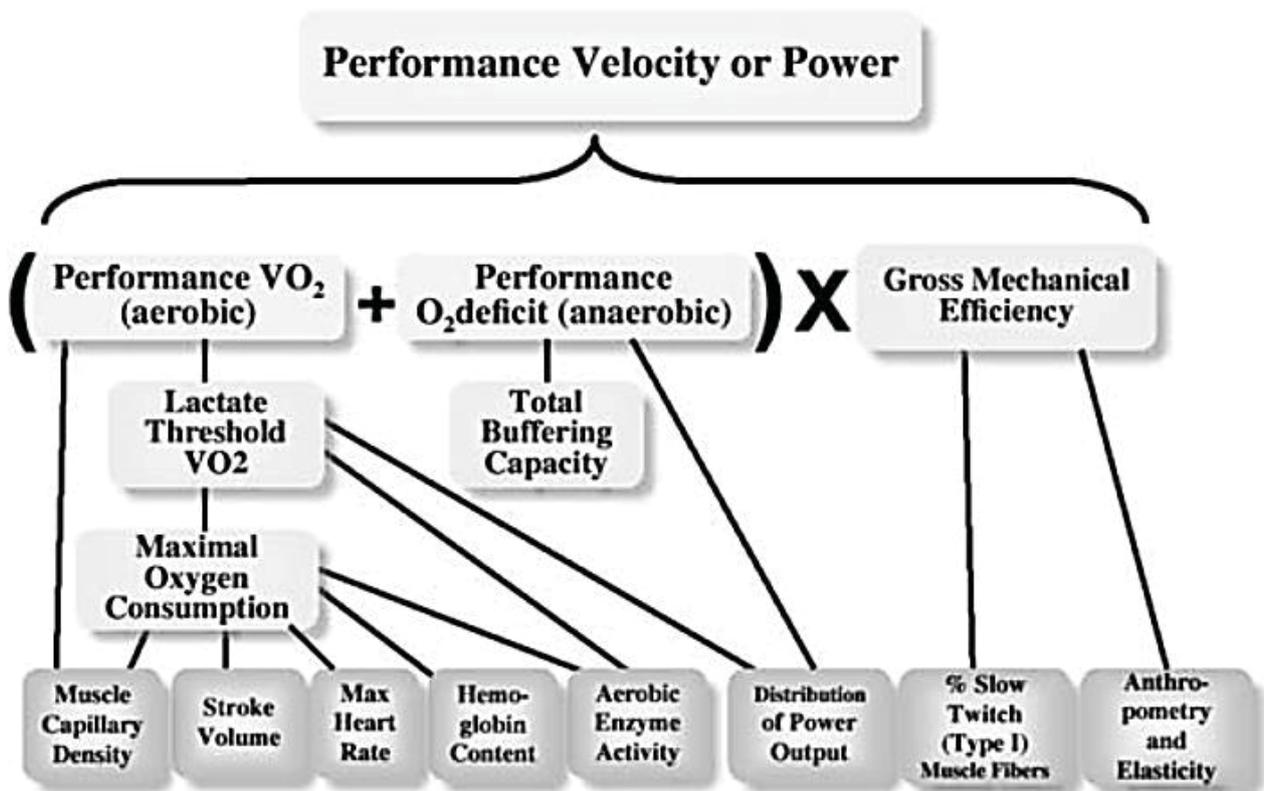


Figure 1. Overall schematic presentation of the determinants of performance velocity during a distance run and the physiological factors that impinges on them. From Joyner & Coyle (2008).

All four factors can change with training, which can roughly be divided into aerobic and anaerobic training. 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 VO<sub>2</sub>-max, respectively (Bangsbo 2015). Aerobic training can be sub-divided into *aerobic low-intensity*, *aerobic moderate-intensity*, and *aerobic high-intensity* training, with the primary aim of improving endurance performance (>10 min). And anaerobic training can be sub-divided into *strength-training*, *sprint training* and *speed endurance training*, with the primary aim of improving the ability to work with high intensity (<10 min) and increase maximal power in maximal efforts such as sprinting and jumping (Bangsbo et al. 2006; Bangsbo 2015).

Unpreserved gradient of  $K^+$  across the muscle membrane is the dominant cellular process for the development of fatigue during high-intensity exercise (Allen et al. 2008). This is due to the cellular  $Na^+$  influx and  $K^+$  efflux that can lead to marked muscle membrane depolarization and in-excitability (Dutka & Lamb 2007; McKenna et al. 2008; Sejersted & Sjogaard 2000). The action of the  $Na^+,K^+$ -ATPase (NKA) pump reduce the net fluxes of  $Na^+$  and  $K^+$  and preserves muscle membrane excitability and contractile function (McKenna et al. 2008; Clausen 2013).

Almost any type of training will improve the performance of untrained subjects and induce physiological adaptations to the increased level of physical activity (Bangsbo 2015). Consequently, such studies are of limited interest and relevance in the discussion on the training structure of the athletic population. Such studies will therefore only be included in this thesis where studies on trained subjects are lacking or where otherwise relevant.

### **4.3. State of the art**

Exercise training is known to increase the muscle-force output for a fixed time and/or maintain a fixed muscle-force output for a longer period of time. When untrained individuals commence a period of training characterized by moderate-intensity exercise for long duration, increases in mitochondrial content and respiratory capacity of muscle fibres are reported (Holloszy & Coyle 1984). This type of training is likely to contribute to an ability to perform with a high power output for a long duration (Coyle et al. 1988) and an ability to recover from high-intensity exercise (Seiler et al. 2007). However, as Costill et al. (1991) concludes, “it is difficult to understand how training at speeds that are markedly slower than competitive pace for 3-4 h/day will prepare (an athlete) for the supramaximal efforts of competition” (Costill et al. 1991).

The finding of higher mRNA level of muscle peroxisome proliferator-activated receptor- $\gamma$  coactivator-1 (PGC-1 $\alpha$ ), a key regulator of mitochondrial biogenesis and oxidative genes (Handschin & Spiegelman 2006; Handschin & Spiegelman 2008; Puigserver et al. 1998), as a response to intense exercise, performed as speed endurance exercise (Gibala et al. 2009; Little et al. 2011), could suggest that this type of exercise training elicits the same type of adaptations as moderate-intensity training in untrained subjects (Gibala et al. 2006; Burgomaster et al. 2008). This could likely explain the findings of improved short and long-term performance found in untrained subjects with chronic intense training (Gibala et al. 2006; Gibala & McGee 2008).

It may be that intense training, such as speed endurance training (SET; 10-40 s repeated all-out efforts with rest periods lasting  $>5$  times the duration of each exercise bout), targeting both slow twitch (ST) and fast twitch (FT) fibres (Egan & Zierath 2013), is essential for eliciting oxidative

adaptations in trained subjects. In support, PGC-1 $\alpha$  mRNA has been shown to increase in an exercise intensity-dependent manner (Egan et al. 2010; Nordsborg et al. 2010). However, studies investigating the effect of SET in trained subjects do not support this explanation as VO<sub>2</sub>-max and muscle expression of oxidative proteins and maximal oxidative enzyme activity remains unchanged (Iaia & Bangsbo 2010; Bangsbo 2015). A possible explanation for the lack of oxidative adaptations in the studies of trained subjects could be the reduction in training volume typically accompanying a period of intense training. In the studies by Christensen et al. (2015) and Iaia et al. (2009) unchanged muscle expression of oxidative proteins and maximal oxidative enzyme activity were found together with unchanged long-term running performance (Iaia et al. 2009) after reductions in training volume of ~70% (Iaia et al. 2009; Christensen et al. 2015). This dramatic reduction could serve as a de-training stimuli as suggested by both authors. Correspondingly, de-training in trained athletes is known to reduce the content and maximal activity of oxidative enzymes (Christensen et al. 2011; Chi et al. 1983). Thus, even though regular intense training may lead to higher oxidative capacity of FT fibres (Jansson & Kaijser 1977), this may be counteracted by the de-training stimuli of the lack of aerobic training.

However, studies have investigated the combination of SET and a more modest decrease in the amount of aerobic training (Bangsbo et al. 2009; Skovgaard et al. 2014; Vorup et al. 2016; Laursen et al. 2002). Findings cover improved movement economy, improved endurance performance and increased muscle expression of proteins related to transportation of Na<sup>+</sup>/K<sup>+</sup> with the latter being suggested to play an important role for improved short-term performance after a period with SET (Iaia & Bangsbo 2010; Hostrup & Bangsbo 2016; Bangsbo 2015; Laursen 2010). Accordingly, Nielsen et al. (2004) reported that elevated levels of NKA subunits after 8 weeks of SET for the knee extensors were associated with a reduced interstitial K<sup>+</sup> concentration during exercise as well as improved performance during intense exercise (Nielsen et al. 2004). In addition, changes in other muscle ion transport proteins, such as NHE1, facilitating lactate and H<sup>+</sup> exchange across the muscle membrane, have also been reported with intense training and may contribute to postpone the development of fatigue during high-intensity exercise (Iaia et al. 2008; Skovgaard et al. 2014; Hostrup & Bangsbo 2016).

A candidate of training-induced improvement in running economy is an increased mitochondrial efficiency (i.e., increased ATP/O<sub>2</sub>) which could be due to reduced uncoupled respiration. The mitochondrial uncoupling protein 3 (UCP3) is suggested to be involved in thermogenesis by dispersing energy as heat instead of converting it to ATP (Boss et al. 2000; Gong et al. 1997) and improved running economy may therefore be related to reduced levels of UCP3. Cross-sectional studies have shown that endurance-trained subjects have lower muscle UCP3 expression than

untrained subjects (Mogensen et al. 2006; Russell et al. 2003), which has been associated with a reduced cost of movement. Similarly, reduced energy expenditure during submaximal exercise was reported in a study where trained subjects ( $\text{VO}_2\text{-max}$ :  $56 \pm 1$  mL/min/kg) performed SET (8-12 x 30-s at a speed corresponding to 93% of 30-s “all-out” speed 3 times/week) and a 65% reduced training volume for 4 weeks. However, the authors reported unchanged muscle expression of UCP3 and it could be speculated that the reduction in training volume was too large to elicit changes in UCP3 expression. It would therefore be worthwhile exploring how a period of SET together with a more modest reduction in the amount of aerobic training in already trained subjects would affect UCP3 expression in relation to running economy.

No study has investigated whether the mRNA response to combined speed endurance and endurance exercise would be enhanced compared to single-mode exercise in trained subjects (i.e., mirror the chronic training studies, that, based on performance, seems in favour of the combination). Furthermore, how a modest decrease (~30%) in training volume together with training that specifically recruits FT muscle fibres, as investigated in the study by Bangsbo et al. (2009), affects oxidative proteins in FT and ST muscle fibres in trained subjects.

SET is typically performed 2-3 times per week (Iaia et al. 2008; Bangsbo et al. 2009; Skovgaard et al. 2014; Vorup et al. 2016; Bangsbo 2015), which might be based on findings from Parra et al. (2000) who found that in untrained subjects intense performance (peak and mean power during a 30-s Wingate test) was impeded when SET was performed every day for 14 days and recovery between sessions was speculated to be insufficient (Parra et al. 2000). However, fatigue resistance (Bogdanis 2012) and the ability to recover between sessions (Newton et al. 2008; Vincent & Vincent 1997) are determined by training state and no study has investigated how trained subjects adapt to a period of high-frequency intense training (e.g. ~4 times/week). It could be speculated that the initial changes in short-term performance (<10 min) and 10-km running performance as well as the physiological adaptations to SET could be further enhanced if a subsequent period with high-frequency SET together with a basic volume of aerobic training is performed. Likewise, as highlighted elsewhere (Iaia & Bangsbo 2010; Hostrup & Bangsbo 2016), it would be worthwhile exploring the effect of a prolonged period of SET and a basic volume of aerobic training on short-term performance (<10 min), 10-km running performance and physiological measures.

The goal in training competitive athletes is to provide training loads that are effective in improving performance. During this process, athletes may go through several stages within a competitive season of periodized training. Such phases may include overload training, which

includes maladaptation and diminished competitive performance. Successful training must involve overload, but must also avoid the combination of excessive overload plus inadequate recovery (Meeusen et al. 2013). Studies on trained subjects have shown performance improvements of ~3% when training volume is decreased and training intensity maintained for 7–21 days after a period of overload training (Neary et al. 2003; Trappe et al. 2000; Luden et al. 2010). The purpose of such interventions, termed tapering, is to reduce accumulated fatigue induced by intense training while maximizing physiological adaptations and consequently performance (Mujika 2010). The conventional principles of successful tapering are to maintain or even increase training-intensity, maintain training-frequency and decrease training-volume (Bosquet et al. 2007). However, the optimal way to taper in relation to prior training background needs to be established, since previous studies have mainly focused on tapering after prolonged periods of high-volume aerobic moderate-intensity training (Shepley et al. 1992; Mujika et al. 2004) and not prolonged periods of intense training. It would therefore be interesting to investigate how performance is affected by tapering from a period of overload (i.e., high-frequency) SET as performance gains could be achieved by both the SET intervention (Bangsbo 2015) as well as the tapering phase (Le Meur et al. 2012).

Within a strength and conditioning setting, "muscle memory" is a phrase used to describe the ability of human skeletal muscle to respond more advantageously to a period of training that has already been encountered in the past (Sharples et al. 2016). This cellular memory mechanism facilitates morphological and functional muscle adaptations following a repeated period of training (Staron et al. 1991; Taaffe & Marcus 1997; Henwood & Taaffe 2008; Taaffe et al. 2009), preserves myonuclei after prior encounters with anabolic milieu (Bruusgaard et al. 2010; Egner et al. 2013; Gundersen 2016) and creates epigenetic modifications in skeletal muscle following exercise (Tzanninis et al. 2013). Studies investigating the effect of repeated strength-training interventions in men and women (65-84 years old) and women (21 years old) reports that 6-12 weeks of re-training improves strength to the same level as initial 20-24 weeks of resistance training with 12-32 weeks of training-cessation in between (Taaffe & Marcus 1997; Henwood & Taaffe 2008; Staron et al. 1991; Taaffe et al. 2009). These studies demonstrate that comparable strength gains are obtained faster during re-training than during the first training phase. Hence, it could be speculated that during equally long training interventions, gains during the re-training phase would be enlarged compared to the first training phase. However, the effect of a repeated period of SET on performance, energy expenditure during submaximal exercise and muscle expression remains unknown.