

**INFLUENCE OF TIME-OF-DAY-SPECIFIC SAME-SESSION  
COMBINED ENDURANCE AND STRENGTH TRAINING ON  
MAXIMAL AND SUBMAXIMAL ENDURANCE  
PARAMETERS**

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## ABSTRACT

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Endurance and strength training are often performed concurrently by both elite athletes and recreational individuals. The question of whether the order of exercises or training at certain daytimes yields to different adaptations in endurance and strength parameters, when endurance and strength training are combined into a single training session, has received limited scientific attention. Moreover, effects on cardiorespiratory and neuromuscular variables after same-session concurrent training have shown conflicting results, particularly regarding exercise sequence or time-of-day characteristics. The purpose of the present study was to examine the effect of time-of-day-specific same-session combined endurance and strength training on maximal and submaximal endurance parameters.

52 previously physically active men (age 18-40) completed the study that consisted of a progressive 24-week same-session endurance and strength training program. Subjects were assigned into one of the four training groups: morning training groups performing endurance training before strength training in the same session (mE+S) or performing the opposite training order (mS+E) and evening training groups performing either one of the training sequences (eE+S or eS+E). A fifth group served as a control group (CON) that continued their habitual physical activity. Morning and evening measurements for endurance (maximal graded cycling test) and strength (dynamic leg press) performance were carried out at the beginning, at week 12 and after the intervention at week 24.

The primary results showed significant increases in endurance and strength parameters throughout the 24-week intervention period in maximal oxygen consumption (morning measurements: mE+S, mS+E  $p < 0.01$ ; eE+S  $p < 0.001$ ; eS+E  $p < 0.05$ ; at evening: mE+S, mS+E  $p < 0.05$ ; eE+S  $p < 0.01$ ) except for eS+E at the evening tests ( $p = 0.239$ ) and in maximal work rate (at morning: mE+S, eE+S  $p < 0.001$ ; mS+E, eS+E  $p < 0.01$ ; at evening:  $p < 0.001$ ). Significant between-group differences in endurance performance were reported in morning tests between eE+S vs. eS+E ( $VO_{2max}$ : 13.3% vs. 4.3%,  $p < 0.05$ ;  $W_{max}$ : 23.9% vs. 13.7%,  $p < 0.05$ ) and when sorted by training order E+S vs. S+E ( $VO_{2max}$ : 12.1% vs. 5.7%,  $p < 0.05$ ;  $W_{max}$ : 22.0% vs. 15.9%,  $p < 0.05$ ). Dynamic 1RM leg press increased significantly throughout the intervention (at morning and evening tests: mE+S, eE+S, eS+E  $p < 0.001$ ; mS+E  $p < 0.01$ ).

In conclusion, this study demonstrated that 24 weeks of time-of-day specific same-session combined endurance and strength training led to significant improvements both in endurance and strength variables. Training sequence influenced positively endurance performance when endurance training preceded strength training. Time-of-day effects and preferable training times for endurance improvements were not confirmed by our findings.

**Keywords: combined training, order effect, time-of-day effect, maximal oxygen consumption, strength**

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## LIST OF ABBREVIATIONS

1RM – One repetition maximum

bLA – Blood lactate

CSA – Cross-sectional area

CON – Control group

E – Endurance training

e – Training in the evening

E+S – Combined endurance and strength training, endurance prior to strength

eE+S – Combined endurance and strength training in the evening

eS+E – Combined strength and endurance training in the evening

EVE – Evening group

HR – Heart rate

m – Training in the morning

mE+S – Combined endurance and strength training in the morning

MOR – Morning group

mS+E – Combined strength and endurance training in the morning

RFD – Rate of force development

RPE – Rate of perceived exhaustion

rpm – Revolutions per minute

S – Strength training

S+E – Combined endurance and strength training, strength prior to endurance

SD – Standard deviation

TTE – Time to exhaustion

VO<sub>2</sub> – Oxygen consumption

VO<sub>2</sub>max – Maximal oxygen uptake

W<sub>max</sub> – Maximal work rate

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# 1 INTRODUCTION

Both elite athletes and recreational individuals often perform combined endurance and strength training either within a same-session or in different session or days. A great number of sports require both components for optimising sports-related performance (García-Pallarés et al. 2009; Nader 2006).

From a health-promoting point of view, combined endurance and strength training is considered as a convenient and time-efficient training approach, particularly within a same session, that delivers similar benefits as if separately train endurance and strength (Dolezal & Potteiger 1998; Fyfe et al. 2014; Ghahramanloo et al. 2009). The combination of those two training modalities is investigated by a number of studies reporting various outcomes after the application of a combined training program. The term “interference effect” is often mentioned, which displays the occurrence of a compromised development or adaptation of either endurance or strength performance when training is concurrently performed (Hickson 1980; Wilson et al. 2012). However, literature is vague about its influence whether it may hold true or not and further attraction is given to the possible impact of exercise sequence. It is presumed to take the order effect into consideration, since it can ensure optimal strength and endurance enhancements (Davis et al. 2008a; Izquierdo-Gabarrén et al. 2010).

While the order might be important to influence or modulate interference (Fyfe et al. 2014; Izquierdo-Gabarrén et al. 2010), investigations cannot represent clear answers leading to inconclusive and equivocal findings yet, when time-of-day effects are examined on endurance outcomes. The time-of-day effects are examined with regard to separate endurance or strength training applications, but only a limited amount of research has examined the impact of time-of-day specificity in combination to intra-session exercise order and combined training protocols.

Therefore, the purpose of the present study was to examine the effect of time-of-day-specific same-session combined endurance and strength training on maximal and submaximal endurance parameters.

## **2 SEPARATE ENDURANCE AND STRENGTH TRAINING**

It is widely agreed within sport sciences that the application of either endurance or strength training leads to a variety of outcomes, which has been examined over several decades. The different types of training programs and activities performed greatly affect the degree of physiological adaptations and its performance outcomes in response to different stimuli and environmental changes (Hawley 2009; Pugh et al. 2015). During the process of training plans and design, the appropriate use of training variables including the frequency, intensity and volume of exercise, is needed in order to evoke suitable training effects and to avoid overtraining (García-Pallarés et al. 2009).

### **2.1 Endurance training**

Endurance can be defined as the ability to resist fatigue and persevere a given effort over a period of time (Hollmann & Hettinger 1976). It represents one extreme of physical activity, in which repeated, continuous skeletal muscle contractions are performed over several minutes up to a prolonged period (e.g., several hours) at various intensity levels, supporting and improving the capacity to sustain repetitive high-intensity, low-resistance exercise such as cycling, running and swimming (Hawley 2009; Nader 2006; Tanaka & Swensen 1998). It is well established that endurance training promotes general health and cardiovascular fitness, as it affects weight loss, lipid profiles and aerobic capacity (Chtara et al. 2005, 2008; Davitt et al. 2014; Dolezal & Potteiger 1998; Psilander et al. 2014; Wang et al. 2011). Physiological adaptations are seen at both central (cardiorespiratory) and peripheral (local musculature) levels (Costill et al. 1991; Coyle et al. 1991; Holloszy & Coyle 1984; Hoppeler et al. 1985; Neary et al. 2002) and its particular location of adaptation appears to shift on the basis of training intensity and mode of exercise (figure 1) (Docherty & Sporer 2000; Irving et al. 2015; Psilander et al. 2014). Regarding the peripheral level, it is established that slow-twitch muscle fibres feature greater capillary density and oxidative potential than fast-twitch fibres (Costill et al. 1976; Hawley 2002; Saltin et al. 1977). In well-trained endurance athletes, a strong relationship has been observed between years of endurance training and percentage of type I muscle fibres (Coyle et al. 1991). The effects of



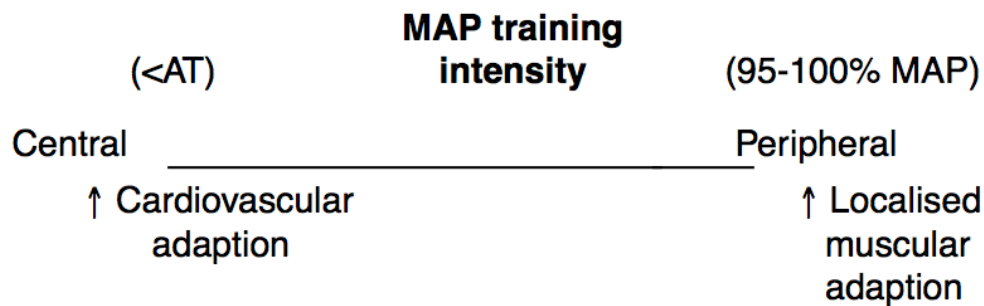


FIGURE 1. Intensity continuum of maximal aerobic power (MAP) training and the primary location of adaptation. AT = anaerobic threshold. (Docherty & Sporer 2000).

aerobic exercise on the muscle fibre composition are versatile. Several studies reported growth in type I fibre percentages after endurance training (Gollnick et al. 1973; Sale et al. 1990a; Simoneau et al. 1985), whereas others observed no or decreasing effects on slow-twitch fibres (Fitts & Widrick 1996; Kraemer et al. 1995; Tanaka & Swensen 1998). The interconversion from type II to type I muscle fibres also remains unclear (Hawley 2002; Kraemer et al. 1995), but it seems to be more likely to monitor changes within the fast-twitch fibres. Following endurance training, it appears to have effects on the ratio of type IIa and IIb muscle fibres suggesting a decrease in type IIb while increasing type IIa fibres (Hansen et al. 2005; Kraemer et al. 1995; Saltin et al. 1977; Tanaka & Swensen 1998). The prior training status of the subject (e.g., athlete vs. non-athlete) might affect the outcome regarding the morphological transformation of the fibre type and fibre area within the musculature (Kraemer et al. 1995; Tanaka & Swensen 1998).

From the molecular perspective of adaptation, the gene expression, allowing the accumulation of specific proteins by a given endurance-training stimuli, is essential involving increases in net protein synthesis in the mitochondrial subfraction (Hansen et al. 2005; Hawley et al. 2009; Wilson et al. 2012). Enhanced oxygen kinetics, substrate transport and muscle buffering capacities are also affecting endurance performances (Holloszy & Coyle 1984), but the main factor elicited by aerobic exercise is the increased oxidative energy capacity. This is predominately initiated through increased vascularisation and mitochondrial biogenesis consisting of increased mitochondrial density and oxidative enzyme activity (Hawley 2009; Holloszy & Coyle 1984; MacNeil

et al. 2014; Yan et al. 2012). The implication of endurance training evokes increased number of capillaries and elevates the activity of enzymes such as 3-hydroxyacyl-CoA dehydrogenase (HAD) and citrate synthase (CS) (Gollnick & Saltin 1982; Hansen et al. 2005; Hawley 2002; Holloszy & Booth 1976). It eventually emerges in a slower rate of muscle glycogen and blood glucose utilization and enhanced fat oxidation while decreasing lactic acid accumulation at submaximal exercise contributing to an enhanced endurance performance (Bassett & Howley 2000; Gollnick & Saltin 1982; Hawley 2009; Holloszy 1967; Holloszy & Coyle 1984; Saltin & Rowell 1980).

When it comes to indicate endurance performance, maximal oxygen uptake ( $VO_{2max}$ ) is mentioned as one of the major and most frequently used determinants in the field of sport sciences (Bassett & Howley 2000; di Prampero 2003; Levine 2008; Nunes et al. 2009). It is used as an invariable parameter that defines the capability of the cardiorespiratory system to transport oxygen to various tissues of the body (Hawkins et al. 2007). As a matter of course, endurance exercise induces systemic changes such as improved maximal oxygen uptake (Hansen et al. 2005). Åstrand & Rodahl (1970) illustrated the training effect, in which the percentage of maximal aerobic power utilised during prolonged work is increased on the basis of an increased  $VO_{2max}$  (figure 2). The maximal oxygen consumption sets the upper limit of intensity for prolonged steady-state exercise (Rønnestad & Mujika 2014). However, it does not serve as a sole index to endurance performance. More importantly, the greatest  $VO_{2max}$  does not necessarily equal best aerobic capacity, but high  $VO_{2max}$  values are required to achieve distinctive endurance results (Bassett & Howley 2000; Impellizzeri et al. 2005; Rønnestad & Mujika 2014). As seen particularly in elite endurance athletes, similar (high)  $VO_{2max}$  levels in individuals can have differing abilities during the competition and may not display the true endurance capacity of the athlete (Beattie et al. 2014; Nummela et al. 2006). Besides the physiological features influences, such as lactate thresholds, economy or efficiency, entail differences in aerobic performance within individuals. Those factors, additionally to  $VO_{2max}$ , cause more than 70% of inter-individual variances in long-duration endurance performances (Fontana et al. 2009; Horowitz et al. 1994; Noakes 2008; Sunde et al. 2010). Regarding training applications in endurance performance, economy and assessments that affect endurance-specific muscle power component, for instance, velocity or power at  $VO_{2max}$  or maximal anaerobic running

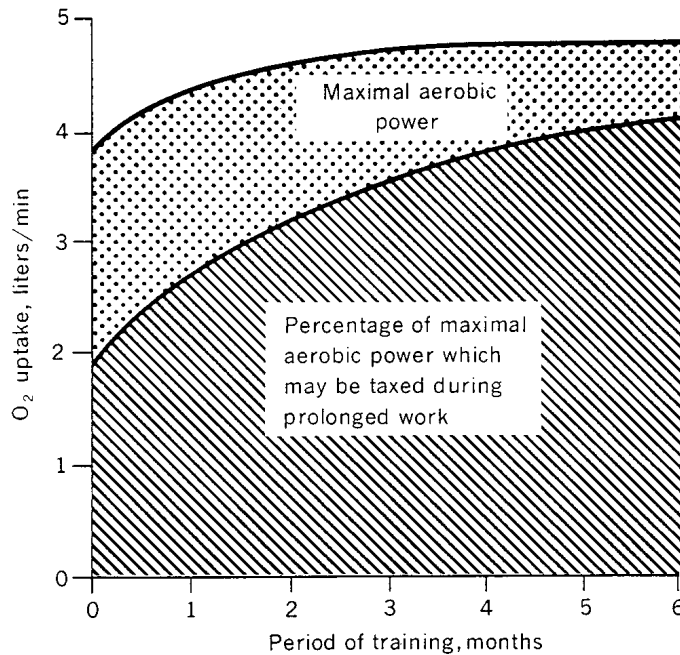


FIGURE 2. Training causes an increase in maximal oxygen uptake. With training a subject is also able to tax a greater percentage of his/her maximal oxygen uptake during prolonged work. (Åstrand & Rohdahl 1970).

velocity, might be taken into consideration, since they seem to be superior performance indicators in elite population (Beattie et al. 2014; Lucia et al. 1998; Noakes et al. 1990; Paavolainen et al. 2000). The eventual endurance performance undergoes processes that include complex interaction of physiological and biomechanical components (Beattie et al. 2014). Figure 3 illustrates the multiple physiological factors, which are interacting with performance velocity or power in endurance athletes (Joyner & Coyle 2008).

## 2.2 Strength training

Strength training is regarded as an effective method to improve the functional capacity of the neuromuscular system (Deschenes & Kraemer 2002) and general adaptations to exercise are highly dependent on the performed type of activity and mode of exercise (Holloszy & Booth 1976; Irving et al. 2015; Jones et al. 2013; McDonagh & Davies 1984). Traditionally seen, resistance training incorporates low repetition muscular contractions or short duration activities with high loads or maximal exercise

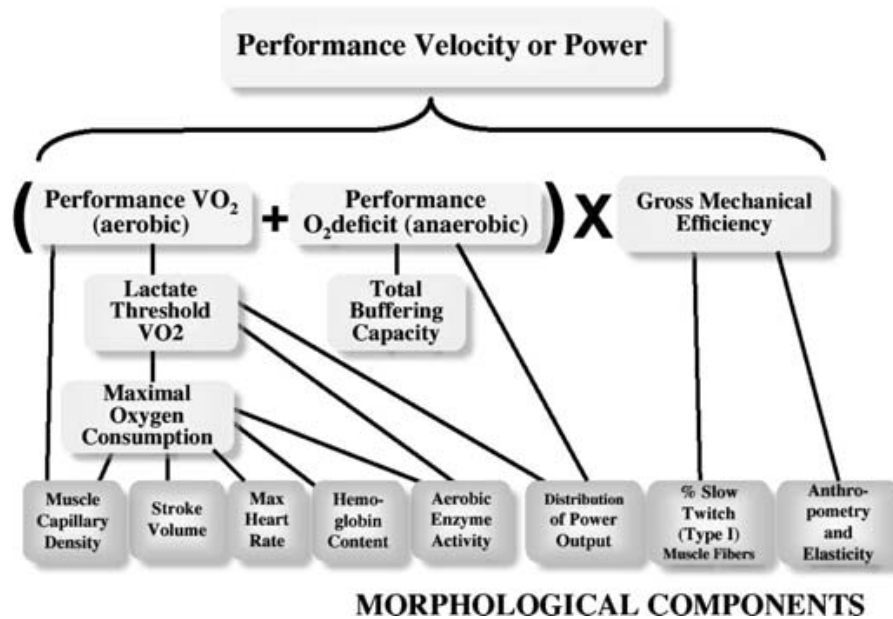


FIGURE 3. Overall schematic of multiple physiological factors that interact as determinants of performance velocity or power output in endurance athletes. (Joyner & Coyle 2008).

intensities (Nader 2006; Tanaka & Swensen 1998). It has been demonstrated to result in considerable improvements in strength of the trained muscle groups when intensity and duration of strength training are sufficient (Hoff et al. 2002; Häkkinen et al. 2003; Paavolainen et al., 1999; Sillanpää et al. 2008; Wilson et al. 2012). The application of strength training evokes multiple benefits in terms of health, fitness and performance as it largely affects strength and lean body mass (LBM), fat loss and ameliorations in lipid profiles and it supports the prevention, delay or reverse the onset of age-related skeletal muscle deficits (Chtara et al. 2008; Davitt et al. 2014; Ghahramanloo et al. 2009; Lindegaard et al. 2008; Irving et al. 2015; Poehlman et al. 2002; Sarsan et al. 2006). Thus, the capacity to perform high-intensive and high-resistance exercises of a single or relatively low repetitions is increased due to strength training (Nader 2006). Studies proved significant meliorations in maximal strength, e.g., in terms of one repetition maximum (1RM), improved power and rate of force development (RFD) or in physiological adaptations like increases in muscle cross-sectional area (CSA) in upper body as well as in lower body after single-mode resistance or strength training (Barrett O'Keefe et al. 2012; Chtara et al. 2008; Davitt et al. 2014; Häkkinen et al. 2003; LeMura et al. 2000; Leveritt et al. 2003; Rønnestad et al. 2012). Heavy resistance training stimulates myofibrillar proteins, which are responsible for muscle hypertrophy,

strength and power and further culminating increases in maximal strength (Fry 2004; Hawley 2009; Tesch 1988; Wang et al. 2011). Sale (2008) described the relative roles of neural and muscular adaptation to resistance training and offers the factors, which broadly characterize the expression of human strength (figure 4). In the early phase of training, neural adaptation is predominantly affecting strength adaptations, but it may not be the only factor to supply to strength increases. Improved strength-related performances are accomplished through neuromuscular learning, increased fibre-recruitment synchronicity and with chronic exercise, muscular adaptation occurs to maintain cellular homeostasis during future bouts (MacNeil et al. 2014; McDonagh & Davies 1984; Moritani & de Vries 1979; Nader 2006). This is referred as a result of an integrated pattern of gene responses and coordinated molecular events that promote the enlargement of pre-existing muscle cells via the incorporation of additional myonuclei (Flück & Hoppeler 2003; Hawley 2009).

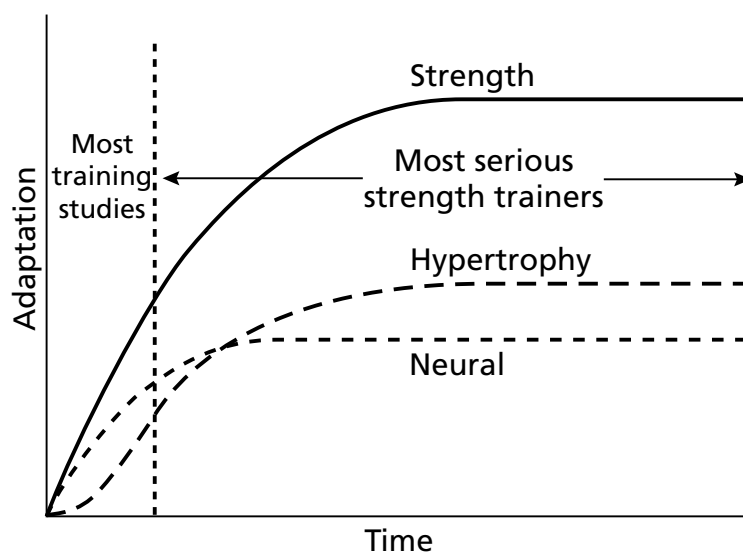


FIGURE 4. The relative roles of neural and muscular adaptation to strength training (Sale, 2008).

### 3 COMBINED ENDURANCE AND STRENGTH TRAINING

The combination of endurance- and strength-based exercise within a training program is termed as concurrent or combined training (Hawley 2009; Psilander et al. 2014; Wilson et al. 2012). The application of combined training has been attracting sport sciences' attention over many years resulting in divergent outcomes after a great variety of investigations and studies. Large numbers of sport disciplines require both components of endurance and strength training in order to optimise (discipline-specific) performance (García-Pallarés et al. 2009; Nader 2006). A hypothetical model of a strength-endurance continuum (SEC) was developed by Nader (2006) to display different sport activities in the range of endurance, strength, duration and energy metabolism in the context of sports performance (figure 5).

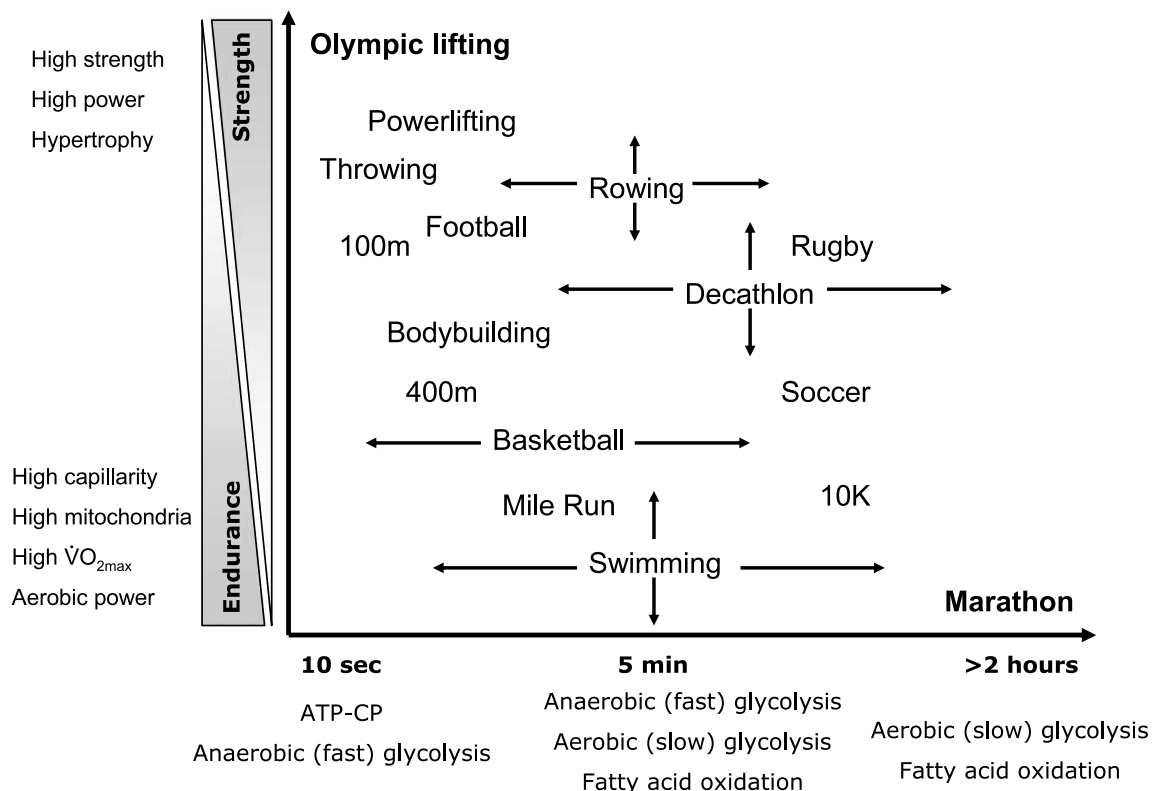


FIGURE 5. The strength-endurance continuum (SEC) is depicted in the context of sports performance and its relation to duration and energy metabolism. (Nader 2006).

The training effects of separate aerobic or resistance training are well-known and have been mentioned previously. But there is evidence that employing endurance and strength concurrently may lead to the occurrence of a compromised development or adaptation of either strength or endurance parameter. This effect is known as the “interference effect”, which was proposed by Hickson in 1980 and has been further investigated since during concurrent training applications.

From a molecular standpoint, it appears to be incongruous to expect compatibility of strength and aerobic training, because myofibrillar proteins (actin and myosin) are stimulated via resistance training, whereas endurance training increases mitochondrial proteins (Hawley 2009; Wilson et al. 2012). Specific combined training might increase molecular interference indirectly via substrate depletion or directly through the increase of activity of proteins acting to hinder protein synthesis and/or stimulate protein breakdown (Fyfe et al. 2014; Nader 2006). However, several investigations found no or minor effects on mitochondrial enzyme activities when endurance and strength were trained concurrently (Bishop et al. 1999; Bell et al. 2000; Psilander et al. 2014).

Interfering effects in leg strength endurance have been perceived when intermittent aerobic exercise is applied and when peripheral fatigue in the same muscle group is produced (de Souza et al. 2007). However, Davis et al. (2008a; 2008b) investigated men and women over 9 and 11 weeks (3 training days per week), respectively, training either serial or integrated concurrent training. Neither endurance (i.e.,  $VO_2\text{max}$ ) nor strength (i.e., 1RM) variables were inhibited by the combined training program. At continuous low intensity and moderate duration aerobic training does not seem to produce interference on the subsequent strength session (de Souza et al. 2007). But high training intensities and high training volumes have been considered to increase the interfering effect (Hickson 1980; Wilson et al. 2012) influencing strength measures, maximal power or rate of force developments (RFD) (Cadore et al. 2010; Hickson 1980; Häkkinen et al. 2003; Kraemer et al. 1995; Wilson et al. 2012).

General strength development and adaptation of single-mode resistance exercise could be compromised by endurance training due to its mode of training (cycling vs. running) or due to the particular movement applied in the endurance exercise (Bell et al. 2000; Gergley 2009; Pugh et al. 2015). For instance, while the quadriceps produces primarily

concentrically movement during leg press resistance and cycling, treadmill exercises emphasizes the more eccentrically movement in the muscle groups, that eventually implicates the attenuation of strength development (Gergley 2009). Furthermore, the residual fatigue from a previous endurance training session may cause strength impairments in the subsequent strength performance measures (Cadore et al. 2012a; García-Pallarés & Izquierdo 2011). Jones et al. (2013) reported interference responses to strength after 6 weeks of training (3 days per week) because of the greater frequency of performed endurance training. Studies indicated that the derogation in strength development after combined training regimens might be hold to the training frequency (Chtara et al. 2008; McCarthy et al. 2002). This frequency factor was not supported in Davis et al. (2008b) over an 11-week period. After high training volumes (21-week training period), the concept of the universal nature of the interference effect regarding strength after concurrent training was not supported, however, interference was observed in explosive strength development (i.e., RFD) during S+E training (Häkkinen et al. 2003). It has been presumed that frequency in strength training can be low in previously untrained subjects.

There are multiple reasons for the appearance of the interfering effect, which are not yet precisely defined (García-Pallarés et al. 2009; Nader 2006; Wilson et al. 2012). Different dependencies are influenced by concurrent training, as Wilson and colleagues (2012) proposed that overall power or rate of force development might be a major indicator, which is prepossessed by concurrent training. Furthermore, the mode of endurance has been expected to influence strength parameters, such as in maximal force or hypertrophy (Gergley 2009; Wilson et al. 2012). With regard to resistance variables, residual fatigue caused by prior endurance exercises seems to be affecting the final strength performance (Fyfe et al. 2014; Izquierdo-Gabarren et al. 2010; Leveritt et al. 1999). While the order might be important to influence or modulate interference (Fyfe et al. 2014; Izquierdo-Gabarren et al. 2010), the greatest potential factors to evoke interference are seen in the framework of training. Coaches and researchers examined training programs, their designs and periodization including subjects (gender, training status), exercise mode, training duration, frequency, intensity and volume in order to adapt to the needs that enhance and maximise physiological adaptations and performance in both elements while minimising interfering effects and possible biological limitations (Baker 2001; de Souza et al. 2007; Docherty & Sporer 2000;



García-Pallarés et al. 2009; Izquierdo-Gabarren et al. 2010; Leveritt et al. 1999; Nader 2006; Sale et al. 1990a). There are plenty of different attributes that are contributing to the level of interference and those might explain the contradictory results when investigating the effects of combining endurance and strength training.

In endurance training programs, training at lower or moderate intensities for improvements at the anaerobic threshold (AT) level mainly induces central adaptations, while intensities for maximal aerobic power (MAP) or at  $VO_{2max}$  levels mainly induce peripheral adaptations. This is similarly adapted to strength training programs with showing either effects on the central level by maximum strength or power training ( $SPT_{max}$ ), or on peripheral levels by local muscle endurance (LME) or hypertrophy training (Docherty & Sporer 2000; García-Pallarés & Izquierdo 2011; Leveritt et al. 1999). The proposed model in figure 6 is based on those adaptations and presumes the optimal combination of endurance and strength training intensities to reduce or even avoid interference effects (García-Pallarés & Izquierdo 2011). The idea is to employ the

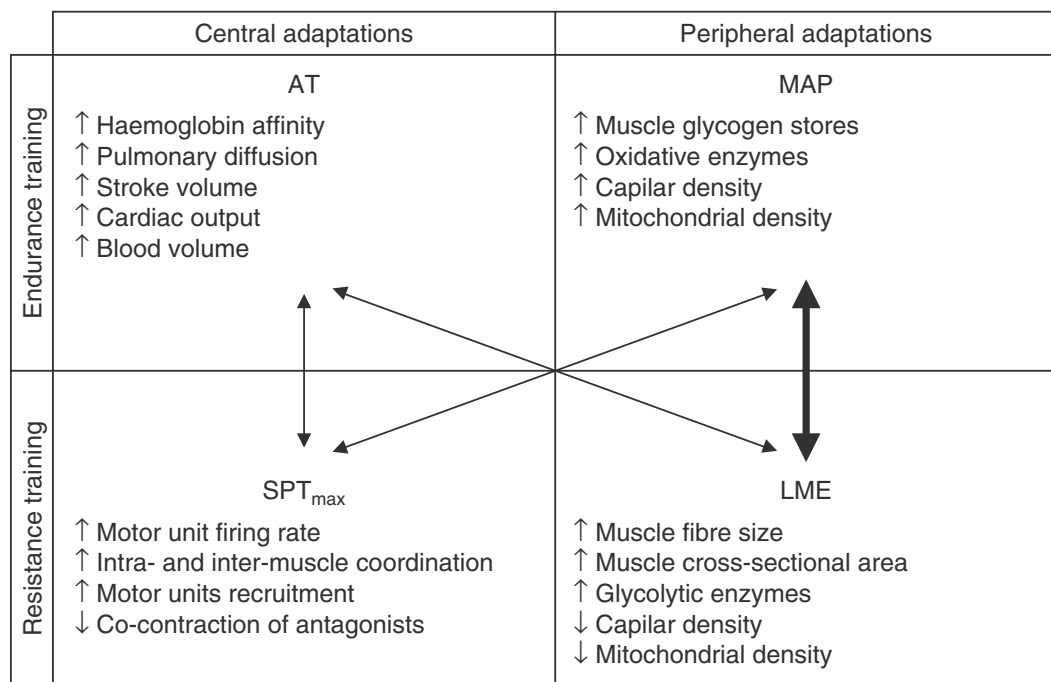


FIGURE 6. Optimal combination between resistance and endurance training intensities. AT=anaerobic threshold or lower endurance training intensities; LME=local muscle endurance training; MAP=maximal aerobic power;  $SPT_{max}$ =maximum strength and power training. (García-Pallarés & Izquierdo 2011).

suitable intensities in both resistance and aerobic training to diminish inhibiting performance outcomes. This model suggests the idea of rather combining low to moderate intensity training at AT levels in the endurance program with LME training during the resistance program to avoid interference and in contrast, combining MAP and  $SPT_{max}$ , which seems to be more suitable and causes less interference (Docherty & Sporer 2000; García-Pallarés & Izquierdo 2011; Leveritt et al. 1999).

From the health-promoting perspective, combined endurance and strength training is considered as a common and time-efficient training approach that yields similar benefits as seen when endurance or resistance is separately trained (Dolezal & Potteiger 1998; Fyfe et al. 2014; Ghahramanloo et al. 2009). Even though concurrent training might not provide the same results in endurance and strength as in the separate training mode, researchers preferred the combined mode of exercise due to its beneficial effects with regard to general health objectives (Cadore et al. 2010; Ghahramanloo et al. 2009; LeMura et al. 2000; Leveritt et al. 2003). Combining both types of training within a training session might not only be suitable for fitness enthusiasts or athletes (Sale et al. 1990b), but for sedentary or untrained individuals alike. Besides the reported benefits in strength and endurance parameters, it appears to have great impact on body composition, blood lipid characteristics and weight loss and thus, it seems to represent a more effective exercise program strategy when those benefits are desired (Davitt et al. 2014; Dolezal & Potteiger 1988; Ghahramanloo et al. 2009; LeMura et al. 2000; Leveritt et al. 2003; McCarthy et al. 1995; Wilson et al. 2012). Moreover, MacNeil et al. (2014) considered concurrent exercise as an effective modality for the rehabilitation of loss of skeletal muscle mass, maximum strength and peak aerobic capacity resulting from disuse.

### **3.1 Effects on endurance performance**

Various studies in sport-scientific research have been examined the impact on endurance performance after combined endurance and strength training and have been offered equivocal findings. Several investigations reported a reduction in aerobic capacity from combined training interventions (Gravelle & Blessing 2000; Hickson 1980; Izquierdo et al. 2005), while others noticed the opposite outcome showing mainly

positive effects in endurance (Chtara et al. 2005; Davis et al. 2008a; Davitt et al. 2014; Leveritt et al. 2003; Schumann et al. 2014a). Davis et al. (2008a) demonstrated discernible cardiovascular and cardiorespiratory adaptations after 9 weeks (men) to 11 weeks (women) of concurrent endurance and strength training in well-trained college athletes, which did not support any harmful or interfering effect on endurance. Furthermore, improvements in aerobic capacity were proposed by Chtara et al. (2005), especially when endurance training preceded strength training (E+S). However, the dependency of cardiorespiratory adaptations was based primarily on intensity, duration and frequency of (strength training) exercise (Chtara et al. 2005). Paavolainen et al. (1999) developed a hypothetical model representing the effect of strength training on endurance performance (figure 7). Especially, [running] economy and maximal velocity in the maximal anaerobic running test (MART) is influenced by strength training, which eventually leads to an improvement of the overall endurance performance. Based upon this model, Beattie et al. (2014) laid further emphasis to the potential benefits of strength training on endurance, including morphological factors, musculotendinous stiffness, motor unit recruitment and intra- and intermuscular coordination as influential parameters within neuromuscular capacities. Regarding elite athletes, it appears to be

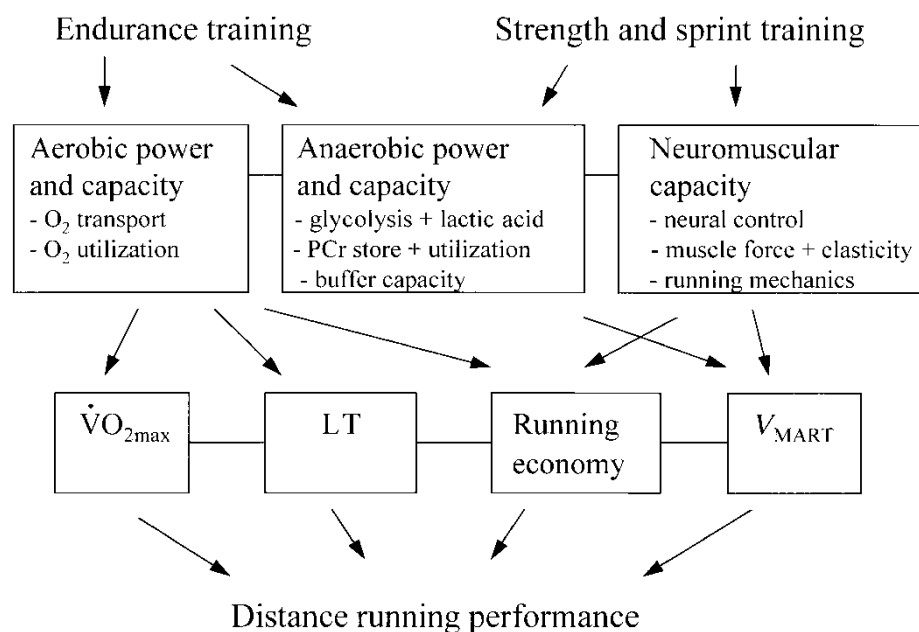


FIGURE 7. Hypothetical model of determinants of distance running performance in well-trained endurance athletes as influenced by endurance and strength training. LT=lactate threshold; PCr=Phosphocreatine;  $\dot{V}O_{2max}$ =maximal oxygen consumption;  $v_{MART}$ =peak velocity in MART. (Paavolainen et al. 1999).

decisive to investigate those indicators (economy, velocity and power at  $VO_{2max}$  and endurance-specific muscle power tests as MART) in order to precisely predict endurance performance (Beattie et al. 2014; Lucia et al. 1998; Noakes et al. 1990; Paavolainen et al. 2000). Apart from their influence on the cardiovascular system, those key variables are also believed to be partly dictated by the neuromuscular system (Beattie et al. 2014).

The improvements in endurance performance by including resistive strength training may be explained by the size of type I fibres and changes in type II subtype ratios and myofibril contractile properties, which more likely induce endurance enhancements (Aagaard et al. 2011; Chtara et al. 2005; Tanaka & Swensen 1998). This leads to the assumption that resistance training may be supportive in endurance performances. The particular effect of resistance training on endurance performance is further illustrated in figure 8 (Aagaard & Andersen 2010). It depicts the stimulatory effects (full lines) or potential interactions (dotted lines) between the described components that eventually affect short-term or long-term endurance performance after combined endurance and

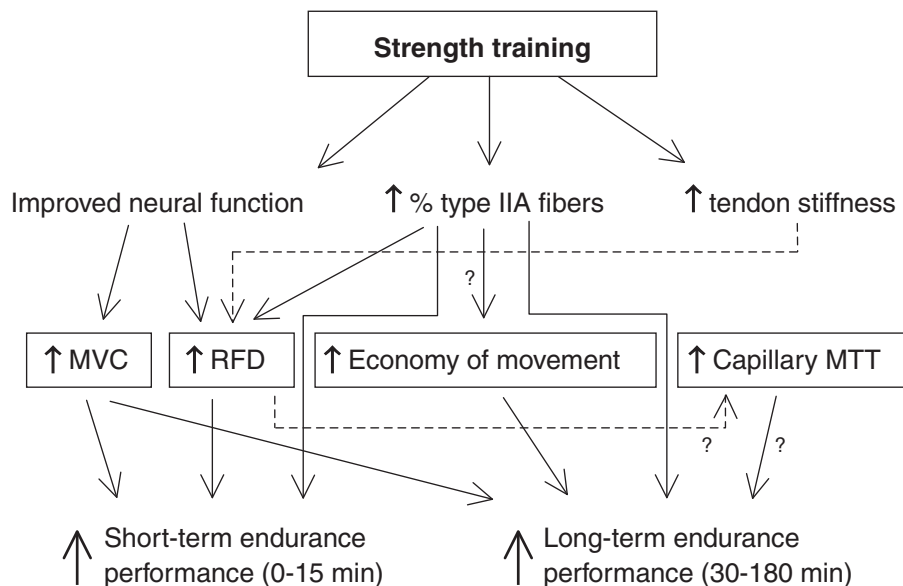


FIGURE 8. Proposed mechanisms to possibly increase short-term and long-term endurance performance in well-trained to highly trained endurance athletes by the addition of strength training to ongoing endurance training. Full lines indicate stimulatory effects; dotted lines indicate proposed potential interactions; question marks [?] indicate potential effects that await general experimental verification (Aagaard & Andersen, 2010).

strength training interventions. The outcomes of their study targets the same direction, in which the proportion of type IIa muscle fibres, gains of maximal muscle strength (MVC) and rapid force development (RFD) are affecting endurance capacities (Aagaard & Andersen 2010; Aagaard et al. 2011; Tanaka & Swensen 1998).

While those outcomes are more likely sufficient to elite endurance trained athletes, the untrained population demonstrates mostly ameliorations in endurance parameters.  $VO_2$ peak is considered to increase significantly in healthy older men with significantly increased number of capillaries (Hepple et al. 1997). In recreationally resistance-trained men, concurrent training programs lead to significant enhancements in muscular endurance responses. Jones et al. (2013) reported amendments by 26.1% and 35.5% in time to exhaustion (TTE) in a 3:1-ratio (strength:endurance) training group and 1:1-ratio training group, respectively.

Similar TTE improvements were indicated by Chtara et al. (2005) when young male sport students improved their TTE by 28% after 12 weeks of concurrent endurance and strength training (E+S) and 21% after the opposite training sequence (S+E). Another investigation by Schumann et al. (2014a) observed significant TTE improvement in cycling following a 24-week period of concurrent training in moderately physical active young men (figure 9). However, after the first 12 weeks of concurrent training the rate of improvement rose to 9% and 10% and eventually reached 15% and 17% at the end of the 24-week intervention in E+S and S+E training group, respectively (Schumann et al. 2014a).

Within trained population (moderately trained male cyclists), 10% TTE improvements are still expected after 8 weeks of combined E+S training (Psilander et al. 2014). With a prolonged intervention period (24 weeks), endurance-trained runners demonstrate similar increases (7%) after same-session concurrent training (Schumann et al. 2015).

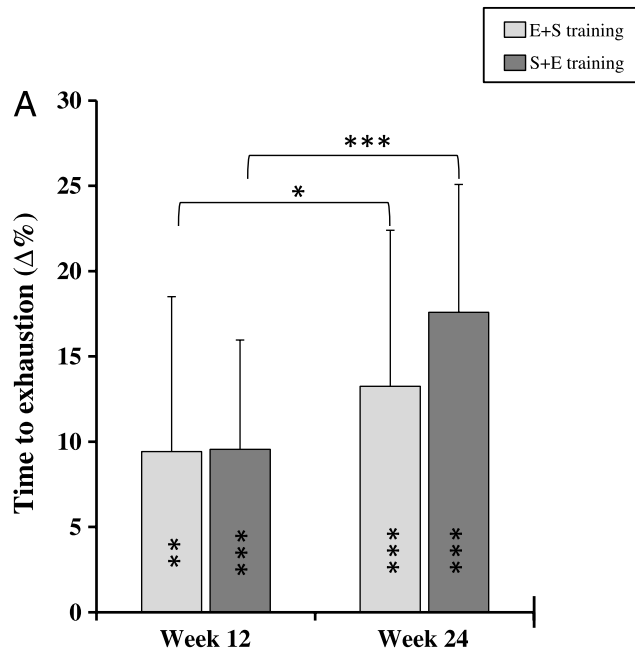


FIGURE 9. Relative changes in time to exhaustion (TTE) after 12 and 24 wk of combined E+S or S+E training. \* $p < 0.05$ ; \*\* $p < 0.01$ ; \*\*\* $p < 0.001$ , within bar compared with pre-training values, outside as indicated. (Schumann et al. 2014a).

### 3.1.1 Maximal oxygen consumption ( $VO_{2max}$ )

A broad range of studies investigated the possible effects of combined endurance and strength training on maximal oxygen consumption ( $VO_{2max}$ ) with multifarious findings. Table 1 summarises the investigated studies about concurrent training application in untrained individuals or non-athletes sorted by intervention period.

General meliorations in  $VO_{2peak}$  were already observed after 6 weeks of concurrent training (3 sessions per week) in young adults independent of the training sequence (Leveritt et al. 2003; MacNeil et al. 2014). The latter investigation supports the positive training effect of concurrent training interventions on the physical condition after immobilisation and thus, implies the healing effect of concurrent training during rehabilitation (MacNeil et al. 2014).

TABLE 1. Investigated studies of combined endurance and strength training on maximal oxygen consumption in untrained subjects or non-athletes.

REFERENCES	PARTICIPANTS			INTERVENTION					RESULTS
	Gender	Physical activity level	Age	Weeks	Volume	Groups	Order	Combined training mode	
Leveritt et al. 2003	both	active university students	female: 18.3±0.6, male:19.2±1.3	6	3 x/wk	ES	E+S	same-session	↑VO <sub>2</sub> peak*
MacNeil et al. 2014	both	young, healthy	20±2	6	3 x/wk	ES, SE	both	same-session	VO <sub>2</sub> peak ↑9%* (ES+SE groups cumulated)
Collins & Snow 1993	both	-	-	7	-	ES, SE	both	same-session	ES: ↑6.2%; SE: ↑6.7%
Davitt et al. 2014	female	inactive college subjects	19.8±0.2	8	4 days/wk	ES, SE	both	same-session	ES: ↑15.6%*; SE: ↑15.3%*
Irving et al. 2015	both	sedentary	18-30; ≥65	8	3-5 d/wk	SE	both	mixed: separate and same-session	young: ↑12.1%; old: ↑23.3%*; together: ↑16.9%*
Psilander et al. 2014	male	moderately trained cyclists	36±2	8	2 x/wk	ES	E+S	same-session	ES: ↑3%*
Davis et al. 2008a	female	college athletes	mean 19.6	11	3 d/wk	serial, integrated	S+E	same-session	serial SE: ↑18.9%*; integrated SE: ↑22.9%*
Cadore et al. 2010	male	healthy elderly	65±4	12	3 d/wk	ES	E+S	same-session	VO <sub>2</sub> peak ES: ↑22%*
Chtara et al. 2005	male	sport students	21.4±1.3	12	2 x/wk	ES, SE	both	same-session	ES: ↑14.1%*; SE: ↑12.0%*
Gravelle & Blessing 2000	female	recreationally fit, inactive students	?	12	3 d/wk	ES, SE	-	same-session	ES: ↑5.3%; SE: ↑8.0%*
Kraemer et al. 1995	male	healthy	23.3±3.6; 22.0±5.0	12	4 d/wk	ES, upper-body ES	E+S	same day, 5-6h gap between	ES: ↑7.7%*; upper-body-only ES: ↑9.6%*
Cadore et al. 2012a	male	healthy elderly	64.7±4.1	12	3 x/wk	ES, SE	both	same-session	VO <sub>2</sub> peak SE: ↑8.1%*; ES: ↑9.3%*
Fisher et al. 2013	female	elderly	≥60	16	1-3 x/wk depending on group	CT1x/wk, CT2x/wk, CT3x/wk	mixed	mixed: separate only for CT1; separate and same-session for CT2&3	↑VO <sub>2</sub> peak
Taipale et al. 2014b	both	recreationally endurance runners	21-45	16	12x/8wk + wk 9-12: 1.75±0.5x/wk; wk 13-16: 1.25±0.5x/wk	ES	-	-	↑VO <sub>2</sub> max, partly *
Sale et al. 1990b	male	-	young	20	2 d/wk; 2+2 d/wk	SE	S+E	same-session and separate day	same-session: ↑7%; separate day: ↑6%
Häkkinen et al. 2003	male	healthy men	37±5	21	2+2 d/wk	SE	S+E	separate days	SE: ↑18.5%*
Karavirta et al. 2011a	both	healthy, untrained	40-67	21	2+2 x/wk	ES	-	separate days/alternating days	↑VO <sub>2</sub> peak; inter-individual variance in combined groups: -8 to 42%
Karavirta et al. 2011b	male	healthy, untrained	40-67	21	2+2 x/wk	SE	-	separate days/alternating days	VO <sub>2</sub> peak SE: ↑10%*
Sale et al. 1990a	both	-	young, adult	22	3 d/wk	ES, SE	both	same-session	ES: ↑7.2%; SE: ↑8.3%
Schumann et al. 2014a	male	healthy men	30±5	24	2-3 x/wk	ES, SE	both	same-session	@wk12: ES: ↑4.8%*; SE: ↑7.3%*; @wk24: ES: ↑6.1%*; SE: ↑6.4%*

CT= combined training; d=days; wk=week; E+S=endurance prior to strength training; S+E=strength prior to endurance training; ↑=improvement; \*=significantly different; -=no information/unclear

Collins & Snow (1993) and Davitt et al. (2014) utilised concurrent strength and endurance training for 7 and 8 weeks, respectively. Although the weeks and the training programs were similar, the improvements were twice as high in Davitt and colleagues' study (15% vs. 7% in Collins & Snow 1993). The first suggestions for those differences in the improvements may lead to the effect of training volume (4 training days per week in Davitt et al. 2014), as to the different intervention groups (female only in Davitt et al.

2014 vs. mixed gender group in Collins & Snow 1993). The VO<sub>2</sub>max improvements in Irving et al. (2015) were alike within the younger subjects (12%), but differed in the older population (23%) after an 8-week period. The differences might be related to the age groups (younger population: age 18-30; older subjects: age  $\geq$ 65) and to the intervention protocol (mixed mode of separate days and same-session combined S+E training) (Irving et al. 2015).

With prolonged intervention periods, effects on VO<sub>2</sub>max can be also detected. A 12-week intervention (2 sessions/week) in male sport students led to 12-14% improvement in maximal oxygen consumption (Chtara et al. 2005). During the same period, Gravelle & Blessing (2000) found increased VO<sub>2</sub>max in both training orders (E+S: 5%; S+E: 8%) in recreationally fit, but inactive female students. The greatest differences were hold in the previous fitness levels and gender (Chtara et al. 2005: aerobically fit male vs. Gravelle & Blessing 2000: inactive female), and hence, the studied population may influence those diverse values. This presumption is in accordance with the outcomes by Kraemer and colleagues (1995). They discovered 8% improvements in VO<sub>2</sub>max in E+S training groups after 12 weeks of training in healthy young untrained men (age 23 $\pm$ 4) compared to Chtara and colleagues' (2005) results (14%). Although both studies included male subjects, the previous fitness level could have been decisive to the outcomes (healthy untrained vs. sport students). It has been assumed that concurrent training lead to greater impact in trained than untrained individuals (Davitt et al. 2014), even though that this has not been confirmed within a shorter period (Psilander et al. 2014). Further, those lower results may be explained by the influence of the used training intervention. While the previous mentioned studies applied same-session concurrent training, Kraemer et al. (1995) utilised same-day sessions with 5-6 hour gaps between each strength and endurance exercise mode.

Davis et al. (2008a) investigated combined training programs in young female college athletes for 11 weeks (3 days/week) with employing different protocols (figure 10). While the serial concurrent training was composed of strength training prior to endurance exercises, the integrated protocol consisted of alternating S+E exercises. The findings demonstrated increases in mean VO<sub>2</sub>max by 19% in the serial concurrent group and 23% in the integrated concurrent group. Comparing both groups, a greater



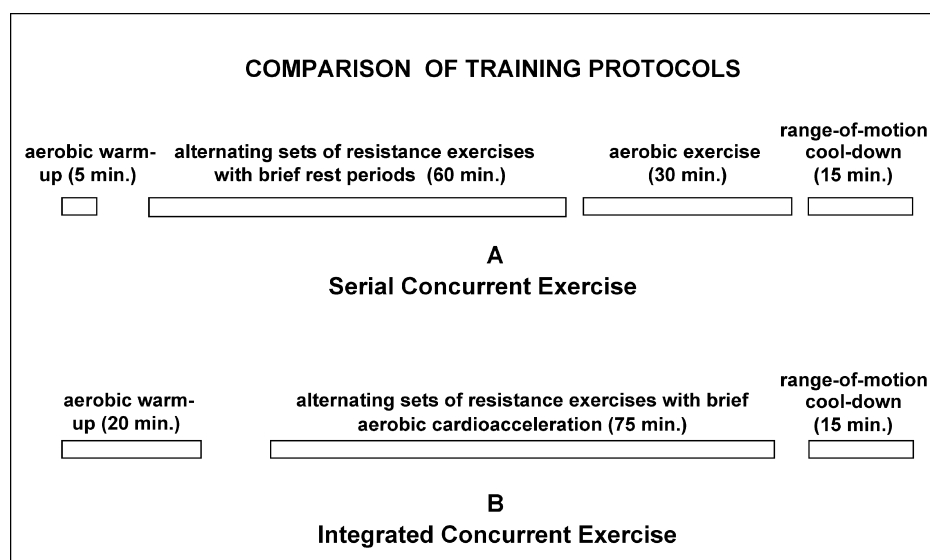


FIGURE 10. Serial concurrent exercise (CE) protocol (A) and integrated CE protocol (B) employed in the studies by Davis et al. (2008a; 2008b).

progression by 21% was observed in the integrated compared to the serial concurrent group. The volume in both groups including warm-up was similar (95 min), but the integrated concurrent group passed a longer warm-up phase, which led to a slightly lower duration of the concurrent exercises. The main difference between both protocols was that the participants rested before each set of strength exercises in the serial concurrent protocol, whereas in the integrated concurrent protocol, subjects increased their heart rate by brief cardio-acceleration before each set of resistance exercises (Davis et al. 2008a). The additional amount of aerobic exercise during weightlifting in the integrated concurrent group was therefore balanced by the increased duration of the aerobic exercise phase in the serial concurrent group. This additional stimulus of increased HR during the strength exercises in the integrated group may lead to the enhanced aerobic endurance adaptations, which offers the suggestion that exercise timing and sequence within a session influence  $\text{VO}_2\text{max}$  significantly (Davitt et al. 2014). The idea of alternating instead of sequent concurrent exercises may offer another input in combined endurance and strength training patterns.

Häkkinen et al. (2003) induced a 21-week training period in non-strength-trained male individuals showing a 19% improvement of  $\text{VO}_2\text{max}$  in the combined strength and endurance trained group (figure 11). Even with a comparable high volume of training,

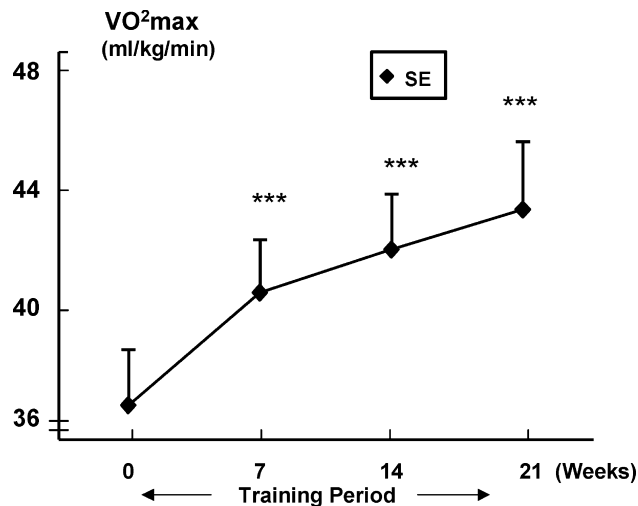


FIGURE 11. Mean (and SD)  $VO_2$ max recorded in a bicycle ergometer test in the combined SE group during 21-week period. \*\*\* $p < 0.001$ . (Häkkinen et al. 2003).

the general nature of the interference effect is not proven like in some investigations before (Hickson 1980; Wilson et al. 2012). It has been presumed that the concept of central circulation may be predominant, which influence mainly maximal aerobic power during exercise with large muscles (Häkkinen et al. 2003). Central circulatory adaptations are most likely related to endurance performance and seem to be only slightly affected by resistance interventions (McCarthy et al. 1995).

Sale and colleagues (1990b) demonstrated absolute  $VO_2$ max enhancements, whether trained concurrently in same-session (7%) or on separate days (6%) for 20 weeks (2 days/week in same-session; 2+2 days/week in separate days). The same-session combined E+S and S+E training and the followed  $VO_2$ max results (7% and 8%, respectively) support the previous hypothesis of no interference after a higher volume (22 weeks, 3 days/week) of intervention (Sale et al. 1990a). In an older testing population (age 40-67),  $VO_2$ peak significantly increased as well after 21 weeks (10%) (Karavirta et al. 2011b). However, inter-individual differences regarding the grade of adaptations have been also monitored (ranges in  $VO_2$ peak changes from -8 to 42%) and it has been recommended to adapt the concurrent training programs individually to the individual subject's needs (Karavirta et al. 2011a).

In trained populations, studies mostly detected no (significant) effects on  $\text{VO}_2\text{max}$  when strength training was added to their endurance training programs regardless of the length and volume of the interventions (table 2). The lack of  $\text{VO}_2\text{max}$  improvements are manifold: maximal oxygen consumption levels are usually well-developed already in endurance athletes due to their training level and expertise; endurance exercise intensities during their training might be unknown and difficult to interpret; the timing of conducting the intervention may affect whether  $\text{VO}_2\text{max}$  improvements are expected or not; and the length of intervention periods might not be sufficient to evoke significant  $\text{VO}_2\text{max}$  increases within this studied population (Aagaard et al. 2011; Hoff et al. 1999, 2002; Millet et al. 2002; Rønnestad et al. 2015).

TABLE 2. Investigated studies of combined endurance and strength training on maximal oxygen consumption in trained subjects or athletes.

REFERENCES	PARTICIPANTS			INTERVENTION					RESULTS
	Gender	Physical activity level	Age	Weeks	Volume	Groups	Order	Combined training mode	
Hoff et al. 2002	male	competitive cross-country skiers	19.7±4.0	8	aST 3 x/wk	ES	-	as supplement; mixed, separate and same-session?	no significant changes in $\text{VO}_2\text{max}$ and $\text{VO}_{2\text{peak}}$
Støren et al. 2008	both	well-trained runners	28.6±10.1	8	aST 3 d/wk	ES	-	“	ns in $\text{VO}_2\text{max}$
Sunde et al. 2010	both	well-trained and competitive cyclists	29.9±7.2	8	aST 3 d/wk	ES	E+S?	“	ns in $\text{VO}_2\text{max}$
Hoff et al. 1999	female	competitive cross-country skiers	17.9±0.3	9	8.5±0.8h/wk; aST 3 d/wk	ES	-	“	ns in $\text{VO}_2\text{max}$ and $\text{VO}_{2\text{peak}}$
Paavolainen et al. 1999	male	elite cross-country runners (orienteers)	23±3	9	9±2 x/wk	ES	-	mixed (?); circuit training included	ns in $\text{VO}_2\text{max}$
Vikmoen et al. 2015	female	well-trained cyclists	31.5±8.0	11	aST 2 x/wk	ES	E+S?	as supplement; mixed, separate and same-session?	unchanged ES: -1.1%
Rønnestad et al. 2010-2012	male	well-trained cyclists	27±2	12	aST 2 x/wk	SE	S+E	same-day, separate session	SE: ↑3%*
Millet et al. 2002	-	triathletes	24.3±5.2	14	aST 2 x/wk	ES	E+S	as supplement; mixed, separate and same-session?	ns in $\text{VO}_2\text{max}$
Aagaard et al. 2011	male	elite cyclists	19.5±0.8	16	aST 5 x/2wks	SE	-	“	ns in $\text{VO}_2\text{max}$
Rønnestad et al. 2015	-	young elite cyclists	19.1±1.7	25	wk 1-10: 2 x/wk; wk 11-25 1 x/7-10d	ES	-	“	ns in $\text{VO}_2\text{max}$

aST=additional strength training to their normal endurance training; d=days; wk=week; E+S=endurance prior to strength training; S+E=strength prior to endurance training; ns=no significant changes; ↑=improvement; \*=significantly different; -/?=no information/unclear

However, Rønnestad et al. (2010) found increased  $\text{VO}_2\text{max}$  (3%) in the E+S group in well-trained male cyclists. It has been indicated that this minor improvement was elicited by the time of the study, in which it was conducted (Rønnestad et al. 2010). One month after the end of the competitive phase, when endurance training volume typically drops, the intervention was executed and it simultaneously collided with the preparatory phase, at which endurance training volume was increased emerging  $\text{VO}_2\text{max}$  improvements. This is in accordance to Hoff and colleagues (2002) suggestion, whether

maximal oxygen uptake will or will not improve based on the timing of the study and athletes' training periodization: during the preparatory phase, it is more likely that  $\text{VO}_2\text{max}$  of the athletes will increase rather than during the competitive phase or at the end of the season.

### 3.1.2 Effects on maximal work rate ( $W_{\text{max}}$ )

After a 16-week period of concurrent training, maximal work rate ( $W_{\text{max}}$ ) increased by 12% in untrained healthy men (Izquierdo et al. 2005). Likewise, significant improvements in maximal aerobic power were observed in both E+S (13%) and S+E (16%) groups after a 24-week intervention of combined endurance and strength training regardless of the order (Schumann et al. 2014a) (figure 12). Maximal power output has been reported to significantly increase after 24 weeks regardless whether concurrent endurance and strength training is performed during the same-session or at different days (Eklund et al. 2014).

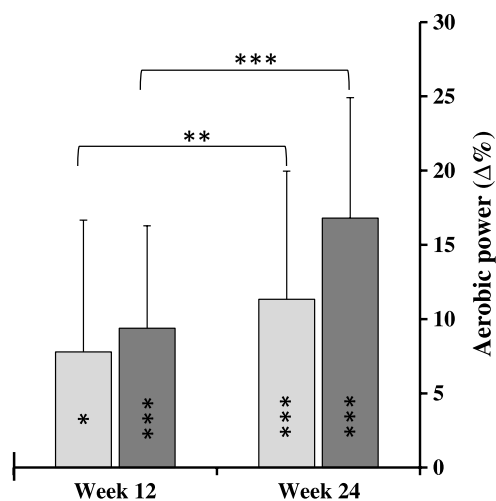


FIGURE 12. Relative changes in maximal aerobic power (W) after 12 and 24 wk of combined E+S or S+E training. \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ , within the bar compared with pre-training values, outside the bar as indicated. (Schumann et al. 2014a).

In trained populations, 11 weeks of strength training in well-trained cyclists led to a minor change in  $W_{\text{max}}$  of the E+S group (4%), which was not significant (Vikmoen et al. 2015). With a prolonged period, a moderate effect in the combined ES group was

observed in young elite cyclists after 25 weeks, even though the increase in  $W_{\max}$  was rather small (3%) (Rønnestad et al. 2015).

The general betterments are expected and caused by different factors, such as lower body strength, muscle fibre type profiles, improvements at submaximal levels or training design. Increased mean watt production is explained by the substantial gains in maximal muscle strength (MVC) and rapid force development and capacity (RFD) in top-level endurance athletes, which is induced by concurrent E+S training (Aagaard & Andersen 2010; Aagaard et al. 2011) and hence, the main dependency on peak power output is linked to maximal leg strength (Cadore et al. 2013; Izquierdo et al. 2004; Psilander et al. 2014; Rønnestad et al. 2015).

Nevertheless, the development of maximal work rate may be based upon the supportive effects of strength training on the muscle fibre types. The changes in the fibre type ratios and properties (size of type I fibres and changes in type II subtype ratios and myofibril contractile properties) may induce improvements on maximum aerobic power as well as in neuromuscular economy during aerobic exercise (Aagaard et al. 2011; Cadore et al. 2011, 2012a; Chtara et al. 2005; Tanaka & Swensen 1998). Peak power increase could result in fewer muscle fibres being recruited or muscle fibres working on a lower percentage of their maximal force potential during submaximal loads and thus, it might eventually implicate a delay of fatigue of individual motor units (Loveless et al. 2005). Due to those neuromuscular adjustments, increased efficiency of movement at lower workloads in middle-aged or elderly as well as maintained force production during high-intensities can be expected (Barclay 1996; Loveless et al. 2005). Increased strength and power could result in attenuated blood flow restriction, faster force development in each movement cycle or enhanced neuromuscular function (Aagaard & Andersen 2010; Rønnestad & Mujika 2014) and therefore, support the enhancement of efficiency after concurrent training. From the viewpoint of periodization, optimal resistance training volumes may be applicable to maximal strength and power gains that support the development in aerobic power performance (Izquierdo et al. 2005; Izquierdo-Gabarron et al. 2010).

### 3.2 Effects on strength performance

The consequences in strength performance after a combined endurance and strength training intervention are dependent on various factors, similarly to endurance parameters. The experimental design and its chosen variables, such as subjects, type of training, training intensities and so forth (Bell et al. 2000; Chtara et al. 2008; Davitt et al. 2014; Häkkinen et al. 2003; Leveritt et al. 2003; Schumann et al. 2014a) may lead to different impacts on strength performances after concurrent training (table 3).

TABLE 3. Investigated studies of combined endurance and strength training on 1RM in untrained and trained study population.

REFERENCES	PARTICIPANTS			INTERVENTION					RESULTS
	Gender	Physical activity level	Age	Weeks	Volume	Groups	Order	Combined training mode	
MacNeil et al. 2014	both	young, healthy	20±2	6	3 x/wk	ES, SE	both	same-session	knee extensors ↑35%* (ES+SE cumulated)
Irving et al. 2015	both	sedentary	18-30; ≥65	8	3-5 d/wk	SE	both	mixed: separate and same-session	young: ↑22.0%*; old: ↑47.8%*
Psilander et al. 2014	male	moderately trained cyclists	36±2	8	2 x/wk	ES	E+S	same-session	leg press ES: ↑19%*
Sunde et al. 2010	both	well-trained and competitive cyclists	29.9±7.2	8	aST 3 d/wk	ES	E+S?	as supplement; separate and same-session?	half squat ↑14%*
Davis et al. 2008b	female	college athletes	mean 19.6	11	3 d/wk	serial, integrated	S+E	same-session	serial SE: ↑17.2%*; integrated SE: ↑23.3%*
Cadore et al. 2013	male	healthy elderly men	64.7±4.1	12	3 x/wk	ES, SE	both	same-session	knee extensors ES: ↑22%*; SE: ↑35%*
Millet et al. 2002	-	triathletes	24.3±5.2	14	aST 2 x/wk	ES	E+S	“	half squat ↑25%*; calf raise ↑17%*
Taipale et al. 2014b	both	recreationally endurance runners	21-45	16	compare table 1	ES	-	-	knee extensors female: ↑13%*; male: ↑6%*
Sale et al. 1990b	male	-	young	20	2 d/wk; 2+2 d/wk	SE	S+E	same-session and separate day	same-session: ↑13%; separate day: ↑25%
Schumann et al. 2014a	male	healthy men	30±5	24	2-3 x/wk	ES, SE	both	same-session	leg extensors ES: ↑12%*; SE: ↑17%*
Schumann et al. 2015	male	recreationally endurance trained	33±7	24		ES	E+S	same-session	↑4% after 12 wks

aST=additional strength training to their normal endurance training; d=days; wk=week; E+S=endurance prior to strength training; S+E=strength prior to endurance training; ↑=improvement; \*=significantly different; -/?=no information/unclear

Six weeks of combined training (3 times/week) during rehabilitation after 2 weeks of complete leg immobilisation in young adults induced a 35% increase in 1RM (MacNeil et al. 2014). In sedentary adults (age 18-30) and older adults (≥65 years), 8 weeks of concurrent training (3-5 days/week) led to 22% and 48% increases in 1RM leg press in PRE-POST comparison, respectively (Irving et al. 2015). Those similar ranges of strength development might have their origin from the subjects' physical condition. Primary mechanisms for increased strength in untrained or elderly people might be neural factors that include increases in motor unit recruitment or firing rate capacity (Cadore et al. 2012a; Häkkinen et al. 2000). This corresponds to the findings by Cadore

et al. (2013) in elderly men after 12 weeks of concurrent training (S+E: 35%; E+S: 22% increase in 1RM).

With extended intervention periods, the rate of maximal strength development seems to decrease, but remains present. After 24 weeks (2-3 times/week) of combined endurance and strength training in physical active young men, both intervention groups increased 1RM by 12% and 17% in E+S and S+E group, respectively (Schumann et al. 2014a). This was similarly observed in the study by Eklund et al. (2014), in which separate-day concurrent strength prior to endurance training evoked 13% improvements in 1RM after 24 weeks (4-6 training days/week).

Sale et al. (1990b) have documented increases in 1RM leg press in both, same-session SE training (2 training days/week: 13%) and separate-day SE training (2+2 training days/week: 25%) in men after 20 weeks of combined strength and endurance training. However, different-day SE training produced greater increase in voluntary strength in comparison to SE same-day, but not a greater increase in muscle or muscle fibre size.

Also the manipulation of the training regimens has not necessarily brought impairing effects to maximal strength. The used serial and integrated concurrent endurance and strength training protocols in the study by Davis et al. (2008a; 2008b) (compare figure 10) led to 1RM increases. Those 1RM values were evaluated via summing the 1RM weights for the corresponding exercises leg press, leg extension and leg flexion after an 11-week training programme (3 days/week). The serial combined group increased their 1RM by 17%, the integrated combined group by 23%; in comparison with both groups, the integrated combined protocol, hence, yielded a 35% greater mean gain in lower body strength than the serial group (figure 13) (Davis et al. 2008b).

In moderately trained male cyclists, 1RM increased by 19% in the combined ES training group after same-session ES training over 8 weeks (2 times/week) (Psilander et al. 2014). Similar improvements were reported in competitive road cyclists after an 8-week-intervention; 1-RM in half squat increased significantly by 14% (Sunde et al., 2010). 14 weeks of additional heavy strength training sessions (twice a week) in triathletes led to significant increases in 1RM in the ES intervention group (Millet et al. 2002).

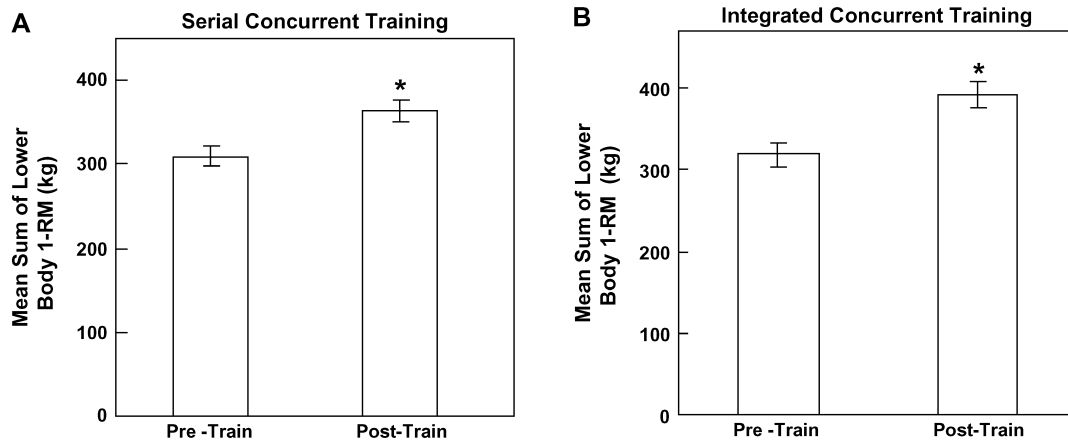


FIGURE 13. Mean lower-body muscle strength before (Pre-train) and after (Post-train) 11 weeks of concurrent exercise (CE) training program. A: serial CE group; B: integrated CE group. \* $p < 0.05$ . (Davis et al. 2008b).

The addition of heavy strength training in well-trained cyclists to high-volume endurance training has been reported to increase leg strength as expected (Aagaard & Andersen 2010). Reasons for strength gains could be explained by selected protocols and low training frequency, which allow sufficient recovery and gains, specificity of the strength training, and either neural or hypertrophic adaptations or a combination of both (Kraemer & Ratamess 2004; Rønnestad et al. 2010; Schumann et al. 2014b; Sunde et al. 2010). The effects in athletes applying concurrent training have to be considered more specifically with regard to their training objectives. It might cause differences in peak performances when looking for maximal gains in either endurance or strength, especially with heavier loads in strength (i.e., 3-5 RM) or greater intensities for endurance (Davitt et al. 2014). If the athlete's discipline relies primarily on hypertrophy and maximal strength, it is expected, that concurrent training may not lead to significant decrements, when the proper modality of endurance training is selected (Wilson et al. 2012). It means that the selection of endurance exercises is crucial and should be proper to the own specific sport. For example, hockey players may prefer cycling exercises than running, because it is closer to the skating demands (Martinez et al. 1993).

Female and male recreational runners showed systematically progressive and significant increases in 1RM (female: 13%; male 6%) after performing 16 weeks of mixed maximal and explosive exercise in addition to their endurance training program (Taipale et al. 2014). It is suggested that the differences between strength development among



men and women may be due to the fact that men are generally stronger and thus, have less potential for increases in strength compared to woman (Taipale et al. 2014).

In recreationally endurance-trained males, dynamic 1RM leg press strength remained statistically unaltered after 24 weeks of E+S training (4% after 12 weeks, not significant) (Schumann et al. 2015). Impairments or attenuations in strength development might attend due to different training regimens, in which both endurance and strength training modes are engaging the same muscle groups (Kraemer et al. 1995). The endurance exercise selection is previously reported to possibly affect strength adaptations. From the biomechanical point of view, the mechanical stress and the risk for eccentric muscle damage could be higher in running than cycling training (Bell et al. 2000). Davis et al. (2008b) hypothesised that subjects' physical condition may cause impairment or development in strength. However, the presumption that synergetic effects in subjects with physically good conditions and compromising effects with poor condition may occur has not been clarified.

### **3.3 The order effect in combined endurance and strength training**

When combined endurance and strength training is applied as training intervention, the question naturally arises whether the order of training endurance prior to strength or vice-versa (E+S vs. S+E) is important and whether it crucially influences final endurance and strength performances. It has been supposed that attention should be paid regarding the sequence to ensure optimal strength and endurance enhancements (Izquierdo-Gabarren et al. 2010). An amount of studies have reviewed the order effect with various findings.

Chtara et al. (2005) reported an influence of the training sequence on aerobic parameters. The E+S intervention group improved 4km time trial, aerobic power or  $\text{VO}_2\text{max}$  significantly more than S+E or S and E separated in male sport students. It has been speculated that performing aerobics before strength training in concurrent protocols may enhance endurance adaptations by synergic interactions and yields larger adaptations than vice versa (Davis et al. 2008a). Dolezal & Potteiger (1998) similarly documented that their combined intervention group (S+E) led to limitations in

enhancements or only disrupted gains in aerobic measures. The attenuation of endurance performance might base upon intensity, duration and frequency of the strength training exercise and thus, has been caused by the training design (Chtara et al. 2005). Other approaches indicate that the impairment in endurance results from residual fatigue as it has been evoked by the previous resistance workload and possibly reduce capillary and mitochondrial volume density (Chtara et al. 2005; Davitt et al. 2014; Dolezal & Potteiger 1998).

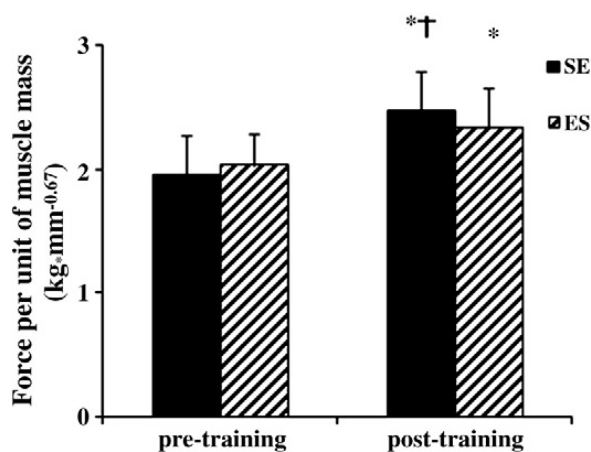


FIGURE 14. Mean  $\pm$  SD of the quadriceps femoris force per unit of muscle mass pre and post 12 weeks of concurrent training. \*Significant differences from pre-training values ( $p < 0.001$ ). †Significant time vs. group interaction ( $p < 0.02$ ). (Cadore et al. 2012a).

From the strength point of view, diminutions in chronic strength gains when performing endurance prior to strength may occur due to a diminished ability of the neuromuscular pathway leading to the reduction in strength gains (Cadore et al. 2012a; Davitt et al. 2014; Lepers et al. 2001). In accordance to that, Cadore and colleagues (2012a) detected a significantly greater increase in strength, gained by subjects performing resistance before endurance in comparison to the group performing the reversed order, which was related to an increase in the qualitative force generation of the muscle per unit of muscle mass (figure 14). Interestingly, while the intra-session exercise sequence seemed to have no impact in maximal endurance power adaptations to concurrent training, the magnitude of muscle quality enhancement was prepossessed by order (Cadore et al. 2012a). As discussed above, the endurance and strength exercise sequence and thus, the preceded acute bouts of endurance and exhaustive dynamic resistance exercises might impair the quality subsequent strength training by compromising the neuromuscular

functions (García-Pallarés & Izquierdo 2011; Gravelle & Blessing 2000; Wilhelm et al. 2014). The residual fatigue caused by previous endurance sessions may inhibit the ability of the neuromuscular system to rapidly develop force and reduce the absolute volume of strength training (Izquierdo-Gabarren et al. 2010; Leveritt et al. 1999; Sale et al. 1990b). Further mechanism associated to concurrent endurance prior to strength training is that less muscle tissue is being used to carry out the exercise due to decreased neuromuscular motor unit time or muscular recruitment (Davitt et al. 2014; Häkkinen et al. 2003; Kraemer et al. 1995; Lepers et al. 2001). Possible explanations may be offered by the different bioenergetical demands in the nature of strength and endurance (Davitt et al. 2014). While endurance relies on oxidative phosphorylation and induces changes in the metabolic machinery to increase oxidative metabolism capabilities that inhibit hypertrophy and power-generating muscle fibres, strength training often results in hypertrophy of type II fibres with increased recruitments of faster and more force-generating muscle fibres and is highly reliant to short-term energy system (Davitt et al. 2014; Fitts & Widrick 1996; Kraemer et al. 1995; Nader 2006; Tanaka & Swensen 1998).

However, regarding untrained or sedentary participants, the training order (E+S or S+E) may not necessarily matter, as either training sequence will produce neuromuscular adaptations and improvements in aerobic fitness as reported in Davitt et al. (2014) (figure 15). Similar documentation by Schumann et al. (2014a) demonstrated that time to exhaustion and aerobic power increased significantly in both groups without showing

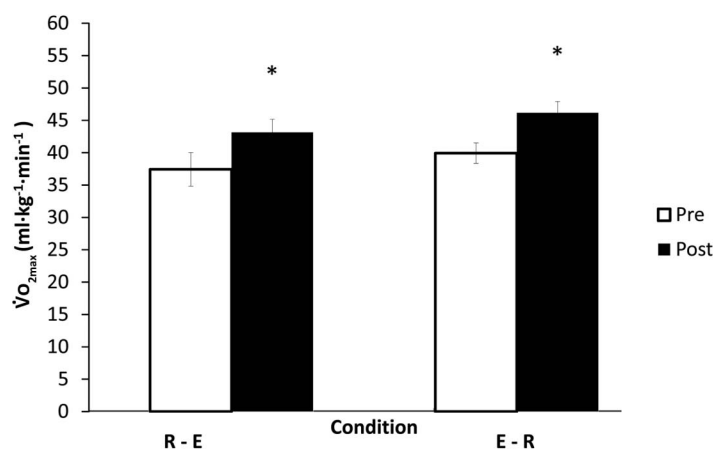


FIGURE 15.  $VO_{2max}$  before and after an 8-week training program. \* $p \leq 0.05$ : significantly different from corresponding pre-value. (Davitt et al. 2014).

any between-group differences, indicating that loading order does not presume to be influencing training adaptations.

In accordance to that, MacNeil and colleagues (2014) applied combined endurance and strength training during rehabilitation reporting an increase in maximum strength and peak aerobic capacity regardless of the exercise order. It was displayed that the sequence does not differentially affect chronic mitochondrial enzyme activities changes or increases in strength or endurance capacities when either modality has been performed immediately after one another (MacNeil et al. 2014). The primary finding by Cadore et al. (2012a) was that same magnitudes of maximal endurance performance increases have been reported with different intra-session exercise sequences of concurrent training. Other studies have also indicated no significant differences in aerobic fitness gains (i.e.,  $VO_{2max}$ ) between combined E+S or S+E training (Alves et al. 2012; Collins & Snow 1993).

The same phenomena were observed in strength. No differences between training orders were found in increases of 1RM leg press in inactive recreationally fit students (Gravelle & Blessing 2000). This is in accordance to the findings of the other investigations carrying out the effect of concurrent training order on strength (Chtara et al. 2008; Collins & Snow 1993; Schumann et al. 2014b; Wilhelm et al. 2014).

The inconsistent outcomes in matters of the order effect in combined endurance and strength training have a great variety of origins. As mentioned above, the subject selection and their previous physical activity level may explain the different results. While gains and developments in endurance and strength parameter and a rather small effect of the exercise order might be more obvious in untrained subjects, possibly greater impacts of the order could be observed in trained populations (Davitt et al. 2014). A variety of investigations see potential explanations in the variability in training volume, frequency and intensity that is applied in the studies (Cadore et al. 2012; Chtara et al. 2005, 2008; Davitt et al. 2014; Gravelle & Blessing 2000; Wilhelm et al. 2014). If the question arises in those cases of which order might be chosen and be more suitable, the final decision will be answered in the personal preference with implications towards adherence (Davitt et al. 2014).

## **4 TIME-OF-DAY SPECIFICITY**

A large amount of investigations have observed whether time-of-day effects influence performance resulting in miscellaneous findings. In time-of-day settings, terminology includes either “circadian” or “diurnal” rhythm. The latter is generally used in cases of effects during daytime, while circadian expresses effects over the entire solar cycle of 24 hours (Chtourou & Souissi 2012). When considering time-of-day specificity in athletic performances, circadian rhythms may change the level of several physiological processes in a time-dependent manner (di Cagno et al. 2013). Based on the performance tasks, “simple” tasks that include small cognitive components tend to peak in the late afternoon and evening, while more “complex” tasks involving larger cognitive components tend to peak earlier in the morning and follow a more marked fall afterwards (di Cagno et al. 2013; Folkard & Rosen 1990).

When regarding stabilometry, used to study orthostatic postural control in sports sciences and in clinical settings, time-of-day seems not to affect the results of stabilometry evaluation (Russo et al. 2015). Also coordination seems not be affected by the diurnal rhythm as seen in elite gymnasts or untrained adolescents after applying test batteries to examine coordination skills (di Cagno et al. 2013). Hammouda and colleagues (2011) have investigated biological markers of muscle injuries in young football players. Their findings confirmed diurnal variation in the selected markers that led to higher performances in the evening in repeated-sprint ability (Hammouda et al. 2011). This seems to be in accordance to previous research that found more influential time-of-day effects when it comes to short-term, high-intensity or anaerobic performances. Influences on performances due to time-of-day effects are estimated within a range of 10 to 30% of the daily mean (di Cagno et al. 2013; Klein 1979).

### **4.1 Influence on short-term, high-intensity or anaerobic performance**

When short-term, high-intensity performances are investigated, a trend for diurnal characteristics can be observed. It has been suggested that anaerobic or short-term maximal performances in continuous or intermittent exercises (e.g., Wingate test) are found to be better in the afternoon-evening times around 16:00 to 20:00 hours than in

the morning (between 6:00 and 10:00 hours), particularly for MVC between 18:00 and 20:00 hours, with daily variations ranging from 3-21 % depending on studied population, study design or used muscle groups and thus, exercise should be scheduled then to guarantee maximum performance (Cappert 1999; Chtourou & Souissi 2012; Hill 2014; Nicolas et al. 2007; Thun et al. 2015).

Data suggested peak performance during the evening in knee flexors and extensors additionally to improved back strength (Phillips 1994; Squarcini et al. 2013; Thun et al. 2015). In hopping and reactive strength tests, better results in ground contact and flight times were observed in elite gymnasts during the evening times compared to the results from the morning (di Cagno et al. 2013).

Force and power output of counter-movement jump were reported to score higher values during the afternoon (at 16:00 hours) than during morning or late evening times (Teo et al. 2011; Thun et al. 2015). Similarly, superior performances on vertical jump tests (SJ and CMJ) and MVC were observed in the afternoon than in the morning, thus, proving a temporal specificity in strength training in boys (Souissi et al. 2012). Souissi and colleagues (2012) further stated that adaptations to resistance training in adults appeared to be time-of-day dependent (Sedliak et al. 2007, 2008b, 2009). Ammar et al. (2015) measured the total volume lifted in Olympic lifting (snatch, “clean and jerk”) at

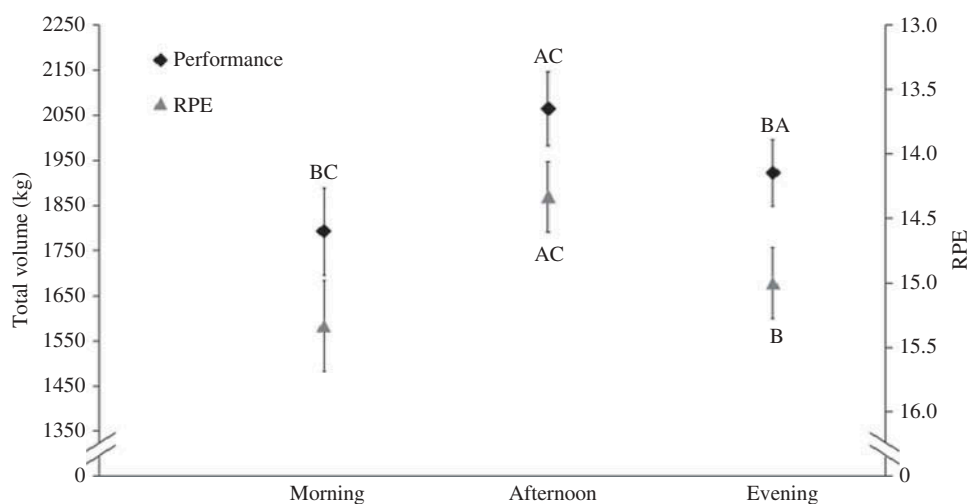


FIGURE 16. Intra-day comparison between performances in the Olympic lifts [and RPE]. Significant difference between time-of-day is represented with “A”, “B”, “C” between 8:00, 14:00 and 18:00 hours, respectively,  $p < 0.05$ . (Ammar et al. 2015).

three different times of day that resulted in higher total amount raised in the two Olympic lifts in the evening than in the morning (figure 16).

In variables as peak power tested from maximal intensity exercise tests, time-of-day effects were documented to display greater maximal intensity power ( $P_{\max}$ ) during sessions at 12:30, 14:30, 16:30 or 18:30 hours than at morning 08:30 and 10:30 hours (figure 17) (Petit et al. 2013). It has been indicated that peak power from anaerobic cycle leg exercises has significant circadian rhythm with an acrophase in the afternoon (17:10±00:52 hours) and an amplitude of 7% (Souissi et al. 2004), which is similar to the finding by Lericollais and colleagues (2009), who observed significantly higher values (8% difference) in peak power at 18:00 than at 6:00 hours.

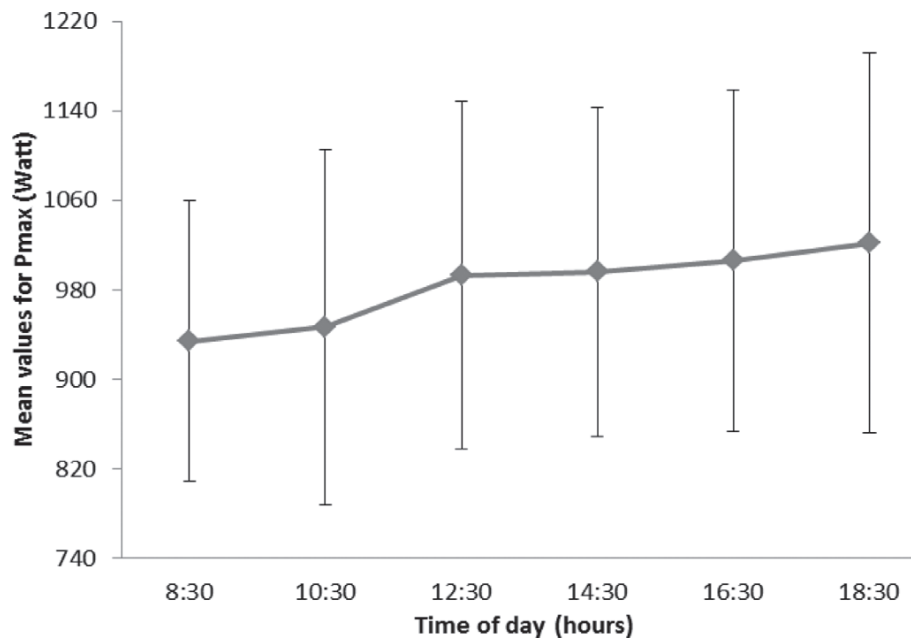


FIGURE 17. Time-of-day effects on maximal intensity exercise. (Petit et al. 2013).

However, the exact underlying mechanisms of time-of-day effects have been examined, but are yet unknown. It is proposed that temporal specificity of strength training is more dependent in accordance to the training design and its program variables and acute effects (frequency, volume, limited sample size, studied subjects, learning effects) and further investigations are needed to clarify that (Chtourou & Souissi 2012; Petit et al. 2013; Sedliak et al. 2007, 2008a, 2008b, 2009).

## 4.2 Time-of-day effects on aerobic parameters

The effects of time-of-day on aerobic performances are conflicting as well (Chtourou & Souissi 2012). Literature cannot represent clear answers leading to inconclusive and equivocal findings yet when time-of-day effects are examined on endurance outcomes.

In recreational cyclists, time trial completion time was significantly shorter in the evening (18:00 hours) than in the morning (08:00 hours) completing the time trial around 7% quicker (Fernandes et al. 2014). In ergometer cycling, different investigations documented improved time to exhaustion (TTE) during evening tests compared to the morning (Bessot et al. 2006) with differences up to 20% (Hill 2014) or even in morning-type athletes (Atkinson et al. 2005). In contrast, several studies examined diurnal or circadian influences in maximal cycling exercise or work rate during submaximal cycling, but failed to determine any variation (Deschenes et al. 1998; Edwards et al. 2005; Reilly et al. 2007). Other works did not observe any time-of-day effects in TTE, which was explained by sample sizes or body temperature in the morning (Deschenes et al. 1998; Reilly & Garrett 1998; Thun et al. 2015).

In endurance parameters such as  $\text{VO}_2\text{max}$ , maximal HR, ventilatory thresholds, and running/cycling economy, time-of-day effect has not been proven to be biased on daily effects (Racinais et al. 2004). Furthermore, Deschenes and co-workers (1998) did not find significant differences in  $\text{VO}_2\text{peak}$ , even though a progressive increase of time in peak oxygen consumption by 9% was documented over the four measurement time-points (8:00, 12:00, 16:00, 20:00 hours) (table 4). Possibly the statistical inter-individual variation influences the state of significance in peak oxygen consumption.

TABLE 4. Data recorded under maximal exercise conditions at the time points investigated. Values in mean (SD). (Deschenes et al. 1998).

Variable	0800 hours	1200 hours	1600 hours	2000 hours
Test duration (min)	13.7 (2.9)	14.2 (2.8)	14.1 (2.8)	14.4 (2.7)
$\dot{V}\text{O}_2$ ( $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ )	52.0 (7.0)	55.1 (10.2)	56.7 (9.5)	56.9 (10.2)
$\dot{V}_E$ ( $\text{l} \cdot \text{min}^{-1}$ )	140.3 (15.3)	150.9 (30.7)	152.7 (23.3)	155.4 (26.8)
$R$	0.97 (0.05)	0.96 (0.06)	0.92 (0.07)	0.95 (0.08)
HR ( $\text{beats} \cdot \text{min}^{-1}$ )	192.8 (9.5)	195.5 (8.3)	193.8 (9.4)	196.3 (7.9)



The effect sizes particularly in  $VO_2$ max are relatively small in favour to diurnal variation (1-4 %) (Hill et al. 1988; Williams & Hill 1995). Souissi et al. (2007) observed a greater aerobic contribution in male physical education students after performing a Wingate test in the evening (18:00 hours) than at morning testing (6:00 hours). Oxygen consumption values were reported to be lower in the morning compared to the afternoon. This trend of higher oxygen uptake values in the evening was observed in Fernandes et al. (2014) as well (figure 18). Oxygen uptake (A) and aerobic mechanical power (E) in male recreational cyclists tended to be higher in the evening than in the morning ( $p < 0.07$  and  $0.09$ , respectively) after 1000m cycling time trials.

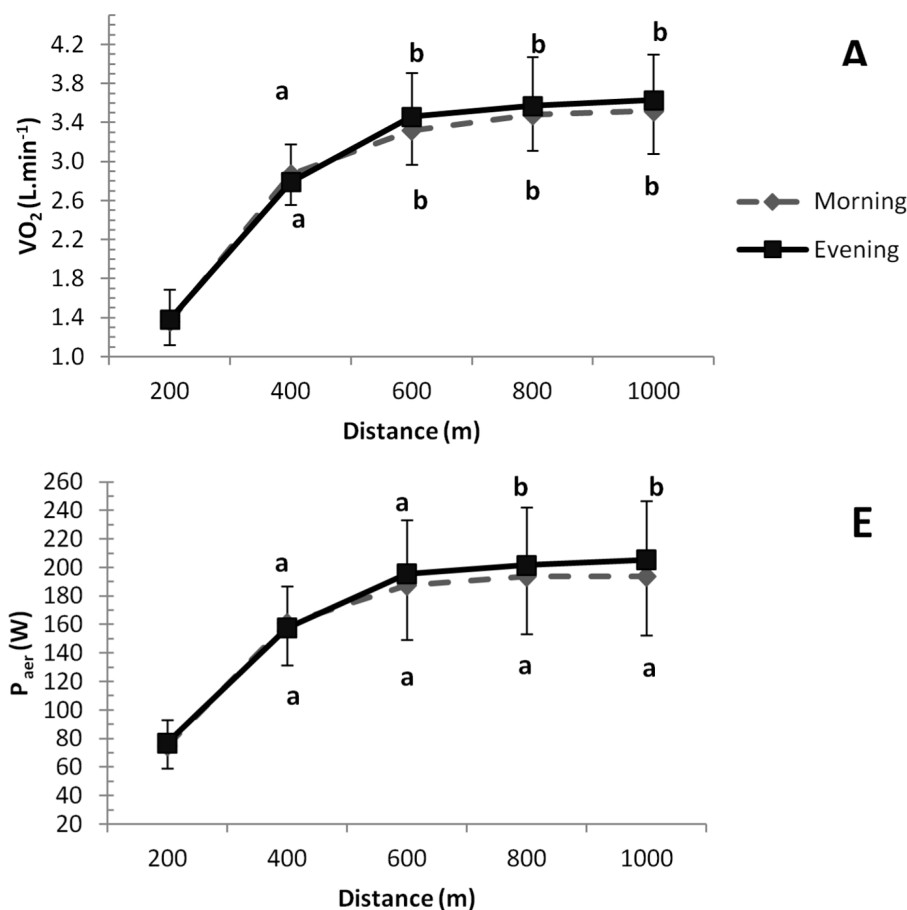


FIGURE 18. Mean and SD for oxygen uptake (A) and aerobic power contribution (E). <sup>a</sup>Significantly different than the 200m value for the same time of day; <sup>b</sup>significantly different than the 400m value for the same time of day;  $VO_2$  increased exponentially with distance for times of day ( $p < 0.05$ ), but there was a tendency for  $P_{aer}$  values at 600 and 800m, and (A) at 600 and 1000m, to be higher in the evening than in the morning ( $p < 0.10$ ). (Fernandes et al. 2014).

Another study by Torii and colleagues (1992) examined time-of-day effects on  $\text{VO}_2\text{max}$  in morning (09:00-09:30 hours), early afternoon (15:00-15:30 hours) and evening (20:00-20:30 hours) groups. The afternoon exercise group displayed significantly improvements in  $\text{VO}_2\text{max}$  compared to the other training groups, which led to the presumption, that aerobic training in the afternoon was most effective compared to morning or evening time (Torii et al. 1992). Likewise, Hill's results (1996) indicated a time-of-day effect showing greater TTE, higher  $\text{VO}_2\text{peak}$  and a faster response of the aerobic system in the PM tests (16:00 hours) compared to the AM tests (08:00 hours), thus, confirming that evening measures might be superior to the morning.

A more recent investigation utilised exhaustive severe-intensity cycle ergometer tests in morning (06:30-09:30 hours) and evening (17:00-20:00 hours) in young male subjects (Hill 2014). While both tests (incremental test, constant-power test) showed increased  $\text{VO}_2\text{max}$  values in the evening than in the morning, only the latter test significantly indicated a time-of-day effect on  $\text{VO}_2\text{max}$  (4% difference; incremental test 2%). The result were explained by the rhythm in anaerobic capacity during the constant-power test that allows a longer exercise duration at the evening measurement and time to achieve true  $\text{VO}_2\text{max}$  (Hill 2014).

### **4.3 Influence of body temperature on performance**

Another factor to time-of-day effects is associated with body temperature. It represents one of the most prominent parameters, which is suggested to have a casual link to the circadian rhythm of physical performances (Chtourou & Souissi 2012; di Cagno 2013). Several investigations regarding time-of-day effects reported significant diurnal variations in [oral] temperature showing higher values during the afternoon or evening than in comparison to obtained morning values (Hammouda et al. 2011; Souissi et al. 2007, 2012).

Thun and colleagues (2015) indicated that “the most robust result is that athletic performance seems to be best in the evening around the time when the core body temperature typically is at its peak.” This has been reported by Bergh and Ekblom

(1979) who observed decreases in jumping performances by around 5% for every 1°C decline in muscle temperature.

Ammar and co-workers (2015) investigated weightlifters on Olympic lifting events on three different times of the day (8:00, 14:00 and 18:00 hours) reporting significant higher core temperatures in afternoon and evening in comparison to the morning (figure 19).

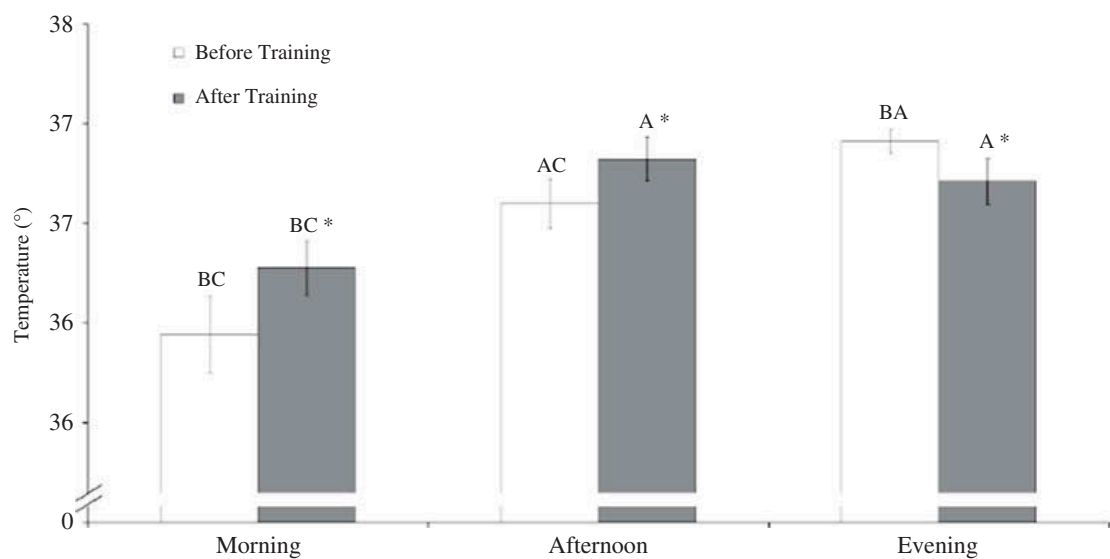


FIGURE 19. Core temperature pre- and post-training session in different time intra-day (mean±SD). \*Significant difference compared to resting values ( $p < 0.05$ ); “A”, “B”, “C” represent significant difference between time-of-day (8:00, 14:00, 18:00 hours, respectively,  $p < 0.05$ ). (Ammar et al. 2015)

In conjunction with oxygen uptake, Hill et al. (1988) displayed significant correlations between the increased body temperature in the afternoon with oxygen consumption below the ventilatory threshold and oxygen consumption/work rate slope above ventilatory threshold during a maximal graded cycle ergometer. The cycle ergometer exercise tests were performed in an AM session (06:00-08:00 hours) and a PM session (15:30-18:00 hours), which eventually induced significant differences in oxygen consumption at all work rates, with the highest results occurring during the PM session. Thus, it was concluded that higher body temperatures increased the demand on the respiratory and thermoregulatory systems at a given exercise intensity, which in the end resulted in a higher oxygen consumption in the evening (Hill et al. 1988).

This trend was also observed by Souissi et al. (2004), who detected significant time-of-day effects in oral temperature with an acrophase at the evening time (18:22±00:34 hours) and its ability to estimate the circadian rhythm of anaerobic performance with regard to the time of occurrence of minimal and maximal values (figure 20).

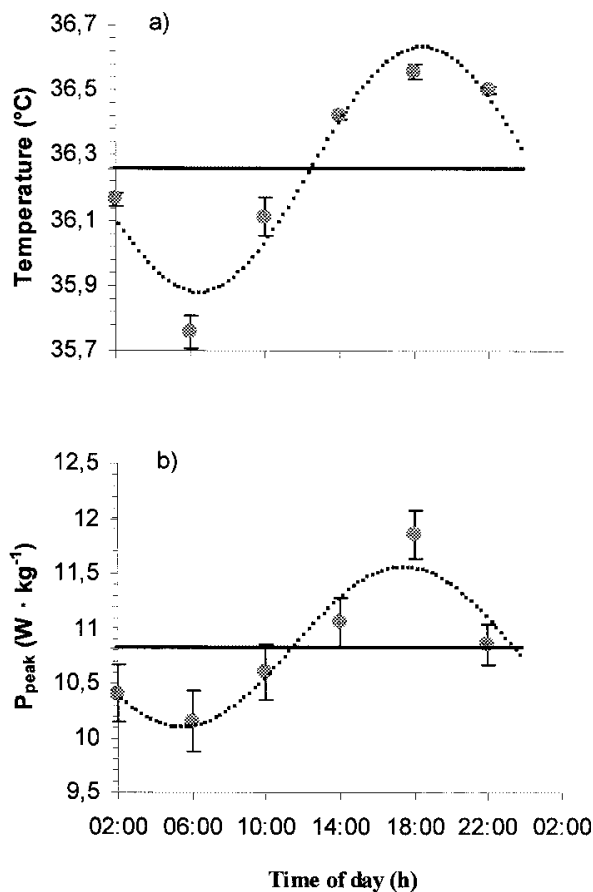


FIGURE 20. Circadian rhythms of (a) oral temperature and (b) peak power. Mean±SD values are shown. Best-fit curves between the experiment data and the cosine curve are shown. (Souissi et al. 2004).

Other investigations referred similar results finding significant diurnal variations between morning (06:00 hours) and evening (18:00 hours) times with higher body temperature during the evening than in the morning (Hill 2014; Lericollais et al. 2009). However, diurnal variations in body temperature are also influenced by the regular training at a particular time of day (Chtourou & Souissi 2012).

#### **4.4 Practical considerations of time-of-day effects**

With view to time-of-day effects and its practical considerations, it has been suggested that training and competitions should be generally scheduled at the same time of day, so training hours coincide with the time of day at which the critical performance is needed in the competition (Cappaert 1999; Chtourou & Souissi 2012). This is recommended also concerning endurance performances (Cappaert 1999). Indeed, a study in swimmers found significant diurnal variation in accordance to their habitual training time-of-day indicating swimmers trained at 06:30 hours were faster in the morning measures and the same for the evening training group at 18:30 hours, respectively (Rae et al. 2015). Nonetheless, previous studies also reported that morning training was able to improve poor morning performances to the same or even greater level as their normal daily peak performance and hence, decreased the effect of diurnal influence (Chtourou et al. 2012a, 2012b; Chtourou & Souissi 2012; Souissi et al. 2002, 2012).

However, if the training scheduling is impractical and not possible whatsoever (i.e., the competition time is not known), studies recommended to either adjust the sleep/wake cycle in order to synchronise highest performance to a particular rhythm (Cappaert 1999) or as to resistance training schedule exercises during morning time to minimize time-of-day effects on physical performances (Chtourou & Souissi 2012). If no restrictions are apparent in designing training programs, athletes and coaches might take it into account that evening times may be the optimal training time since it is affiliated to greater demands in the human metabolism that allows greater levels of both aerobic and anaerobic energy production (Hill 2014). Additionally, the requirements of the sport discipline should be considered relating to the selection of the training time. With greater demands of technical skills involving fine motor controls or with the application of more complex movements to a greater extend, it has been advised to shift the training to the earlier day of time because sport techniques might be more susceptible to time-of-day effects (Lericollais et al. 2009; Reilly et al. 1997; Thun et al. 2015).

Eventually, subjects or athletes have to be considered as well due to possible inter-individual differences. While gender difference is regarded to unlikely bear any time-of-day variation to performance (Cappaert 1999; Kline et al. 2007; Rae et al. 2015),

personal circadian typology and chronotypes have to be taken into account, since individuals evaluated to rather “morning” or “evening” types influence final performances in endurance or strength (Cappaert et al. 1999; Petit et al. 2013). As mentioned above, habitual training time-of-day might be related to diurnal variation, although it is yet to be known whether endogenous factors or the training time conditioning, or both are responsible to that (Rae et al. 2015). Coaches and researchers might need experimentation in order to find the optimal time for training and performances in different populations.

Therefore, effects of naturally occurring biorhythmic influences on human physiology and its responses to stress has to be considered by coaches, researchers, athletes or practitioners when it comes to scheduling and/or designing training or investigations (Cappaert 1999; Chtourou & Souissi 2012; Deschenes et al. 1998; Hill et al. 2014; Petit et al. 2013; Rae et al. 2015; Thun et al. 2015).

## **5 PURPOSE OF THE STUDY**

The purpose of the present study was to examine the effect of time-of-day-specific same-session combined endurance (E) and strength (S) training over 24 weeks on submaximal and maximal endurance parameters in untrained men aged 18 to 40. The study evaluated the influence of the exercise sequence (E+S vs. S+E) in combination to the time of day (morning vs. evening), at which training was performed.

### **Research questions**

- 1) Do chronic adaptations in endurance and strength variables in untrained men following a 24-week period of same-session combined endurance and strength training differ between training groups (mE+S vs. mS+E vs. eE+S vs. eS+E)?
- 2) Does the exercise sequence in same-session combined training modes (E+S vs. S+E) affect the outcomes on endurance and strength variables?
- 3) Is time-of-day-specificity during same-session concurrent endurance and strength training (morning vs. evening) influencing endurance or strength performance during the morning or evening measurements, respectively?

## 6 RESEARCH HYPOTHESES

The hypotheses with reference to the research questions were as follows:

- 1) Overall adaptations will be elicited both in  $VO_{2max}$  and in 1RM in all intervention groups after concurrent endurance and strength training (Schumann et al. 2014a). The gains in endurance and strength variables will be of similar magnitudes in all groups (mE+S vs. mS+E vs. eE+S vs. eS+E) (Cadore et al. 2013).
- 2) The gains in endurance performance will be superior when endurance training is conducted prior to strength (E+S) compared to the opposite exercise order (S+E) (Davis et al. 2008a, 2008b). The gains in strength performance, intervention groups will perform better when strength precedes endurance exercises compared to the contrary order (Cadore et al. 2012a, 2013).
- 3) The intervention groups training in the morning times (mE+S, mS+E) tend to gain more during the morning measurements compared to the evening training groups (eE+S, eS+E). This trend will be observed likewise with the evening measurements in the opposite direction (eE+S, eS+E perform better than mE+S, mS+E) (Cappaert 1999; Chtourou & Souissi 2012).



## 7 METHODS

### 7.1 Subjects

Seventy-two men between 18 to 40 years of age were recruited from the Jyväskylä region to participate for the current study. Subject acquisition was performed through advertisements in e-mailing lists, newspapers and public places. None of the participants were involved in prior systematic endurance or strength training for at least one year prior to the study. The subjects were free of any acute or chronic illnesses, injuries or diseases and had a BMI of less than 30 kg/m<sup>2</sup>. All subjects were fully provided with information about the study design and possible risks that might occur during testing. An informed consent document was given and signed by all participants. The health status of the subjects was examined by a qualified physician before the start of the testing to approve their participation. Furthermore subjects' chronotypes were assessed by the Munich Chronotype questionnaire (Ronneberg et al. 2003). Extreme chronotypes or shift workers were excluded from the study while moderate morning- and evening-types or indifferent-types were selected. The study was performed according to the Declaration of Helsinki and was approved by the Ethical Committee of the University of Jyväskylä.

Not all participants were able to complete the training interventions. Subject dropouts occurred due to medical issues, health reasons, motivational issues or other reasons. This eventually led to a total of 52 subjects completing the entire study. The anthropometric data of the participating subjects are presented in table 5. Standing height was measured with a wall-mounted tape measurer (accuracy 0.1 cm) and subjects' body weight via digital scale (accuracy 0.1 kg). BMI (in kg/m<sup>2</sup>) was calculated as the weight (in kg) divided by the square of the subject's height (in m).

TABLE 5. Anthropometric data of study participants obtained before start of the intervention.

Group	n	Age [years]	Height [cm]	Body weight [kg]	BMI [kg/m <sup>2</sup> ]
mE+S	9	36.1 ± 6.5	180.1 ± 4.2	86.1 ± 8.9	26.5 ± 2.2
mS+E	9	30.8 ± 5.0	181.7 ± 7.6	82.0 ± 14.0	24.8 ± 3.8
eE+S	12	31.4 ± 4.6	179.8 ± 7.4	78.0 ± 8.5	24.1 ± 2.5
eS+E	12	31.4 ± 6.5	180.7 ± 5.6	80.0 ± 10.6	24.5 ± 2.7
CON	10	32.4 ± 4.9	181.3 ± 7.7	79.0 ± 12.8	23.9 ± 2.7

n=52; E+S=endurance before strength training; S+E=strength before endurance training; m=training in the morning; e=training in the evening; CON=control group.

## 7.2 Study design

The study was conducted as longitudinal with its onset in Autumn 2013 and lasted over six months until Spring 2014. Basal measurements for endurance and strength were carried out at week 0 (PRE-measurements), week 12 (MID-measurements) and week 24 (POST-measurements). Within the basal PRE-, MID- and POST-measurements, subjects were tested in the morning (between 06:00–10:00 h) and in the evening (between 16:00–20:00 h). After the PRE-measurements, subjects were assigned into one of the four training groups for the entire duration of the study, ensuring that pre-level performances of all groups were as similar as possible: morning training groups (m) performing endurance training before strength training in the same session (mE+S) or performing the opposite training order (mS+E) and evening training groups (e) performing either one of the training sequences (eE+S or eS+E). A fifth group served as a control group (CON) that did not undergo any training intervention. The 24-week training period was designed as two 12-week intervention periods, which was separated by the MID-measurements. The first part of the training period (intervention period I) consisted of 2 training sessions per week (2x E+S or 2x S+E). During the second block of the training (intervention period II), training intensity was progressively adapted, leading to 5 training sessions within 14-days (5x E+S/2 weeks or 5x S+E/2 weeks). All participants from the intervention groups and control group were instructed to keep their habitual physical activities throughout the training periods. Figure 21 illustrates the overview of the study design.

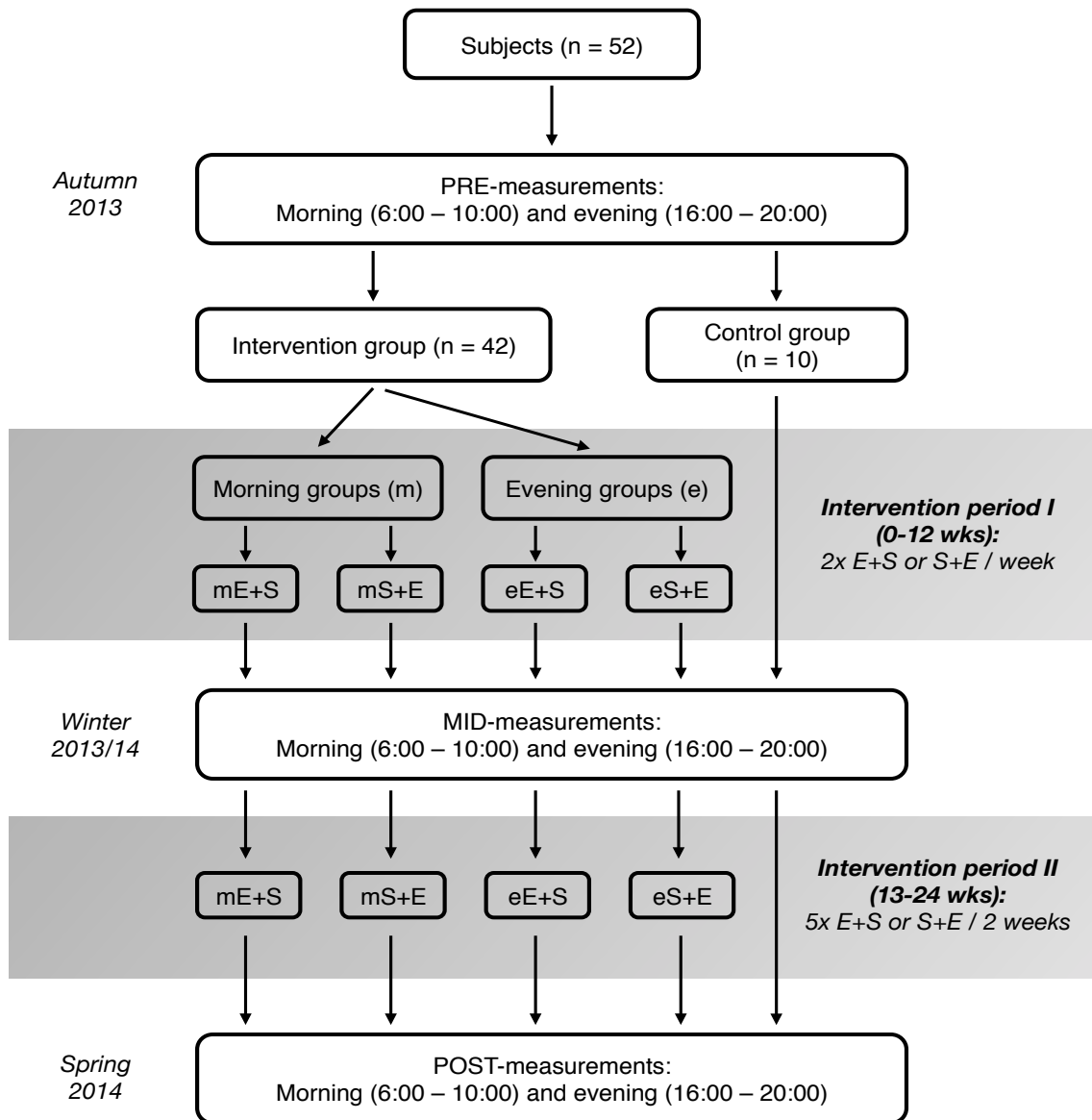


FIGURE 21. Overview of study design.

### 7.3 Training protocols

The training included a total of 24 weeks of same-session combined endurance and strength training either in the morning or evening time (mE+S, mS+E, eE+S, eS+E). All subjects were familiarised with the used training equipment, loads and procedures. The completed training programs of each intervention group were identical, except sequence of the endurance and strength training (E+S or S+E) or training time (morning or evening). The duration of the combined endurance and strength training sessions varied

from 60 to 120 minutes in length. During all training sessions qualified instructors supervised the subjects. The training implied linear progression and gradually adaptation throughout both 12-week intervention periods by manipulation of training intensity, mode and volume.

### 7.3.1 Endurance training protocol

Endurance training was carried out on a cycle ergometer and the training intensity was based on the maximal heart rate determined from the graded maximal incremental cycling test. The intensity was selected from the time-specific test, so that maximal heart rate for the morning training group was taken from the morning measurement and similarly, evening training group from the evening measures. Endurance training sessions lasted from 30-50 minutes in average. The protocol induced a gradual increase in intensity within the first three weeks of the mesocycle (4 weeks of training) followed by a 4<sup>th</sup> week of training with lower training intensity. This periodization model of training was kept throughout the first 12-week intervention period (macrocycle). The training protocol and periodization model was also applied during the second intervention period, but, as previously mentioned, intensities were adjusted from the MID-measurements and training volume was manipulated resulting in five training sessions per two weeks. Table 6 presents a more detailed description of the complete endurance training protocol.

TABLE 6. Endurance training program for the intervention groups of the study from week 1-24.

Week	<i>Intervention period I</i>			<i>Intervention period II</i>		
	1-4	5-8	9-12	13-16	17-20	21-24
Intensity*	65-80 %	70-90 %	70-95 %	65-80 %	70-90 %	70-95 %
Mode	Continuous	Continuous/ Interval	Continuous/ Interval	Continuous	Continuous/ Interval	Continuous/ Interval
Volume	2x/week	2x/week	2x/week	5x/ 2 weeks	5x/ 2 weeks	5x/ 2 weeks

\*Intensity: Based on maximal heart rate obtained from PRE-measurement. During intervention period II, intensity was adjusted from MID-measurements.

### 7.3.2 Strength training protocol

Strength training during the intervention periods included exercises for lower body, upper body and torso (table 7). All lower extremity exercises (bilateral leg press, seated knee flexion and extension) were performed in every training session. Only during the last four weeks of each intervention period (week 9-12 and 21-24, respectively) seated knee flexion and extension were executed unilaterally, otherwise bilaterally. For the muscle groups of upper body and torso, 4-6 exercises were chosen per training session. Similar training protocols were used during both intervention periods.

TABLE 7. Performed strength training exercises during the study.

		<i>Intervention period I</i>			<i>Intervention period II</i>		
		Week 1-4	5-8	9-12	13-16	17-20	21-24
Lower body	Bilateral leg press	X	X	X	X	X	X
	Seated knee flexion	X	X	X	X	X	X
	Seated knee extension	X	X	X	X	X	X
Upper body	Seated military press	X	X	X			X
	Seated dumbbell shoulder press				X	X	
	Lateral pulldown	X	X		X (front)		
	Lying dumbbell fly		X			X	
	Standing triceps pushdown on cable machine		X		X	X	
	Standing barbell biceps curl			X			X
Torso	Torso flexion/crunch on HUR bench	X		X	X	X	X
	Torso flexion/crunch		X	X			
	Back extension / hyperextension	X	X	X	X	X	X
	Standing torso twist on machine				X	X	X
Total exercises:		7	9	8	8	10	8

The first 4 weeks of each period were performed as circuit training in order to acquaint the subjects with the resistance training program, equipment and exercise techniques. The upcoming weeks were carried out as hypertrophic or as a mix of hypertrophic and maximal strength training. Explosive strength training elements were included during

both intervention periods. Table 8 illustrates the applied strength training protocol in the study more in detail.

TABLE 8. Strength training program for the intervention groups of the study from week 1-24.

Week	<i>Intervention period I</i>			<i>Intervention period II</i>		
	1-4	5-8	9-12	13-16	17-20	21-24
Training type	CT (END)	HYP	HYP / MAX / EXP	CT (END) / HYP	END / HYP	MAX / HYP / EXP-END
Intensity [%]	40-50	70-85	70-85 / 80-95 / 40	40-70 / 70-80	40-75 / 75-85	80-95 / 75-85 / 40-75
Rest [min]	-	1.5-2	1-2 / 2-3 / 1-2	-	1.5-2	2-3 / 1-2 / 1.5-2
Repetitions	15-20	8-12	8-12 / 3-5 / 10	12-20 / 10-12	12-20 / 5-12	3-5 / 8-10 / 12-20
Sets	2-3	2-4	2-4	2-3	2-3 / 2-5	4-5 / 3-4 / 2-3

Training types: CT=Circuit training; END=Strength-endurance; HYP=Hypertrophy; MAX=Maximal; EXP=Explosive.

## 7.4 Cardiorespiratory measures

### 7.4.1 Maximal cycling performance

The subjects performed a graded maximal cycling test to volitional exhaustion on a cycle ergometer (Ergometrics 800, Ergoline, Bitz, Germany) in order to determine maximal oxygen consumption ( $\text{VO}_2\text{max}$ ). The seat height on the ergometer was individually adjusted allowing a 5-15° knee angle with leg extension. No warm-up was performed before the measurement. The initial load for all participants was set at 50W and increased by 25W every two minutes. Subjects were asked to maintain pedalling frequency at  $70 \pm 3$ rpm throughout the measurement. The test terminated when the subject failed to keep the required pedalling frequency or volitionally stopped the test. After test termination subjects cycled for 5-minutes at low intensity for cool-down.

Pulmonary gas exchange was recorded continuously throughout the test by using a breath-by-breath gas analyser (MasterScreen CPX, CareFusion, Hoechberg, Germany). The subjects wore an oro-nasal facemask (VMask Model 7500, Hans Rudolph Inc, Kansas City, MO, USA) and were breathing through an attached mouthpiece with integrated volume sensors (Triple V Sensor, CareFusion, Hoechberg, Germany). At every testing occasion, the complete gas analysing system was calibrated based on the manuals and instructions of the manufacturer. Before each test air flow calibration was performed manually with a 3L ( $\pm 0.4\%$ ) calibration pump (Jaeger, CareFusion, Hoechberg, Germany) in combination with an automatic flow calibration software (Lab Manager v5.32.0, CareFusion, Hoechberg, Germany). Standardised gas concentrations of O<sub>2</sub> (16%) and CO<sub>2</sub> (4%) were used to calibrate the gas analyser. Oxygen consumption values were averaged over 60 seconds and the highest VO<sub>2</sub> value was accounted as VO<sub>2</sub>max. Maximal work rate ( $W_{\max}$ ) was calculated based on following formula:  $W_{\max} = W_{\text{com}} + (t/120) \cdot 25$ , with  $W_{\text{com}}$  representing the last completed cycling stage and with  $t$  representing the time in seconds of the last incomplete stage (Kuipers et al. 1985). A heart rate monitor was used during the entire test (Polar RS800CX and FT7, Polar Electro Oy, Kempele, Finland) and the average of the last 10 seconds at each stage was recorded. Capillary blood samples were taken from subjects' fingertips during the last 30 seconds of each stage and analysed using a lactate analyser (Biosen C-Line, EKF Diagnostic, Magdeburg, Germany). The rate of perceived exhaustion (RPE) was conducted during the last 30 seconds of each stage using the Borg scale (Borg 1982).

#### **7.4.2 Submaximal cycling performance**

The submaximal measures were taken from the graded maximal cycling test. Oxygen consumption (VO<sub>2</sub>), blood lactate (bLA) and heart rate (HR) values were combined at several watt stages of the cycling protocol (50W, 125W, 175W and 250W) and compared from PRE- to MID- and POST-measurements.

The 50W stage was taken as it represented the first stage of the graded cycling test. The 125W and 175W stages were selected after analysing all obtained blood lactate values from the intervention and control groups at PRE-measurements. The reason for taking those stages was based on the 2mmol- and 4mmol-lactate thresholds with both stages representing the closest blood lactate values to the threshold levels. After examining the

maximal work rate ( $W_{\max}$ ) at PRE-measurement of all subjects, the 250W stage came closest to the reached final stage of the maximal cycling test.

## **7.5 Dynamic strength measurements**

One repetition maximum (1RM) of the leg extensors was determined using a dynamic leg press (David 210, David Sports Ltd., Helsinki, Finland). Subjects were seated in the measuring device with a starting knee angle of around  $60^\circ$ . They were instructed to execute a bilateral concentric leg extension with the knee angle reaching  $180^\circ$  while maintaining contact to the seat and backrest. The subjects grasped from the handles on the machine to support the proper movement execution. Prior to the 1RM determination, subjects performed warm-up sets. A one-minute rest interval was used between all sets. The load for the leg press was increased after each successful attempt by 1.25kg to maximal 5kg. The test was terminated when subjects had used the maximal amount of attempts (five trials) or when subjects were unable to perform a leg press with the correct technique. All participants were encouraged verbally by the tester to evoke maximal efforts. The last successful and correctly executed attempt was set as the 1RM of the subjects (accuracy 1.25kg).

## **7.6 Statistical analysis**

Means and standard deviations (SD) were calculated with conventional statistical methods. Normal distribution of the data was checked via the Shapiro-Wilk Test of Normality and the Normal Q-Q Plots. Between-group differences of all intervention groups (mE+S, mS+E, eE+S, eS+E) and control group (CON) were analysed by using one-way ANOVA analysis of variance. Repeated measures ANOVA at three levels (PRE, MID, POST) was applied to analyse within-group differences for all given variables. Multiple and pairwise comparisons of means were provided by Bonferroni post-hoc procedures. The significance level of all tests was set at  $*p<0.05$ ,  $**p<0.01$  and  $***p<0.001$ . Statistical analysis was performed with IBM SPSS Statistics Version 21 software (IBM SPSS Inc., Chicago, IL, USA).



## 8 RESULTS

The results are sorted by the intervention groups (mE+S, mS+E, eE+S, eS+E), by the training order regardless of the training time (E+S included mE+S and eE+S; S+E consisted of mS+E and eS+E) and by the time-of-day training (morning training group=MOR and evening training group=EVE) regardless of the training sequence (MOR consisted of mE+S and mS+E and remaining groups to EVE, respectively). All groups were compared to the control group (CON).

No significant differences were observed beforehand at PRE-levels between intervention groups and controls.

### 8.1 Endurance measurements

#### 8.1.1 Maximal oxygen consumption (VO<sub>2</sub>max)

*Intervention groups.* All intervention groups improved significantly in VO<sub>2</sub>max PRE-POST comparison during morning measurements (PRE vs. POST: mE+S: 36.1±4.4 vs. 39.8±4.9 ml·min<sup>-1</sup>·kg<sup>-1</sup>, p<0.01; mS+E: 37.7±8.3 vs. 40.3±7.9, p<0.01; eE+S: 35.8±3.6 vs. 40.5±4.3, p<0.001; eS+E: 39.3±6.7 vs. 41.0±6.7, p<0.05). Changes in the control group were not statistically significant.

The only between-group difference in the intervention groups was reported in the relative changes between eE+S vs. eS+E (13.3% vs. 4.3%, p<0.05). Further significant differences were found between mE+S vs. CON (p<0.05) and eE+S vs. CON (p<0.01). Regarding relative changes between PRE-MID, eE+S tended to differ from the control group (p=0.055) (figure 22).

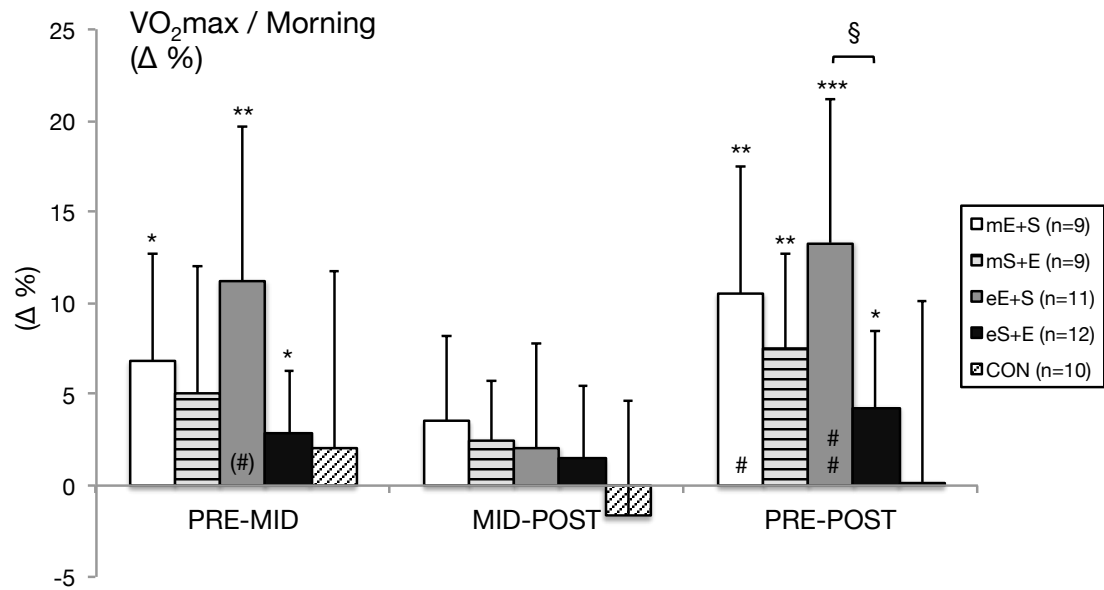


FIGURE 22. Changes in maximal oxygen consumption ( $VO_2\max$ ) during the morning measurement in all groups. \* $p < 0.05$ , \*\* $p < 0.01$  and \*\*\* $p < 0.001$  refer to within-group changes. # $p < 0.05$  and ## $p < 0.01$  indicate between-group differences compared to the control group. (#) $p < 0.06$  illustrates a trend of between group difference. § $p < 0.05$  expresses significant between-group difference between intervention groups.

At POST  $VO_2\max$  measurements in the evening, all intervention groups improved their values compared to the obtained PRE-values (figure 23). The increase of mE+S ( $36.0 \pm 3.8$  vs.  $40.5 \pm 4.6$   $\text{ml} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$ ,  $p < 0.05$ ), mS+E ( $36.3 \pm 8.3$  vs.  $39.6 \pm 8.3$ ,  $p < 0.05$ ) and eE+S ( $37.8 \pm 4.0$  vs.  $40.6 \pm 3.5$ ,  $p < 0.01$ ) were statistically significant. The eS+E intervention group ( $39.0 \pm 6.6$  vs.  $40.8 \pm 5.6$ ,  $p = 0.239$ ) showed no statistical significant change. The changes of  $VO_2\max$  values in the control group were only significant between MID-POST ( $41.5 \pm 5.7$  vs.  $40.3 \pm 5.2$ ,  $p < 0.05$ ).

The mE+S and mS+E intervention groups were the only ones, which differed statistically from the control group when comparing relative changes between PRE to POST (mE+S vs. CON:  $p < 0.01$ ; mS+E vs. CON:  $p < 0.05$ ). In relative MID to POST changes, the mE+S intervention group statistically differed from CON ( $p < 0.01$ ), while eE+S indicated a trend of differing from the controls ( $p = 0.050$ ).

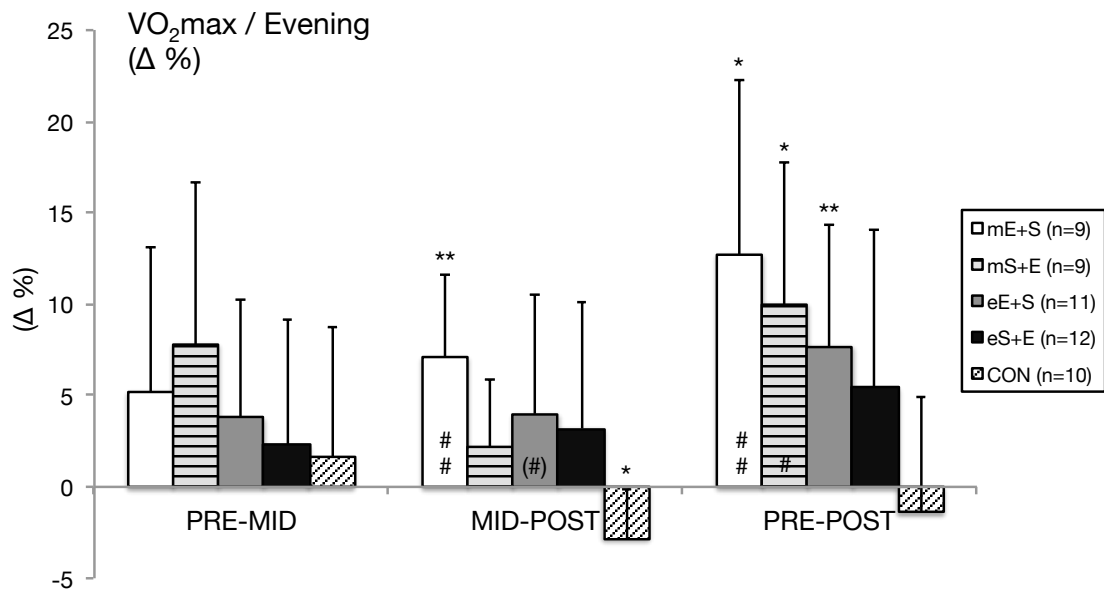


FIGURE 23. Changes in VO<sub>2</sub>max in the evening measurement in all groups. \*p<0.05 and \*\*p<0.01 refer to within-group changes. #p<0.05 and ##p<0.01 indicate between-group differences compared to the control group. (#)p<0.06 illustrates a trend of between group difference.

*Training order groups.* When classifying the outcomes by training order (figure 24), both E+S and S+E improved significantly VO<sub>2</sub>max in the morning after the 24-week training intervention (PRE-POST improvement E+S: 35.9±3.8 vs. 40.2±4.4 ml·min<sup>-1</sup>·kg<sup>-1</sup>, p<0.001; S+E: 38.6±7.3 vs. 40.7±7.1, p<0.001). The relative PRE-POST change of the E+S training sequence (12.1%) was significantly different from the S+E order (5.7%; p<0.05) and from CON (0.2% p<0.001). A similar trend was observed between E+S vs. S+E at PRE-MID comparison (9.2 vs. 3.8%, p=0.059).

Both E+S and S+E orders improved their VO<sub>2</sub>max by 10.0% and 7.4%, respectively from PRE to POST when measured in the evening (E+S: 37.0±3.9 vs. 40.5±3.9 ml·min<sup>-1</sup>·kg<sup>-1</sup>, p<0.001; S+E: 37.8±7.3 vs. 40.3±6.7, p<0.01). Significant between-group differences were between E+S vs. CON (p<0.01) and between S+E vs. CON (p<0.05) in relative MID-POST and PRE-POST comparisons, respectively.

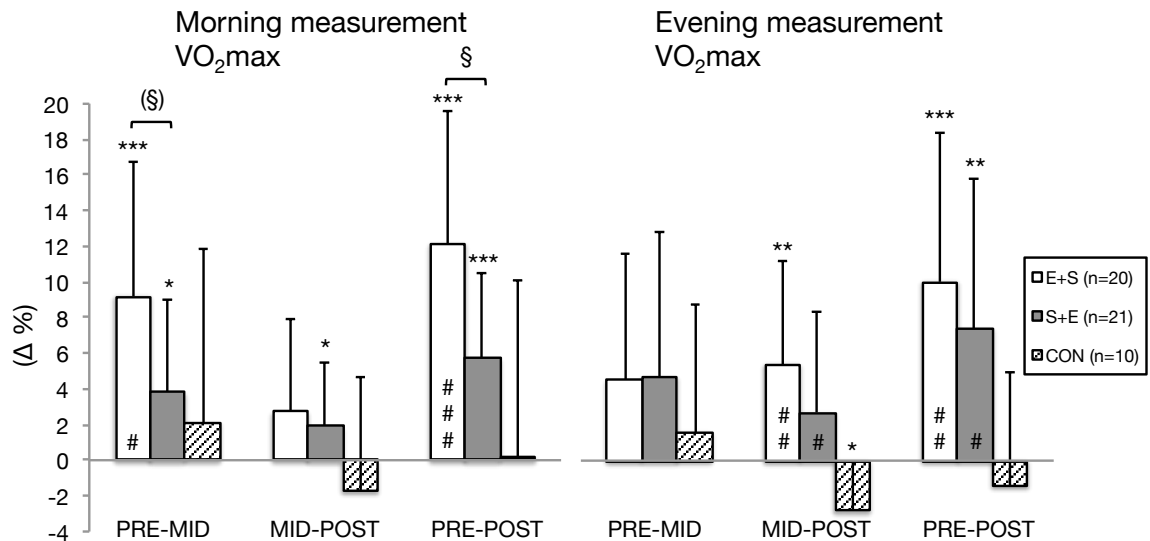


FIGURE 24. Changes of VO<sub>2</sub>max sorted by training order. \*p<0.05, \*\*p<0.01 and \*\*\*p<0.001 refer to within-group changes. #p<0.05, ##p<0.01 and ###p<0.001 indicate between-group differences compared to the control group. §p<0.05 expresses significant between-group difference between intervention groups. Symbols in brackets (#)/(§)p<0.06 illustrate a trend of between-group difference.

*Time-of-day training groups.* During the morning measurements, the morning training group differed significantly regarding the relative PRE-POST changes (MOR: 36.9±6.5 vs. 40.0±6.4 ml·min<sup>-1</sup>·kg<sup>-1</sup>, p<0.001). This was also observed for the evening training group (PRE-POST improvement: EVE: 37.6±5.6 vs. 40.7±5.6, p<0.001). No between-group difference between the MOR and EVE training group was observed, whether during the morning measurements or evening measurement. Significant between-group differences were only reported in both MOR and EVE groups compared to CON, respectively concerning relative PRE-POST changes (MOR, EVE vs. CON: p<0.05).

Concerning PRE-POST differences in the evening measurements, significant changes were observed for both morning and evening training group (MOR: 36.2±6.3 vs. 40.1±6.5 ml·min<sup>-1</sup>·kg<sup>-1</sup>, p<0.001; EVE: 38.4±5.4 vs. 40.7±4.6, p<0.01). Between-group differences were found in comparison to the control group only (MOR vs. CON: p<0.001; EVE vs. CON: p<0.05).

### 8.1.2 Maximal work rate ( $W_{max}$ )

*Intervention groups.* Maximal work rate ( $W_{max}$ ) values in the morning (figure 25) improved significantly in all intervention groups after the 24-week training intervention (PRE-POST improvement mE+S:  $254.2 \pm 28.6$  vs.  $304.8 \pm 42.0$  W,  $p < 0.001$ ; mS+E:  $241.7 \pm 41.7$  vs.  $283.2 \pm 26.9$ ,  $p < 0.01$ ; eE+S:  $236.7 \pm 34.6$  vs.  $291.7 \pm 30.1$ ,  $p < 0.001$ ; eS+E:  $254.6 \pm 45.6$  vs.  $288.1 \pm 45.0$ ,  $p < 0.01$ ).

With regard to between-group differences, the relative improvement in the eE+S intervention group (23.9%) was statistically significant in comparison to the eS+E intervention group (13.7%,  $p < 0.05$ ). Further, statistical significances in between-group differences were found for all intervention groups in comparison to the controls in relative PRE-POST changes (mE+S, mS+E, eE+S vs. CON:  $p < 0.001$ ; eS+E vs. CON:  $p < 0.01$ ).

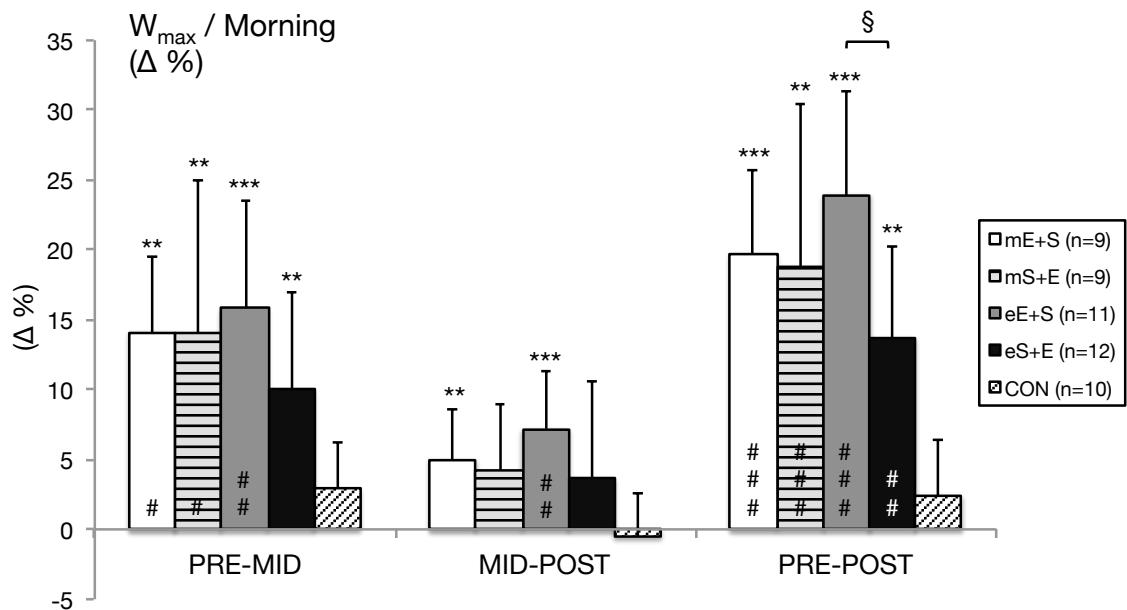


FIGURE 25. Changes in maximal work rate ( $W_{max}$ ) during the morning measurement in all groups. \*\* $p < 0.01$  and \*\*\* $p < 0.001$  refer to within-group changes. # $p < 0.05$ , ## $p < 0.01$  and ### $p < 0.001$  express between-group differences compared to the control group. § $p < 0.05$  indicates significant between-group difference between intervention groups.

During the evening measurements (figure 26),  $W_{\max}$  also significantly increased at POST in all intervention groups compared to the PRE-measurement values (mE+S:  $259.7 \pm 35.3$  vs.  $305.2 \pm 41.8$  W,  $p < 0.001$ ; mS+E:  $243.4 \pm 37.3$  vs.  $282.7 \pm 30.4$ ,  $p < 0.001$ ; eE+S:  $240.3 \pm 37.2$  vs.  $295.0 \pm 30.0$ ,  $p < 0.001$ ; eS+E:  $256.7 \pm 46.8$  vs.  $294.7 \pm 37.4$ ,  $p < 0.001$ ).

In relative MID-POST changes, mS+E vs. eE+S comparison was the only between-group difference observed within intervention groups. The relative improvement by 2.9% in mS+E differed significantly from the relative change in the eE+S intervention group (9.7%,  $p < 0.05$ ). Significant between-group differences were found for all intervention groups in comparison to CON in relative PRE-POST changes (mE+S, mS+E, eS+E vs. CON:  $p < 0.01$ ; eE+S vs. CON:  $p < 0.001$ ).

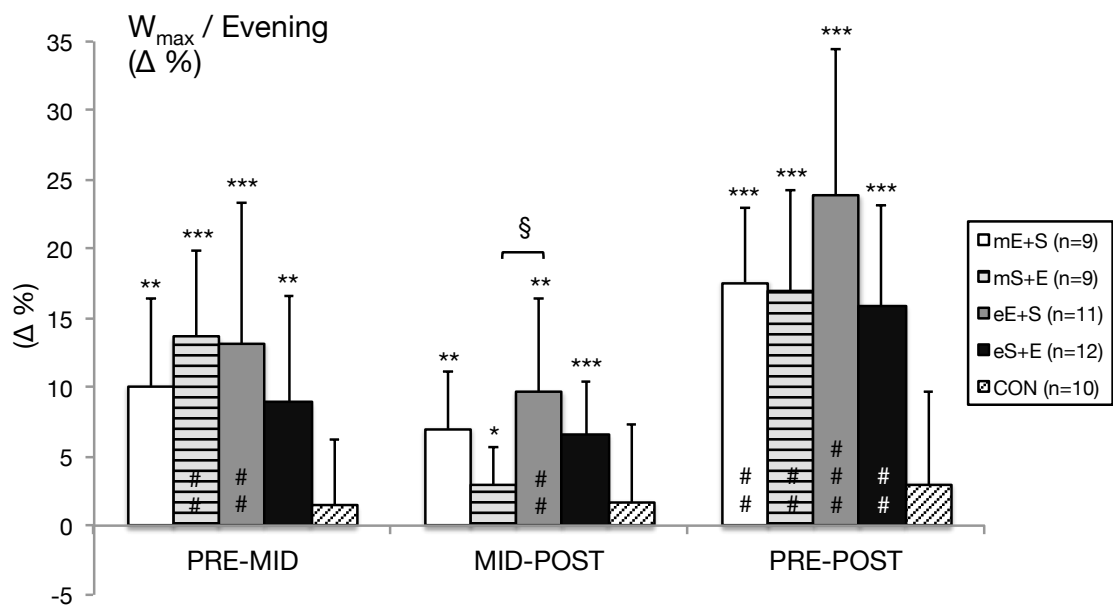


FIGURE 26. Changes in  $W_{\max}$  during the evening measurement in all groups. \* $p < 0.05$ , \*\* $p < 0.01$  and \*\*\* $p < 0.001$  refer to within-group changes. ## $p < 0.01$  and ### $p < 0.001$  illustrate between-group differences compared to the control group. § $p < 0.05$  indicates significant between-group difference between intervention groups.

*Training order groups.* During the morning measurements E+S and S+E increased their  $W_{\max}$  significantly when comparing changes from PRE- to POST-measurements (E+S:  $244.6 \pm 32.5$  vs.  $297.6 \pm 35.6$  W,  $p < 0.001$ ; S+E:  $249.1 \pm 43.4$  vs.  $286.0 \pm 37.6$ ,  $p < 0.001$ ).

Only during the morning measurement, a significant difference in intervention groups was observed between the E+S vs. the S+E sequence (22.0 vs. 15.9%,  $p<0.05$ ).

During the evening measurements, both training orders significantly improved their  $W_{\max}$  levels from PRE- to POST (E+S:  $249.1\pm36.7$  vs.  $299.6\pm35.2$  W,  $p<0.001$ ; S+E:  $251.0\pm42.5$  vs.  $289.5\pm34.3$ ,  $p<0.001$ ). Both training order groups showed significant differences to the controls at morning and evening measurements ( $p<0.001$ ) (figure 27).

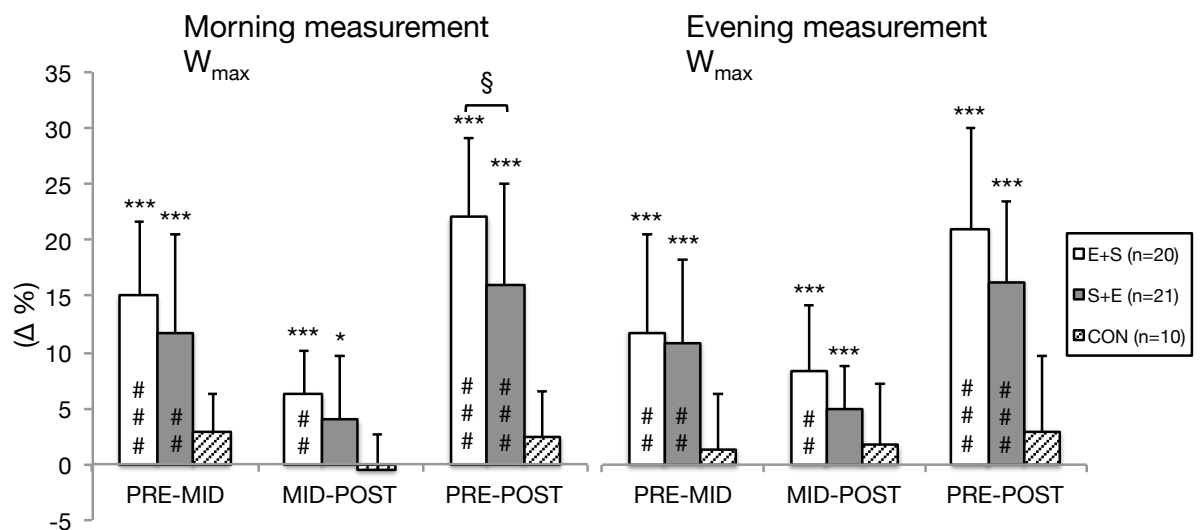


FIGURE 27. Changes in  $W_{\max}$  sorted by training order. \* $p<0.05$ , \*\* $p<0.01$  and \*\*\* $p<0.001$  refer to within-group changes. ## $p<0.01$  and ### $p<0.001$  indicate between-group differences compared to the control group. § $p<0.05$  expresses significant between-group difference between intervention groups. Symbols in brackets (#)/(\$) $p<0.06$  illustrate a trend of between-group difference.

*Time-of-day training groups.* When all intervention groups were arranged by time-of-day, morning and evening training groups showed significant increases at POST compared to the PRE-values in the morning measurements (MOR:  $248.0\pm35.3$  vs.  $294.0\pm36.0$  W,  $p<0.001$ ; EVE:  $246.1\pm40.8$  vs.  $289.9\pm37.8$ ,  $p<0.001$ ). Between-group differences were only observed between MOR and EVE group vs. control group in morning and evening measurements in relative PRE-POST changes ( $p<0.001$ ).

In the evening, both MOR and EVE groups showed significant increases in relative PRE-POST changes (MOR:  $251.6 \pm 36.2$  vs.  $293.9 \pm 37.3$  W,  $p < 0.001$ ; EVE:  $248.9 \pm 42.4$  vs.  $294.8 \pm 33.3$ ,  $p < 0.001$ ).

## 8.2 Submaximal performance

*50W stage.* The submaximal results of oxygen consumption ( $VO_2$ ), blood lactate (bLA) and heart rate (HR) at the 50W stage of the graded maximal cycling test are shown in table 9. No statistically significant changes were observed in oxygen consumption ( $VO_2$ ) neither during morning measurements nor during evening measurements.

TABLE 9. Submaximal measures at the 50W stage from the graded maximal cycling test.

		Submaximal measures at 50W, 0:00-1:59					
		At morning measurement			At evening measurement		
		PRE	MID	POST	PRE	MID	POST
mE+S	<b>VO<sub>2</sub></b>	$12.6 \pm 2.3$	$12.6 \pm 1.0$	$12.4 \pm 1.1$	$12.9 \pm 1.5$	$12.6 \pm 1.1$	$12.9 \pm 1.5$
	<b>bLA</b>	$1.3 \pm 0.5$	$1.3 \pm 0.3$	$1.7 \pm 0.5$	$1.1 \pm 0.4$	$1.0 \pm 0.3$	$1.5 \pm 0.4^{**\#}$
	<b>HR</b>	$106.4 \pm 13.1$	$98.3 \pm 10.9$	$95.0 \pm 11.8$	$102.1 \pm 16.6$	$99.2 \pm 12.5$	$98.2 \pm 14.8$
mS+E	<b>VO<sub>2</sub></b>	$12.5 \pm 2.0$	$13.1 \pm 2.3$	$12.8 \pm 2.0$	$13.3 \pm 1.8$	$12.7 \pm 2.0$	$12.5 \pm 1.6$
	<b>bLA</b>	$1.2 \pm 0.5$	$1.4 \pm 0.4$	$1.7 \pm 0.5^{**}$	$1.4 \pm 0.4$	$1.3 \pm 0.3$	$1.8 \pm 0.5\#$
	<b>HR</b>	$105.1 \pm 13.2$	$100.9 \pm 11.4$	$99.2 \pm 8.8$	$109.7 \pm 22.8$	$100.2 \pm 11.4$	$98.9 \pm 9.9$
eE+S	<b>VO<sub>2</sub></b>	$13.3 \pm 1.1$	$13.6 \pm 1.3$	$12.8 \pm 1.2$	$13.3 \pm 1.2$	$14.1 \pm 1.7$	$13.6 \pm 1.3$
	<b>bLA</b>	$1.2 \pm 0.3$	$1.2 \pm 0.2$	$1.6 \pm 0.3^{**}$	$1.1 \pm 0.3$	$1.1 \pm 0.3$	$1.4 \pm 0.3^{**\#}$
	<b>HR</b>	$96.9 \pm 7.1$	$99.5 \pm 8.3$	$94.8 \pm 7.4$	$105.3 \pm 11.2$	$102.6 \pm 12.3$	$98.2 \pm 7.0$
eS+E	<b>VO<sub>2</sub></b>	$13.7 \pm 1.2$	$13.3 \pm 1.8$	$13.4 \pm 1.8$	$13.3 \pm 1.3$	$13.4 \pm 1.6$	$13.3 \pm 1.5$
	<b>bLA</b>	$1.1 \pm 0.2$	$1.1 \pm 0.3$	$1.7 \pm 0.5^{**}$	$0.9 \pm 0.2$	$1.0 \pm 0.2$	$1.5 \pm 0.3^{**\#\#\#}$
	<b>HR</b>	$105.1 \pm 8.8$	$99.4 \pm 8.3$	$100.7 \pm 11.6$	$109.5 \pm 12.2$	$103.4 \pm 11.9$	$98.0 \pm 10.0^{**}$
CON	<b>VO<sub>2</sub></b>	$13.6 \pm 2.6$	$13.7 \pm 2.5$	$13.4 \pm 1.8$	$14.4 \pm 2.3$	$14.1 \pm 2.8$	$13.3 \pm 2.2$
	<b>bLA</b>	$1.4 \pm 0.3$	$1.3 \pm 0.6$	$1.6 \pm 0.2$	$1.3 \pm 0.5$	$1.5 \pm 0.3$	$1.6 \pm 0.5^*$
	<b>HR</b>	$107.3 \pm 17.8$	$103.9 \pm 14.7$	$101.3 \pm 15.3$	$106.4 \pm 14.2$	$102.3 \pm 11.1$	$99.8 \pm 10.0$

All values are shown as mean $\pm$ SD.  $VO_2$  is represented in [ $ml \cdot min^{-1} \cdot kg^{-1}$ ], bLA in [ $mmol \cdot min^{-1}$ ], HR in [bpm]. \* $p < 0.05$ , \*\* $p < 0.01$  and \*\*\* $p < 0.001$  indicate significant within-group changes to PRE-measurement; # $p < 0.05$  and ### $p < 0.001$  illustrate significant difference to MID-measurement.

During the morning tests, blood lactate (bLA) was increased statistically significant in mS+E, eE+S and eS+E ( $p < 0.01$ ) in PRE-POST comparison. Statistical significant increases in PRE-POST difference during the evening measurements were found in mE+S, eE+S, eS+E ( $p < 0.01$ ) and CON ( $p < 0.05$ ). Furthermore, bLA in all intervention



groups rose significantly in MID-POST comparisons (mE+S, mS+E, eE+S:  $p < 0.05$ , eS+E:  $p < 0.01$ ). Heart rate (HR) decreased significantly only in the eS+E intervention group ( $p < 0.01$ ) in PRE-POST change.

*125W stage.* Statistical significant raises in  $VO_2$  were observed in the eS+E group ( $p < 0.01$ ) during the morning and mS+E ( $p < 0.05$ ), eE+S ( $p < 0.001$ ) groups during the evening measures. Regarding blood lactate values, no significant changes were reported. HR decreased in all groups from PRE to POST in both time-of-day measurements. During morning measurements, significant increases were observed in mS+E ( $p < 0.05$ ) and eE+S ( $p < 0.01$ ). During the evening tests, all groups significantly increased  $VO_2$  in PRE-POST comparison (mE+S, mS+E, eE+S, CON:  $p < 0.05$ ; eS+E:  $p < 0.01$ ) (table 10).

TABLE 10. Submaximal measures at the 125W stage from the graded maximal cycling test.

		Submaximal measures at 125W, 6:00-7:59					
		At morning measurement			At evening measurement		
		PRE	MID	POST	PRE	MID	POST
mE+S	<b>VO<sub>2</sub></b>	20.5 ± 2.6	19.6 ± 1.9	19.5 ± 1.6	20.0 ± 1.7	19.8 ± 1.7	20.3 ± 2.2
	<b>bLA</b>	2.1 ± 0.5	1.9 ± 0.5	2.1 ± 0.4	2.0 ± 0.5	1.9 ± 0.6	2.1 ± 0.4
	<b>HR</b>	136.6 ± 17.9	123.0 ± 15.8	119.4 ± 15.1	131.3 ± 15.4	125.3 ± 14.6	121.2 ± 16.2*
mS+E	<b>VO<sub>2</sub></b>	21.9 ± 3.4	21.3 ± 3.4	21.2 ± 3.3	21.5 ± 2.6	20.8 ± 2.9	20.3 ± 3.3*
	<b>bLA</b>	2.6 ± 1.3	2.2 ± 0.8	2.4 ± 0.8	2.7 ± 1.0	2.2 ± 0.5	2.6 ± 0.8
	<b>HR</b>	140.6 ± 15.3	132.7 ± 11.9	128.6 ± 11.0*	140.7 ± 15.9	131.7 ± 9.1	126.2 ± 8.6*
eE+S	<b>VO<sub>2</sub></b>	22.2 ± 2.2	21.5 ± 2.0	21.2 ± 1.8	23.0 ± 1.8	21.9 ± 2.3	21.8 ± 1.7***
	<b>bLA</b>	2.4 ± 0.6	2.1 ± 0.4	2.2 ± 0.4	2.4 ± 0.9	2.1 ± 0.8	2.1 ± 0.5
	<b>HR</b>	133.5 ± 11.3	128.0 ± 8.7	123.1 ± 10.2**	140.9 ± 14.1	133.1 ± 12.7	127.7 ± 11.1*
eS+E	<b>VO<sub>2</sub></b>	22.6 ± 2.5	21.4 ± 2.9	21.0 ± 2.9**	22.1 ± 2.8	21.2 ± 2.8	21.1 ± 3.0
	<b>bLA</b>	2.1 ± 1.0	1.7 ± 0.7	2.2 ± 1.1#	2.0 ± 1.1	1.8 ± 0.8	2.1 ± 0.5
	<b>HR</b>	138.7 ± 14.6	127.4 ± 12.4	127.5 ± 13.7	138.8 ± 16.7	129.9 ± 13.0	124.0 ± 11.8**
CON	<b>VO<sub>2</sub></b>	22.3 ± 3.5	22.1 ± 4.0	22.0 ± 3.4	22.4 ± 3.6	22.5 ± 4.4	21.7 ± 3.4
	<b>bLA</b>	2.1 ± 0.8	2.0 ± 0.7	2.5 ± 0.9	2.0 ± 0.8	2.3 ± 0.7	2.6 ± 0.9
	<b>HR</b>	140.8 ± 16.4	133.3 ± 15.8	134.8 ± 18.3	138.3 ± 14.5	134.1 ± 14.8	130.6 ± 16.3*

All values are shown as mean±SD.  $VO_2$  is represented in [ $ml \cdot min^{-1} \cdot kg^{-1}$ ], bLA in [ $mmol \cdot min^{-1}$ ], HR in [bpm]. \* $p < 0.05$ , \*\* $p < 0.01$  and \*\*\* $p < 0.001$  indicate significant within-group changes to PRE-measurement; # $p < 0.05$  illustrate significant difference to MID-measurement.

*175W stage.* During the 175W stage in the morning measurements (figure 28),  $VO_2$  values decreased significantly in PRE-POST comparison for the mS+E ( $p<0.05$ ) and for eS+E intervention group ( $p<0.01$ ). The mE+S intervention group differed significantly in MID-POST comparison ( $p<0.05$ ), while mE+S and eS+E intervention groups showed significant differences when comparing PRE to MID ( $p<0.05$ ).

Values of bLA decreased only significantly in the eE+S intervention group at POST compared to PRE ( $p<0.01$ ).

HR significantly decreased in all intervention groups from PRE to POST (mE+S:  $p<0.05$ ; mS+E:  $p<0.01$ ; eE+S, eS+E:  $p<0.001$ ). In PRE-MID comparisons, significant differences were observed in the mS+E ( $p<0.05$ ), eE+S ( $p<0.001$ ) and eS+E intervention group ( $p<0.01$ ).

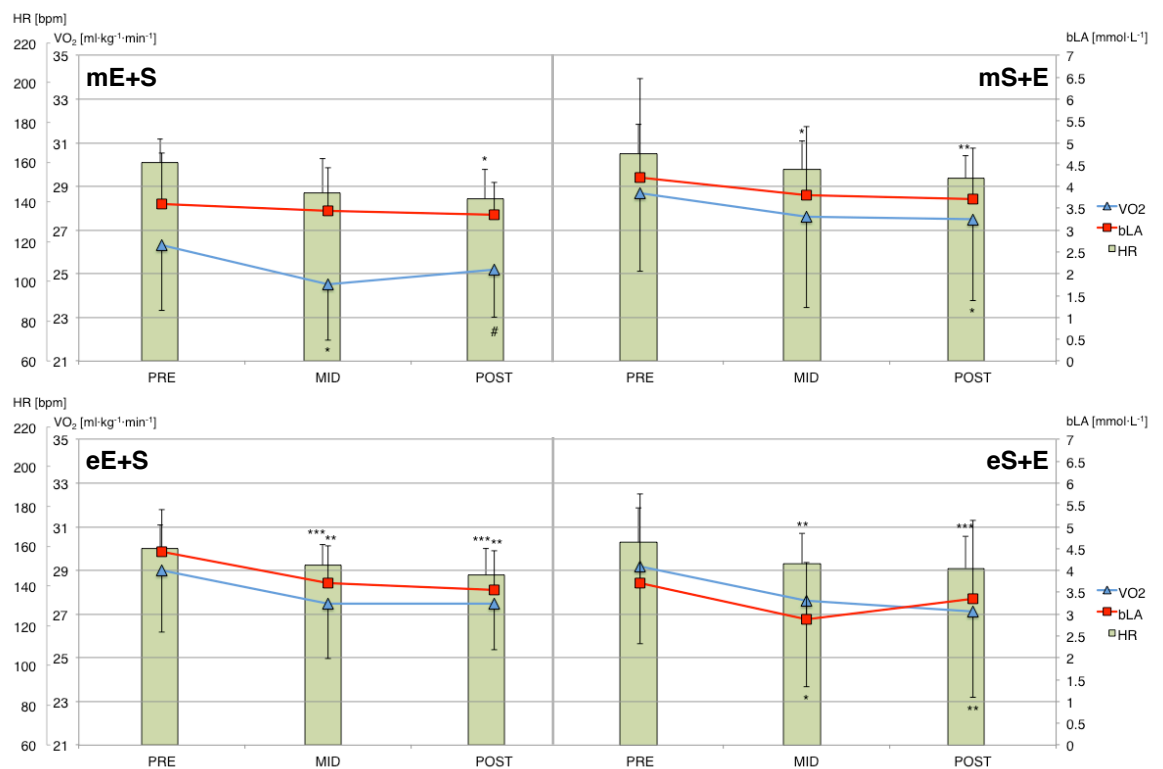


FIGURE 28. Submaximal results at the 175W stage measured in the morning. \* $p<0.05$ , \*\* $p<0.01$  and \*\*\* $p<0.001$  indicate changes to PRE-measurements. # $p<0.05$  represents changes to MID-measurements.

In the evening measurements (figure 29), oxygen consumption decreased significantly in mS+E ( $p<0.05$ ), eE+S ( $p<0.001$ ) and eS+E intervention group ( $p<0.05$ ) in POST comparing to the PRE-values. Both S+E training orders further differed significantly in PRE-MID comparison (mS+E:  $p<0.05$ ; eS+E:  $p<0.01$ ).

None of the blood lactate changes at 175W were statistically significant.

Heart rate values decreased significantly in all groups between PRE-POST (mE+S, mS+E:  $p<0.05$ ; eE+S:  $p<0.001$ ; eS+E/CON:  $p<0.01$ ). In PRE-MID, mS+E, eE+S and eS+E differed statistically significantly ( $p<0.05$ ).

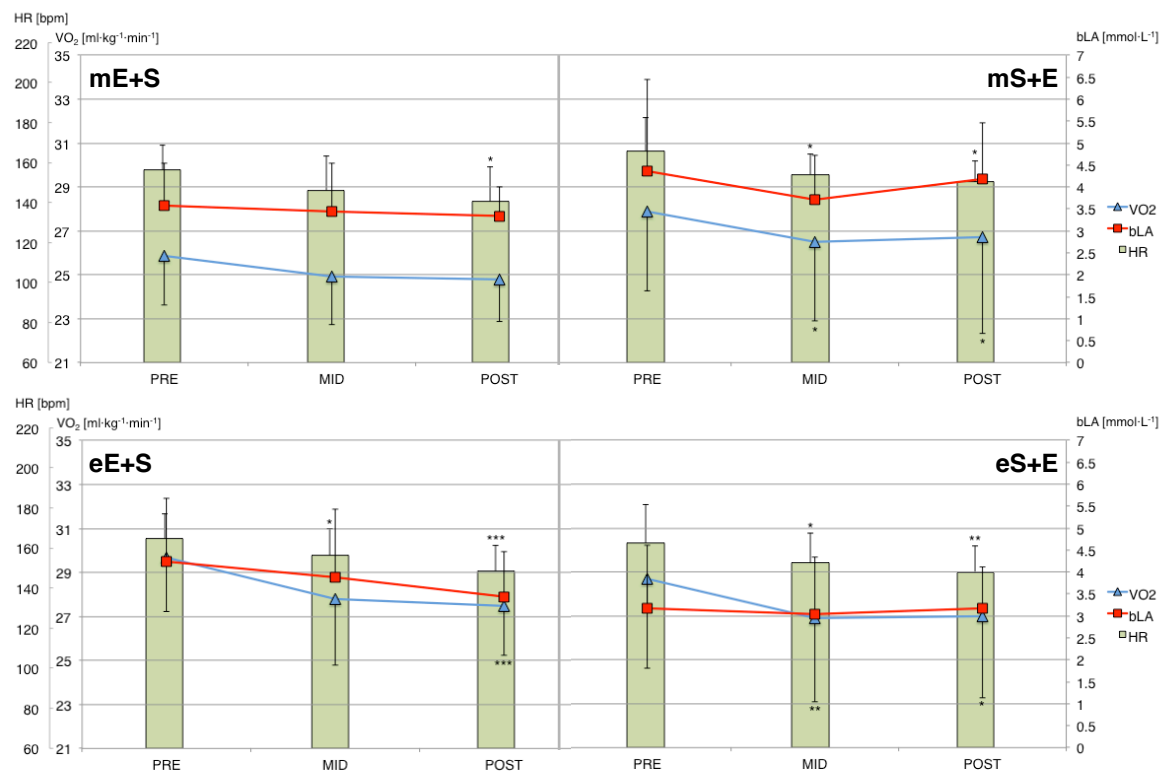


FIGURE 29. Submaximal results at the 175W stage measured in the evening. \* $p<0.05$ , \*\* $p<0.01$  and \*\*\* $p<0.001$  indicate changes to PRE-measurements.

250W stage. Oxygen consumption at 250W decreased significantly only in the eS+E intervention group ( $p<0.05$ ) when comparing PRE to POST. In bLA, eS+E showed a significant decrease in POST-values compared to PRE ( $p<0.05$ ). The intervention groups mS+E ( $p<0.05$ ), eE+S and eS+E (both  $p<0.01$ ) were significantly lowered HR values in PRE-POST comparison in the morning tests. During the evening

measurements, mE+S ( $p<0.01$ ), eE+S, eS+E (both  $p<0.05$ ) and CON ( $p<0.01$ ) showed significant differences when comparing PRE-POST. The mE+S intervention group also differed significantly in MID-POST comparison ( $p<0.01$ ) (table 11).

TABLE 11. Submaximal measures at the 250W stage from the graded maximal cycling test.

		Submaximal measures at 250W, 16:00-17:59					
		At morning measurement			At evening measurement		
		PRE	MID	POST	PRE	MID	POST
mE+S	VO <sub>2</sub>	34.4 ± 4.8	34.3 ± 2.9	34.3 ± 3.3	34.2 ± 3.3	34.1 ± 2.9	34.5 ± 2.9
	bLA	9.4 ± 2.7	8.3 ± 3.1	7.1 ± 2.1	8.3 ± 3.3	8.0 ± 2.7	7.2 ± 2.1
	HR	184.3 ± 12.8	172.8 ± 15.3	168.6 ± 15.6	182.1 ± 9.2	175.6 ± 14.9	161.1 ± 14.2***##
mS+E	VO <sub>2</sub>	41.8 ± 2.7	37.6 ± 5.6	36.6 ± 5.5	40.4 ± 2.6	36.1 ± 5.5	36.0 ± 6.3
	bLA	7.5 ± 1.9	8.6 ± 2.9	8.3 ± 2.7	8.0 ± 2.0	8.0 ± 2.1	9.0 ± 2.8
	HR	183.7 ± 12.1	178.5 ± 13.1	178.1 ± 11.5*	183.6 ± 16.4	178.9 ± 11.7	175.3 ± 11.9
eE+S	VO <sub>2</sub>	34.3 ± 3.3	37.5 ± 3.6	36.7 ± 3.3	36.8 ± 3.3	37.0 ± 3.8	37.1 ± 3.3
	bLA	9.4 ± 2.2	8.9 ± 2.3	8.2 ± 2.2*	8.4 ± 2.5	8.8 ± 2.9	7.7 ± 2.7
	HR	179.4 ± 7.2	178.3 ± 9.1	173.1 ± 12.4**	182.3 ± 5.6	178.4 ± 9.8*	175.6 ± 12.2*
eS+E	VO <sub>2</sub>	37.6 ± 4.0	35.7 ± 5.1	36.3 ± 4.9*	35.1 ± 4.1	36.4 ± 5.6	36.2 ± 5.3
	bLA	7.6 ± 3.0	7.2 ± 2.6	6.7 ± 2.8	6.6 ± 2.6	7.6 ± 2.8	6.8 ± 2.5
	HR	178.3 ± 13.4	177.1 ± 14.9	172.8 ± 14.5**	181.1 ± 14.6	177.5 ± 14.5**	174.4 ± 15.0*
CON	VO <sub>2</sub>	36.2 ± 8.4	36.9 ± 6.0	36.8 ± 5.5	37.9 ± 5.7	38.4 ± 6.4	36.7 ± 5.1
	bLA	8.6 ± 3.0	7.7 ± 3.0	8.4 ± 3.6	8.1 ± 2.7	8.5 ± 2.7	8.4 ± 3.4
	HR	185.3 ± 6.8	181.4 ± 7.6	181.8 ± 10.1	183.0 ± 9.6	182.7 ± 8.1	181.2 ± 10.9**

All values are shown as mean±SD. VO<sub>2</sub> is represented in [ $\text{ml} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$ ], bLA in [ $\text{mmol} \cdot \text{min}^{-1}$ ], HR in [bpm]. \* $p<0.05$ , \*\* $p<0.01$  and \*\*\* $p<0.001$  indicate significant within-group changes to PRE-measurement; # $p<0.05$  and ### $p<0.001$  illustrate significant difference to MID-measurement.

### 8.3 Strength performance

*Intervention groups.* All intervention groups improved significantly their 1RM leg press in POST- compared to PRE-measurements during the morning measurements (mE+S:  $161.8 \pm 20.4$ ,  $p<0.001$ ; mS+E:  $149.1 \pm 22.3$ ,  $p<0.01$ ; eE+S:  $142.6 \pm 24.7$ ,  $p<0.001$ ; eS+E:  $142.5 \pm 25.1$ ,  $p<0.001$ ) (figure 30).

No between-group differences within the intervention groups were observed. The mS+E, eE+S and S+E intervention groups differed statistically significant from the control group (mS+E vs. CON:  $p<0.05$ ; eE+S, eS+E vs. CON:  $p<0.01$ ).

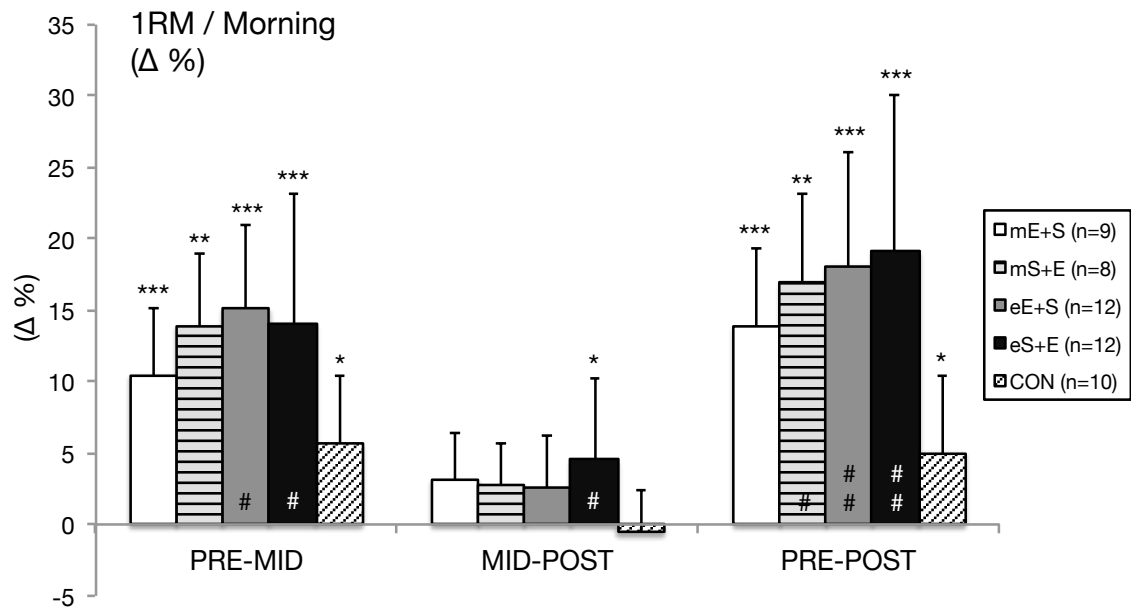


FIGURE 30. Changes in dynamic 1RM leg press during the morning measurement in all groups. \* $p < 0.05$ , \*\* $p < 0.01$  and \*\*\* $p < 0.001$  refer to within-group changes. # $p < 0.05$  and ## $p < 0.01$  indicate between-group differences compared to the control group.

All intervention groups increased significantly in PRE-POST comparison in the evening tests (mE+S:  $158.3 \pm 21.4$ ,  $p < 0.001$ ; mS+E:  $146.6 \pm 24.6$ ,  $p < 0.01$ ; eE+S:  $140.4 \pm 25.6$ ,  $p < 0.01$ ; eS+E:  $138.9 \pm 25.8$ ,  $p < 0.001$ ).

While no between-group differences were found, all intervention groups showed statistical significance in comparison to CON at PRE-POST comparison (mE+S vs. CON:  $p < 0.05$ ; mS+E, eE+S vs. CON:  $p < 0.01$ ; eS+E vs. CON:  $p < 0.001$ ) (figure 31).

*Training order groups.* Both training sequences significantly increased 1RM in PRE-POST comparison in the morning tests (E+S:  $150.8 \pm 24.4$ ,  $p < 0.001$ ; S+E:  $145.1 \pm 23.6$ ,  $p < 0.001$ ) and during the evening measurements (E+S:  $148.1 \pm 25.0$ ,  $p < 0.001$ ; S+E:  $141.9 \pm 25.0$ ,  $p < 0.001$ ). Between-group differences were found only in comparison to the control group (at morning: E+S vs. CON:  $p < 0.01$ ; S+E vs. CON:  $p < 0.001$ ; at evening: E+S, S+E vs. CON:  $p < 0.001$ ).

*Time-of-day training groups.* In the morning tests, both time-of-day groups MOR and EVE statistically increased 1RM at POST- compared to PRE-measurements (MOR:  $155.8 \pm 21.6$ ,  $p < 0.001$ ; EVE:  $142.6 \pm 24.3$ ,  $p < 0.001$ ).

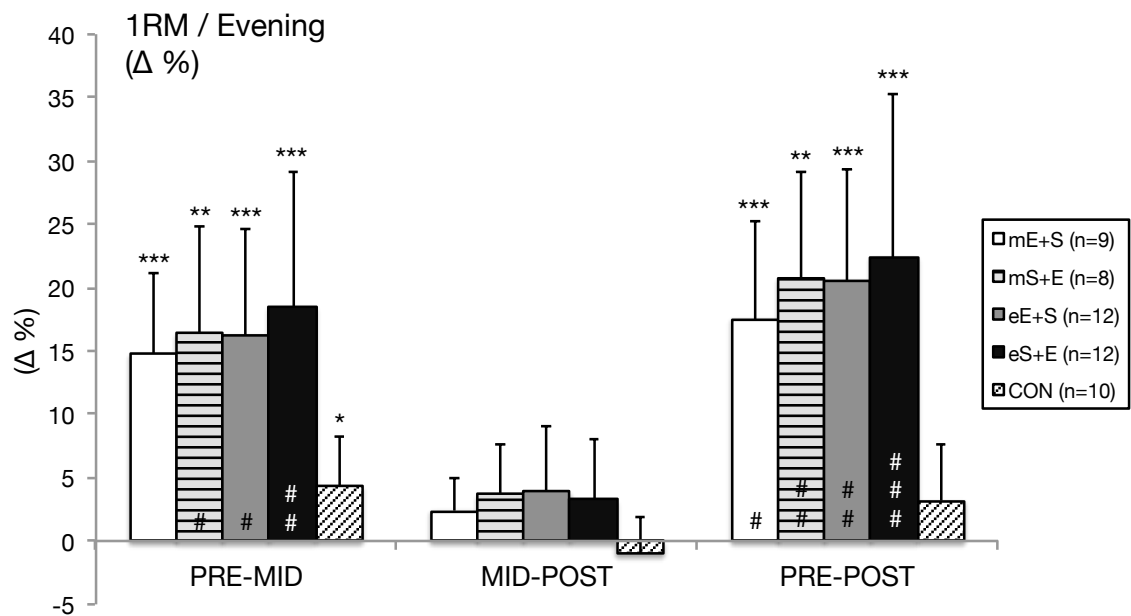


FIGURE 31. Changes in dynamic 1RM leg press during the evening measurement in all groups. \* $p < 0.05$ , \*\* $p < 0.01$  and \*\*\* $p < 0.001$  refer to within-group changes. # $p < 0.05$ , ## $p < 0.01$  and ### $p < 0.001$  indicate between-group differences compared to the control group.

Similarly during the evening measurements, PRE-POST values increased significantly (MOR:  $152.8 \pm 23.0$ ,  $p < 0.001$ ; EVE:  $139.6 \pm 25.2$ ,  $p < 0.001$ ). Both time-of-day groups significantly differed from the control group in both morning and evening measurements (at morning: MOR vs. CON:  $p < 0.01$ ; EVE vs. CON:  $p < 0.001$ ; at evening: MOR, EVE vs. CON:  $p < 0.001$ ). No between-group differences within the time-of-day groups were found.

## 9 DISCUSSION

The purpose of the present study was to examine the effect of time-of-day-specific same-session combined endurance (E) and strength (S) training over 24 weeks on submaximal and maximal endurance parameters in untrained men aged 18 to 40. The study evaluated the influence of the exercise sequence (E+S vs. S+E) in combination to the time of day (morning vs. evening) at which training was performed.

The primary results demonstrated that same-session combined endurance and strength training induced significant increases in endurance and strength performance in untrained men. Moreover, significant between-group differences in endurance performance were found in the morning measurements between eE+S vs. eS+E ( $VO_2\text{max}$ : 13.3% vs. 4.3%,  $p < 0.05$ ;  $W_{\text{max}}$ : 12.1% vs. 5.7%,  $p < 0.05$ ) and when sorted by training order only E+S vs. S+E ( $VO_2\text{max}$ : 24.0% vs. 13.7%,  $p < 0.05$ ;  $W_{\text{max}}$ : 22.0% vs. 15.9%,  $p < 0.05$ ). This led to the suggestion that an order effect was observed presuming superior endurance performance, when endurance exercises preceded strength exercises. The magnitude of adaptations between the intervention groups was not influenced by training at certain daytime, thus, the assumption of an possible time-of-day effect was not confirmed by our findings.

### 9.1 Endurance performance

#### 9.1.1 $VO_2\text{max}$

All intervention groups improved their maximal oxygen consumption following 24 weeks of combined endurance and strength training. The significant changes from PRE- to the POST-measurements ranged from 4.3 to 13.3% during the morning measurements and from 7.7 to 12.7% in the evening tests with one group showed no statistical significant increase (eS+E: 5.4%). This corresponds to other studies that have investigated concurrent training in untrained men over a prolonged period of time (Cadore et al. 2012a; Holviala et al. 2012; Häkkinen et al. 2003; Sale et al. 1990b). The enhancement of endurance performance after concurrent endurance and strength

training was reported previously due to fibre type distributions and properties (increase in size of type I fibres, changes in myofibril contractile properties and in type II subtype ratios) (Aagaard et al. 2011; Chtara et al. 2005; Tanaka & Swensen 1998) and that might have contributed also to our present investigation.

However, the magnitude of  $\text{VO}_2\text{max}$  adaptations in our present study differs e.g. from Häkkinen and colleagues' (2003) investigation reporting an 18.5% improvement after 21 weeks of combined S+E training. In comparison to the results from our S+E intervention groups (at morning measurements: mS+E: 7.5%, eS+E: 4.3%; at evening measurements: mS+E: 10.0%, eS+E: 5.4%), possible influence might be explained by our training volume (24 weeks vs. 21 weeks) and the difference of our same-session combined training vs. the different-day concurrent training. Nonetheless, Sale and colleagues (1990a) showed  $\text{VO}_2\text{max}$  increases by 7% and 8% in same-session combined E+S and S+E training, respectively after a 22-week intervention period, which was closer to our present findings. Thus, the present study design including time-of-day-specific training times of our intervention groups might be another influencing factor to consider.

Significant between-group difference in maximal oxygen consumption was observed in eE+S vs. eS+E (13.3 vs. 4.3%) at morning measurement. This was also reported when the results were sorted by training order comparing E+S vs. S+E (12.1% vs. 5.7%) at morning tests. Thus, those results from our study would suggest an order effect concerning  $\text{VO}_2\text{max}$ . The manipulation of our training design (intensity, volume, frequency) might induce this effect in exercise sequence on endurance performance (Cadore et al. 2012a). Likewise suggestions were proposed by Chtara et al. (2005), in which the gains in aerobic capacity were superior particularly when endurance was trained before strength training, whereas endurance improvements were compromised with the opposite training order (S+E). This was also presumed by Dolezal & Potteiger (1998), who documented limitations in adaptations or disrupted enhancements in endurance when strength preceded endurance exercises. It has been assumed that endurance prior to strength training within combined training interventions may be advantageous to aerobic performance due to synergic interactions (Davis et al. 2008a). The basic indication on the compromised endurance results might be evoked by the previous strength workload that induce residual fatigue for the upcoming endurance



training and therefore, impair aerobic adaptations (e.g. by reducing capillary and mitochondrial volume density) (Chtara et al. 2005; Davitt et al. 2014; Dolezal & Potteiger 1998).

With regard to time-of-day effects, the present study demonstrated no statistical significances according to morning or evening performances. This is similar to previous studies, which failed to prove any diurnal or circadian influences on  $\text{VO}_2\text{max}$  (Deschenes et al. 1998; Edwards et al. 2005; Reilly et al. 2007). While Torii and colleagues (1992) examined possible time-of-day effects on  $\text{VO}_2\text{max}$  with regard to training in the morning, early afternoon and evening groups and concluded that aerobic training in the afternoon was most effective than on the other daytimes, Fernandes et al. (2014) suggested that oxygen uptake tended to be higher in the evening than in the morning. None of those presumptions were supported by our present results. On the contrary, our findings displayed that the morning intervention groups (mE+S, mS+E) showed even somewhat larger increases during the evening measurements in PRE-POST  $\text{VO}_2\text{max}$  (12.7% and 10.0%, respectively) than the evening training groups (eE+S: 7.7%; eS+E: 5.4%). Also when sorting all intervention groups by training time (morning vs. evening), the  $\text{VO}_2\text{max}$  melioration in MOR was nearly twofold in the evening tests compared to the EVE group (11.4% vs. 6.5%). Nevertheless, none of those values were significant in the morning vs. evening arrangement. Inter-individual differences within the subjects might cause the possible influences in maximal oxygen uptake (Hill et al. 1988; Williams & Hill 1995). Further, it has to be considered that those studies did not investigate time-of-day effects in combination with concurrent endurance and strength training and thus, those might have influential consequences on time-of-day specificity. The recommendation that training should be conducted preferably at the same time of day as the competition or occasion to ensure the best performance (Cappaert 1999; Chtourou & Souissi 2012) was not confirmed in our results.

### **9.1.2 $W_{\text{max}}$**

The findings in maximal work rate in the present study demonstrated significant improvements in all intervention groups at both measurement time points. The increases

in  $W_{\max}$  in this study were twice as high in average than the  $VO_{2\max}$  values, which is most likely due to the added strength training in the combined training program (Aagaard et al. 2011, Cadore et al. 2012, Rønnestad et al. 2015). Several studies similarly reported  $W_{\max}$  improvements after concurrent endurance and strength training (Aagaard et al. 2011, Beattie et al. 2014, Schumann et al. 2014a). Izquierdo and co-workers (2005) investigated 16 weeks of concurrent training in untrained healthy men. The maximal work rate increased by 12% and was slightly lower than reported in our investigation, which might be explained by the study duration.

With a 24-week intervention periods, as applied in the current study, ameliorations in maximal aerobic power were also observed (Eklund et al. 2014; Schumann et al. 2014a). The latter study showed significant improvements in both combined E+S and S+E intervention groups (13% and 16%, respectively) (Schumann et al. 2014a). While the  $W_{\max}$  value in the S+E group was similar to our findings, E+S differed in comparison to the present investigation. The eE+S intervention group in particular showed great adaptations following 24 weeks of combined endurance and strength training (24% improvement in PRE-POST comparison in the morning and evening measurements,  $p < 0.001$ ). This intervention group significantly differed from the eS+E group (14%,  $p < 0.05$ ) at the morning test. With regard to the intra-session exercise sequence, E+S also significantly differed from S+E groups at the morning measurement (22% vs. 16%,  $p < 0.05$ ). Both outcomes led to the assumption that an order effect was observed also within  $W_{\max}$  values. As reported previously, endurance performance characteristics, such as maximal work rate are demonstrated to be strongly connected to maximal leg strength, which eventually is support via strength training (Aagaard et al. 2011, Beattie et al. 2014, Cadore et al. 2013; Izquierdo et al. 2004; Psilander et al. 2014; Rønnestad et al. 2015). This relation may explain the detected outcomes in our study. The difference in the E+S group in comparison to the results by Schumann et al. (2014a) are unclear, but expected to be related to individual adaptation. Another aspect, which has been mentioned above, is the residual fatigue that is induced via prior exercises. It can be only speculated that concerning  $W_{\max}$ , the strength factor plays a crucial part and endurance prior to strength training might evoke supportive effects on the maximal work rate, whereas the opposite exercise order fatigue and impair the eventual endurance performance from the acute point of view.

### 9.1.3 Submaximal performance

With regard to the submaximal values at the different stages, decreased HR was observed throughout the stages, but they lacked mostly of statistical significance. It could be only assumed that long-term training effects might have affected performance at the 50W, 125W or 250W stage. Only at the 175W stage, which was utilised to represent the 4mmol-threshold, HR showed statistically significant decrease in all intervention groups when comparing obtained PRE- to POST-values, hence, the training effect might have been more present in the 175W stage than in other stages.

Our bLA values at the 50W were significantly increased in POST compared to PRE, while at the other stages bLA remained mostly inconspicuous. The origin of the raise is unknown, but it could be suggested that it came from the insufficient preparation and standardisation of the subjects when starting the tests protocol: plenty of subjects arrived to the test by bike and therefore, experienced some pre-loading that may have led to increases in their bLA values.

While only some oxygen consumption values at 125W decreased statistically significant, most  $VO_2$  values at 175W were lowered significantly with only eE+S in the morning tests and mE+S in the evening tests failed to show significance. It could be only assumed that a training effect was observed during those submaximal stages, but the reasons for the failed statistical meaning in the mentioned intervention groups are unknown. At the 250W stage,  $VO_2$  and bLA failed to indicate any statistical significance, leading to the proposition that at least concerning higher stages, the training effects have been weakened or fully diminished within those variables.

The present submaximal results of our study are in accordance to studies, which observed training effects at submaximal levels after additional strength or endurance training, respectively or in combined training (Barrett-O'Keefe et al. 2012; Rønnestad et al. 2015). If taken our 175W stage as reference for the 4mmol-threshold, a tendency of economy improvement could be observed as it has been seen in the previous studies, that stated positive influences on cycling performance at submaximal levels or power outputs at 4mmol (Rønnestad et al. 2015). Additional strength training has been

reported to support economy in endurance training (Beattie et al. 2014), however, the protocol to determine submaximal values in the present study has to be taken with caution, since the submaximal data were collected from a maximal incremental cycling tests and not from a specific economy test.

## 9.2 Strength

The current results in 1RM strength measures displayed similarly that all intervention groups improved their 1RM in leg strength from PRE to POST significantly at both measurement time-points. This may be explained by the previous fitness level of the subjects of our present study; our participants were healthy, but untrained without previous experience in systematic strength training. Strength gains due to either neural or hypertrophic adaptations or a combination of both based on the training protocol have been reported previously (Rønnestad et al. 2010; Schumann et al. 2014b; Sunde et al. 2010) and this might have been observed likewise in our present study suggesting that our protocol positively influences increases in strength. The selection of endurance cycling in our present training protocol might have led also to the synergistic effects on strength performance, as reported by several studies that found positive impacts in favour of strength gains after using cycling protocols during combined endurance and strength training investigations (Izquierdo et al. 2005; Schumann et al. 2014a; Wilson et al. 2012).

When comparing all intervention groups with each other, it can be seen that each S+E groups demonstrated greater gains than E+S groups at the same training time (mS+E vs. mE+S and eS+E vs. eE+S, respectively), even though no significant between-group differences were observed. This tendency was supported when observing order groups, in which the S+E groups (18.3% and 21.7% during the morning and evening tests, respectively) showed greater improvements than the E+S groups (16.2% and 19.2% in the morning and evening test, respectively).

In addition, the evening training groups tended to demonstrate greater enhancements in 1RM leg strength than morning training groups, which was seen in comparison of all intervention groups and when sorted by the MOR and EVE group. This may eventually

suggest the trend that evening training might be superior to morning training for strength measures, even with the absence of statistical significance.

The present results correspond to previous studies, which showed greater increase in the S+E compared to E+S training groups (Cadore et al. 2013; Schumann et al. 2014a). Possible explanations aim to the diminution in strength gains when endurance training precedes strength training due to diminished ability of the neuromuscular pathway leading to the reduction in strength gains (Cadore et al. 2012a; Davitt et al. 2014; Lepers et al. 2001) and residual fatigue (Izquierdo-Gabarren et al. 2010; Leveritt et al. 1999; Sale et al. 1990b). Furthermore, the trend of superior strength amendments in the evening training groups is also reported by some studies, suggesting peak performance in leg strength particularly during the evening times (Phillips 1994; Squarcini et al. 2013; Thun et al. 2015).

### **9.3 Strengths and limitations of the study**

The present study applied four different intervention groups that were affected by exercise sequence in combination with specific time-of-day training (mE+S, mS+E, eE+S, eS+E). This gave us a variety of data, in which possible effects cross-linked to order and time-of-day effects could be examined.

Nonetheless, the variety of intervention groups possibly affected the results when observing exercise sequences only (e.g., E+S included morning and evening group) or time-of-day only (e.g. MOR included E+S and S+E group). Neither endurance-only nor strength only groups were included in the current study, which may have been able to display specific effects on time-of-day, order and interference effects more precisely.

The data of the submaximal measures was based on the graded maximal cycling tests that applied 2min-stages. However, several protocols for cycling economy determination usually apply longer stage durations (at least 4-5min) to ensure steady state when collecting gas data in order to examine economy or efficiency changes (Chuang et al. 1999; Hopker et al. 2009; Wasserman et al. 2005). Therefore, our method might be suitable to describe possible tendencies of economy effects, as it was

mentioned above. Thus, to ensure more accurate indications regarding economy, a specific economy cycling tests would have been needed.

Eventually, the subjects of our own study were untrained healthy men aged 18 to 40, thus our findings can be applied only to the selected population. The possible effects on women at the same age and physical activity level, or influences on trained subjects of both genders remain unknown.

## **9.4 Conclusions**

The present findings deliver additional information on exercise sequence to same-session combined endurance and strength training as well as to time-of-day related effects on eventual training performance in endurance and strength variables. The current results suggest that 24 weeks of time-of-day specific same-session combined endurance and strength training support improvements in maximal and submaximal endurance and strength parameters.

With regard to the training sequence in our training intervention, an order effect was observed to be present, hence, endurance variables might display superior adaptations when endurance exercises were applied prior to strength exercises during the present concurrent intervention programs. Similarly, strength adaptations appear to be greater when trained first compared to the contrast training order, even though no statistical significance was observed.

Time-of-day effects were observed for none of the intervention groups. Therefore, our findings could not detect any influential effect concerning time-of-day specificity during the present same-session combined endurance and strength training. However, previous presumptions in other investigations that endurance performance are the best when training is conducted at the same time as the eventual event or competition, were not confirmed within our findings.

## 9.5 Practical applications and future considerations

Based on our present findings, it could be expected that any training intervention regardless of training order and time will induce significant improvements in endurance and strength variables in untrained men. However, when endurance is trained prior to strength within a combined training session, the outcomes might be for the benefit of endurance improvements and hence, more suitable to endurance-related preferences. The aim of the individual applying this concurrent training intervention should consider this possibility beforehand. The certain time of day, at which training is taken place, does not seem to influence endurance or strength outcomes and therefore, could be applied after personal habits during everyday life.

For future considerations different subject groups could be examined within the same study design in order to determine whether the outcomes of the intervention might differ, for instance, gender effects (female vs. male), physical activity level (untrained vs. trained subjects), or team sport athletes. Regarding the study design implementing the comparisons between the intervention groups only, the inclusion of pure endurance-only or strength-only groups could reveal more detailed outcomes of the applied combined endurance and strength training intervention. Another adaptation concerning the intervention design could include integrated combined endurance and strength training intervention in comparison to our applied serial concurrent training model, as it was used in other studies (Davis et al. 2008a, 2008b). Limited scientific evidence exists on time-of-day effects in combined endurance and strength training and future investigations are needed to determine their reciprocal effects more accurately. The present endurance training intervention and measurement were both conducted with cycling ergometers and thus, focused on cycling movements. The idea of changing the endurance part from cycling into running might offer further options and point of views in terms of endurance training for sports using running motions.

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