MUSCULAR STRENGTH TRAINING EFFECTS ON AEROBIC ENDURANCE PERFORMANCE

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Pate and Kriska (1984) have described a model that incorporates the three major factors that account for interindividual variance in aerobic endurance performance, namely maximal oxygen uptake (VO_{2max}), anaerobic or lactate threshold (LT) and work economy (C). Numerous published studies support the model and thus, the model should serve as a useful framework for the comprehensive study of strength training effects on aerobic endurance performance.

VO_{2max} is probably the single most important factor determining success in an extreme aerobic endurance sport. In order to obtain relevant values emphasize is placed on testing in sport specific activities. The best-level male international cyclists, as the best middle and long distance runners, have a maximum oxygen uptake of more than 85 ml · kg^{-1} · min^{-1} (Helgerud et al. 1990). It has been well documented that also mithochondrial density, oxydative enzyme activity and capillary density increase with endurance training. At maximal exercise, the majority of evidence points to a VO_{2max} that is limited by O_2 availability (Richardson 2000), again limited by cardiac output and thus the stroke volume of the heart. The stroke volume of the heart can be twice as high in a trained athlete compared to a sedentary person. Although researchers agree that stroke volume increases as work rates increase up to around 50% of VO_{2max} , reports about what happens after that point differ widely. A study by Zhou et al. (2001) found that stroke volume increased continuously with increased workload up to VO_{2max} in well-trained subjects. However, in sedentary and moderately trained subjects the classical levelling off was found. The increased stroke volume up to the level of VO_{2max} in trained athletes has been the rationale behind using high intensity aerobic training intervention in our endurance training. An endurance athlete is able to maintain repetitive bouts at this intensity level for 3 to 8 minutes. There is no literature proposing that strength training might improve VO_{2max}.

LT determines the fraction of the maximal aerobic power that may be sustained for an extended period of time. The blood lactate level represents a balance between lactate production and removal, and there are individual patterns in this kinetics. Lactate is not wasted and can either be oxidized or to a smaller extent be a substrate for synthesis of glucose and glycogen. When oxidized it yields the remaining 92 % of energy and both resting and submaximally working skeletal muscle, as well as heart muscle and kidney cortex can use lactate as a substrate. Values as high as 90% of maximal oxygen uptake have been observed in some highly proficient endurance athletes. LT changes with the alteration of VO_{2max}, but in terms of % of VO_{2max} the trainability seems to be minor. No literature is proposing that strength might improve LT in % of VO_{2max}.

Work efficiency is referred to as the ratio between work output and oxygen cost. Running economy (C_R) is commonly defined as the steady state VO_2 in ml · kg^{-1}· m^{-1} at a standard velocity or as energy cost of running per meter ($ml \cdot kg^{-1} \cdot m^{-1}$). Several authors have shown intra-individual variations in gross oxygen cost of activity at a standard running velocity (Helgerud 1994). The causes of this variability are not well understood, but it seems likely that anatomical trait, mechanical skill, neuromuscular skill and storage of elastic energy are important. Work economy or work efficiency is the element within the endurance performance that seems to be able to change with certain strength parameters.

Strength training

The main reasons why endurance athletes regularly do not use strength training is that they 1. expect muscular hypertrophy and thus increased weight, and 2. claim that the strength requirements are so small that there is no need for muscular strength, and 3. have to devote their time to improving endurance performance.

Strength is defined as the integrated result of several force-producing muscles performing maximally, either isometric or dynamic during a single voluntary effort of a defined task. Typically, maximal strength is defined in terms of one repetition maximum (1RM) in a standardized movement, as for example the squat exercise. Research within the strength training area is equivocal, often because of differences in measurement techniques. Traditionally a lot of research has been conducted using isometric measures or isokinetic movements. Both of these techniques have limited interest in terms of prediction value for dynamic sports or everyday movements. The development of training methods has traditionally been based upon specificity principles, and training is supposed to meet specificity in the sport itself in terms of contraction type, contraction force, movements and velocity. A logical conclusion from a specificity approach would be that the sport itself represents the most efficient strength training mode, which is obviously not correct. Two different mechanisms, muscular hypertrophy and neural adaptations may be the principal cause for development of muscular strength.

Muscular hypertrophy is an effect of strength training, and there is a connection between cross-section area of the muscle and its potential for force development. This increase is associated with a large increase in the myofibril content of the fibers. During systematic strength training over a period of time, hypertrophy will be present for all muscle fiber types. Several studies show that the fast-twitch fibers have the greatest hypertrophy. In several sports, increased body weight due to hypertrophy is not desirable because the athlete will have to transport a higher body mass. In addition, increased muscle mass does not necessary increase the high velocity strength. Tesch and Larson (1982) reported an impaired ability to develop torque at high velocity in bodybuilders, in comparison to a reference group of competitive weight lifters. Typically bodybuilder-training practices include a great volume of high resistance, slow velocity movement to promote the hypertrophy effect. Methods for developing muscular hypertrophy often used are 8-12 repetitions with submaximal resistance (60-90 % of maximal dynamic strength) in several series (Tesch 1992). The execution of the exercises changes from slow to fast, and particularly the eccentric phase is slow. One goal using this training is to get the muscles totally exhausted.

During the last years the focus of strength training has turned to the area of neural adaptations. The term "neural adaptations" is a broad description involving a number of factors, such as increased neural drive (Aagaard et al. 2002), selective activation of motor units, synchronization, selective activation of muscles, ballistic contractions, increased rate coding (frequency), increased reflex potential, increased recruitment of motor units and increased co-contractions of antagonists (Behm 1995). A notable part of the improvement in the ability of lifting weights is due to an increased ability to coordinate other muscle groups involved in the movement, such as those which stabilize the body (Rutherford and Jones 1986). To develop maximal force a muscle is dependent on as many active motor units as possible. In a maximal voluntary contraction the small oxidative fibres are recruited first and the fastest glycolytic fibers are recruited last in the hierarchy. The central nervous system recruits motor units by sending nerve impulses to the motor neuron. The increased rate coding contributes to increased potential for force development (Sale 1992). An increased activation of the muscle may be due to a lower threshold of recruitment and an increased rate coding. Behm and Sale (1993) suggest two major practical principles for maximal neural adaptation. To train the fastest motor units, which develop the highest force, one has to work against high loads (85-95 % of 1RM) which guarantee maximal voluntary contraction. Maximal advantage would be gained if the movements were trained with a rapid action, in addition to the high resistance. As a method to increase the rate of force development, which is based upon neural adaptations, Schmidtbleicher (1992) suggests dynamic movements with a few repetitions (3-7). The resistance should range from submaximal to maximal (85-100% of 1RM), with explosive movements. This may give raise to neuromuscular adaptation with minimal hypertrophy (Almåsbakk and Hoff 1996).

There has been suggested that the intent to make a high-speed contraction may be the most crucial factor in velocity specificity (Behm 1995). Overall, findings from Almåsbakk and Hoff (1996) point to the development of coordination as the determining factor in early velocity-specific strength gains. Jones and Rutherford (1987) have showed an experimental gain in 1RM of 200%, only followed by a 5% and barely significant hypertrophy. Hoff et al. (2001) showed a 1RM gain in well trained subjects of 35% without changes in weight or size, showing that neural adaptations are not only prevalent in the early stages of strength training.

Strength training effects on endurance performance

The effect of combined strength- and endurance training on physical performance has been a popular research topic in the last decade. It is concluded that endurance training inhibits or interferes with strength development in several studies (Chromiac and Mulvaney 1990, Dudley and Djamil 1985, Hennessy and Watson 1994, Hickson 1980, Kraemer et al 1995). Few studies have, however, examined the impact of strength training on endurance performance. Hickson et al (1988) reported a 27 % increase in parallel squat 1RM after 10 weeks of maximal strength training using squats and three other supplement exercises. $V\mathrm{O}_{2max}$ was unchanged, while short term endurance (4-8 minutes) measured as time to exhaustion during treadmill running and on a bicycle ergometer, increased by 13 % and 11 % respectively.

Johnston et al (1997) were training 6 female runners using 14 different strength exercises. During the intervention period 1 RM parallel squat changed from 58.3 to 81.8 kg. VO_{2max} was not changed during the intervention period, but running economy expressed as $\mathrm{mL} \cdot \mathrm{kg}^{-1} \cdot \mathrm{m}^{-1}$ improved. The experimental group gained weight at an average of 1.3 kg, probably from the 'bodybuilding' - like part of the training regime. Gained weight will overestimate improvements in running economy expressed as $\mathrm{mL} \cdot \mathrm{kg}^{-1} \cdot \mathrm{m}^{-1}$ (Bergh et al 1991, Helgerud 1994). There were no difference in oxygen uptake between the two groups at the submaximal tests, and the difference between the groups in calculated work economy thus has to be due to gained weight in the training group, emphasising the importance of allometric scaling when expressing work economy.

Paavolainen et al. (1999) made an explosive strength training intervention in a group of cross-country skiers. They replaced 32% of endurance training time in the experimental group with 30 to 200 contraction per training session and 5 to 20 repetitions per set, using light loads and high intensity in a variety of jumping exercises and sprints. They found no changes in strength in the experimental group, measured as maximal isometric strength, but a group by time interaction showed a significant difference from the control group as the control group reduced their strength. $V\mathrm{O}_{2max}$ changed in the experimental group from 67.7 to 70.2 $\mathrm{mL} \cdot \mathrm{kg}^{-1} \cdot \mathrm{min}^{-1}$. Improvements in 5km run were shown as group by training interaction, but a correct interpretation is difficult. The experimental group showed an improvement in running economy expressed as $\mathrm{mL} \cdot \mathrm{kg}^{-1} \cdot \mathrm{m}^{-1}$ at a standard velocity. As changes occurred both in $V\mathrm{O}_{2max}$ and in bodyweight (1.2 kg between groups) from pre to posttest, there is a question how much of the reduced oxygen cost per meter is caused by running economy improvements. Nevertheless, along with other studies, this seems to be an indication that power enhancement might improve work economy.

Bishop et al. (1999) made a 12 weeks maximal strength training intervention in a group of female cyclists (n=14) with a $V\mathrm{O}_{2max}$ of 48.2 $\mathrm{mL} \cdot \mathrm{kg}^{-1} \cdot \mathrm{min}^{-1}$. The strength intervention was carried out twice a week using a resistance machine, and three different training protocols ranging from 50 to 80% of 1RM and from 15 to 5 repetitions. 1RM in squat strength in the resistance machine increased with 35.9%, body weight increased in the experimental group with 0.9 kg, but no changes was observed in any of the dependant variables VO_{2peak}, LT or performance in a one hour cycling test. Their conclusion is that factors other than the increase in leg strength per se may be responsible for the previously reported improvements after resistance training.

In line with several other experiments in this type of research, an intervention consisting of different training regimen in the same experimental group makes it difficult to trace physiological mechanisms behind changes in dependant variables.

Body builder training vs. Maximal strength training effects on strength and work economy

Hoff et al. (2006) compared body builder training (10 repetitions maximum in 4 and 5 sets, slow execution) designed for hypertrophy responses in one legged leg extension and maximal strength training (MST) (5 repetitions maximum in 4 sets with emphasis on maximal mobilisation of force in the concentric action) in the other leg, matched for total work, in nine male subjects, 3 times per week for 8 weeks. 1RM increased more in the MST trained leg by 47.9 vs 32.6 % and also Rate of force development (RFD) increased significantly more. Work economy in one-leg cycling in the single leg knee extension ergometer (Andersen and Saltin 1985) was improved in both legs, but significantly more in the MST leg (19 vs 24%). No difference was evident in thigh volume, or body mass, but the cross sectional area of muscle fibers from m. vastus lateralis showed an increase in the body builder trained leg.

Upper body work economy and performance.

If the training regimen used by Behm and Sale (1993) and Almåsbakk and Hoff (1996) proved effective based on co-ordination and neural adaptations rather than muscle hypertrophy, the most valid argument from endurance training, that strength training increases body weight and thereby might impair endurance performance, might not be a valid one.

Our research group has performed 3 maximal strength training intervention studies using well trained cross-country skiers as subjects, in double poling (Hoff et al. 1999, 2002, Østerås et al. 2002). Maximal strength training was 3 sets with 5 repetitions using high loads and emphasis on maximal mobilization of force, 3 times a week in a cable pulley. 1RM improved significantly from 10 to 20% and rate of force development improved by ~50%. No change was apparent in VO_{2peak} or LT, whereas double poling work economy improved by 9 to 27%, and time to exhaustion at maximal aerobic velocity increased by 60-120 %. The 3 series of 6 repetitions strength training regime only employed 15 minutes per session. A shift in the power-load and load-velocity relationship to the right is showed (Figure 1).

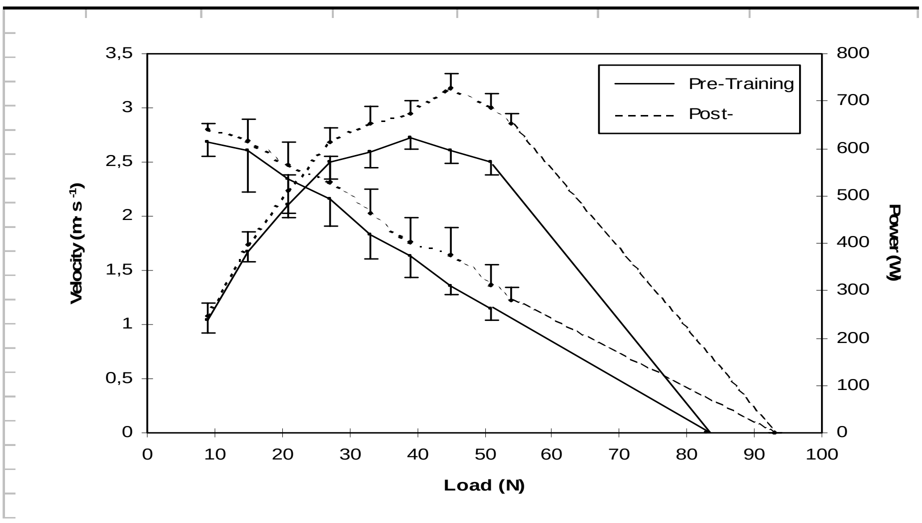

Figure 1. Changes in the load/velocity and power/load relationship after maximal strength training with emphasis on fast mobilization of force (mean and SD).

Peak force employed at maximal aerobic velocity in double poling was equivalent to 25.9% of 1RM pre and 21.1% post training whereas no change was observed in double poling frequency. Power production was enhanced at all loads higher than 10% of maximal voluntary contraction (MVC). In all these studies, improved rate of force development and power production from a maximal strength training regime with emphasis on mobilization of force improved work economy, correlated with a shift in the power/load and load/velocity relationship.

Running economy

Hoff et al. (2002) carried out an experiment similar to the previous studies, but this time training legs, and following running endurance, using highly trained competitive cross-country skiers and runners as subjects (n= 18, $\dot{V}O_{2max}$: 69.2 mL · kg^{-1} · min^{-1}). The half-squat training regime consisted of 4 series of 6 repetitions using heavy loads, increased every time the training regime could be carried out. Emphasis was put on maximal mobilization of force in the concentric part of the exercise. The training regime was carried out 3 times a week for 9 weeks. The training group changed their 1RM from 126.1 to 160.0 kg, no change took place in the control group. Body mass did not change from pre to post-test. Running economy was tested at both 6 degrees and 12 degrees inclination at Lactate threshold. Running economy changed significantly by 4.7% from 0.962±0.040 to 0.919±0.048 mL · kg$^{-0.75}$ · m^{-1}, when running at 6 degrees inclination. The control group showed no change in running economy. When running at 12 degrees inclination the experimental group enhanced their running economy significantly more than at 6 degrees, by 8%. $\dot{V}O_{2max}$ and LT was reduced both for the experimental group and the training group during the experimental training period due to out of season, but a performance test, running at maximal aerobic velocity to exhaustion showed a 22 % improvement from 497 sec to 641 sec.

In a group of 2nd division male soccer players a similar training regime using 4x4 reps gave an increase in half squat strength of 32%, and improved running economy at LT from 0.788 to 0.751 mL · kg$^{-0.75}$ · m^{-1} (4.7 %) at 5% inclination, as well as 5.3% improvement in 10m sprint and 5% in jumping height with no change in body mass (Hoff et al. 2002).

In a football (soccer) team at Champions League level a combined strength and endurance training intervention 3 times a week for 8 weeks using 4x4 reps MST training improved half squat 1RM from 115 to 176 kg. Aerobic endurance training was performed in the same sessions using 4x4 min interval training at 90-95% of maximal heart rate. Running economy improved by 3.7% and 10m sprint by 5%. VO_{2max} increased from 60.5 to 65.1 mL · kg^{-1} · min^{-1}.(Helgerud et al 2002).

In professional football (soccer) players in a youth team (17.5 years) in season, a similar combined MST and endurance intervention using a soccer specific track with ball (Hoff, Helgerud 2004) showed an improved 1RM of 30 kg, a 28% improved RFD and improved running economy from 0.84 to 0.81 mL · kg$^{-0.75}$ · m^{-1}, as well as 0.04 sec improvement in 10m sprint and 4 cm improved jumping height and an improved VO_{2max} from 67.7 to 72.8 mL · kg^{-1} · min^{-1} (McMillan et al. 2005), whereas an endurance training intervention using the same soccer specific track, giving similar improvements in VO_{2max} did not change running economy (McMillan et al. 2005b).

4 male and 4 female runners with VO_{2max} of 63.4 and 59.3 mL · kg^{-1} · min^{-1} respectively trained half squats 4x4 reps MST 3 times per week for 8 weeks and improved 1RM by 33% and RFD by 26% with no change in bodyweight, VO_{2max} or LT. Running economy at LT and 1.5% inclination improved by 5% from 0.679 to 0.645 mL · kg$^{-0.75}$ · m^{-1} and time to exhaustion on maximal aerobic velocity improved from 336.9 to 408.5 sec (Støren et al. 2006).

Like upper body work economy, also running economy (C_R) seems to be improved with maximal strength training with emphasis on fast mobilization of force. The improvement in C_R seems, however, to be smaller in the bigger and weight bearing leg and hip muscles. This might be due to the fact that they are initially better trained during daily use. The improvements seem to be better at a higher workload, as C_R when running at 12 degrees inclination show a higher improvement than at 6 degrees. As shown in fig. 1 the improvements are also higher in the load-velocity and the power-load relation as the load becomes higher.

Cycling economy

When Hickson et al. (1988) showed an improved time to exhaustion after strength training with no change in VO_{2max}, according to the physiological model the reason might be improved cycling economy or improved LT or, since they worked only 4-8 minutes, to anaerobic capacity.

Following the strength training approaches outlined above, Paton and Hopkins (2005) showed an improved cycling efficiency of 3.2% from a 12 sessions strength training intervention in competitive cyclists, although using a combination of explosive and high resistance training.

Aagaard et al. (2006) carried out a training intervention in high level cyclists using endurance and strength training in one group and endurance training only as control. Strength training was 12 weeks of 5-6 RM leg extention and flexion in 4 exercises after a preparatory period of 4 weeks. The endurance and strength group improved maximal strength and RFD as well as long term cycle performance (45 min) over the endurance only group, whereas both groups improved short term cycling performance (5 min all out). The strength training increased type IIa muscle fibre content leading to a more endurant type II muscle fibre profile. Increased ratio of relaxation-to-activation time (reduced ”duty factor”) due to the increased RFD might lead to increased time for restitution in each pedal revolution and thus improved circulation, in line with the mechanisms indicated from upper body strength training.

Conclusions

From the reviewed research there seem to be conclusive evidence that work economy in an aerobic endurance performance is enhanced from a maximal strength training regime with emphasis on neural adaptations. This type of training uses high loads, few repetitions and maximal mobilization of force in the concentric part of a movement. The highest training response seems to be on rate of force development, but also peak force and 1RM show significant changes. 1RM improvement from body builder training alone seems not to have a similar effect, at least partially explaining the differences in findings from previous research. Improved work economy seems to be due to increased power production and a shift in the power-load and load-velocity relationship as well as increased portion of type IIa fibers. Further research is needed to investigate whether this alters vascular blood flow, and thus have a circulatory component.

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