

**EFFECTS OF 24 WEEKS OF SINGLE SESSION COMBINED  
STRENGTH AND ENDURANCE TRAINING ON BODY  
COMPOSITION AND FITNESS: EXAMINATION OF ORDER  
EFFECT**

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## ABSTRACT

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Endurance and strength training are often performed concurrently. The question of whether the order of exercise yields to different adaptations in body composition, when strength (S) and endurance training (E) are combined into the same training session, has received only limited scientific attention. In addition, neuromuscular and cardiorespiratory adaptations to single session combined training have shown conflicting results, especially when examining the intra-session sequence. The purpose of this thesis was to examine the effect of strength and endurance training sequence on body composition as well as on aerobic and strength performances.

56 previously physically active men (18-40 yrs) completed a progressive 24-week single session strength and endurance training period. They were assigned into three groups. One performed E always before S in the training session (E+S; n=14), the other completed the same training sections with the opposite order (S+E; n=18), and the control group continued their habitual physical activity (Control; n=24). In order to determine prolonged training adaptations the measurements were conducted in the beginning, after 12 weeks, and after completing 24 weeks of training. All the subjects were tested for the body composition using DXA, upper and lower body strength (isometric and dynamic leg press and isometric shoulder press) and for the aerobic power during an incremental cycling test.

The main finding was a significant increase in total body lean mass throughout the 24-week period without significant between-group difference (E+S 3.3%; S+E 2.6%;  $p \leq 0.001$ ). In addition, leg lean mass also increased similarly in both E+S (6.0%;  $p < 0.000$ ) and in S+E (4.9%;  $p < 0.000$ ). Body weight had a tendency to increase in both training groups but reached the significance only in the S+E group (2.3%;  $p = 0.013$ ). Physical performance increased similarly in both training groups. Dynamic and isometric leg strength increased ( $p < 0.001$ ) 12.6% and 11.6% in the E+S group and 17.0% and 13.2% in the S+E group. Upper body isometric strength increased ( $p < 0.05$ ) 10.2% and 7.6% in E+S and S+E, respectively. Aerobic power increased ( $p = 0.000$ ) in both E+S (11%) and S+E (16.2%).

In conclusion, this study showed that the current 24-week single session combined strength and endurance training program significantly increased total body and leg lean mass, independent of the strength and endurance order. Training sequence had also little influence on strength and endurance adaptations to concurrent training, as the improvements of the same magnitudes were observed for both E+S and S+E group. Independent of the training sequence the current training program caused positive changes in body composition and physical fitness and can be considered beneficial for long term health maintenance.

**Keywords: combined training, order effect, body composition, strength, aerobic power**

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# 1 INTRODUCTION

Physical fitness among young men in Finland has decreased and body mass increased during the last 15 years (Santtila et al. 2006). Weight control is verified to be an important issue for health promotion and for early intervention in disease prevention (Koutoubi & Huffman 2005, Lo et al. 2011). The understanding how regional fat mass is altered with training is important, because the location of fat deposition is more closely related to the cardiovascular health risk than total fat mass itself (Hunter et al. 2010). Additionally, changes in regional lean soft tissue are important for the maintenance and development of strength in specific regions of the body (Fleck et al. 2006). Young men should be regularly engaged in both resistance and endurance training and for those who are currently at a healthy weight to strive to maintain it, because these factors are associated with a significantly decreased risk of disease (Lo et al. 2011). Resistance and endurance training has long been known to increase functional abilities and health status, primary by changing body composition (Nindl et al. 2000) and physical performance (Broeder et al. 1992). In addition to that, body composition assessment is important for evaluating and monitoring the efficacy of exercise intervention on muscular development and function (Sillanpää 2011).

Nowadays, many people who are interested in general fitness are involved in a combination of cardiorespiratory and resistance training programs. Likewise, the American College of Sports Medicine position stand “The Recommended Quantity and Quality of Exercise for Developing and Maintaining Fitness in Healthy Adults” promotes the inclusion of both resistance and endurance training components in the exercise prescription for health-related fitness. Sillanpää et al (2009) have supportively shown that combined endurance and strength training may be more effective in improving physical fitness, body composition and metabolic health than either method alone in older adults.

To save time people have started to combine strength and endurance training into the same training session. This may cause interference between strength and endurance training

adaptations (Coffey et al. 2009) which may be influenced by the sequence of training sections (Davis et al. 2008). To date, limited scientific evidence exists about the order effect of single session combined strength and endurance training on body composition and concomitant physical fitness. The purpose of that thesis is to examine the effect of single session combined strength and endurance training sequence on body composition as well as on cardiorespiratory and neuromuscular performance.

## **2 EFFECTS OF PHYSICAL TRAINING ON PHYSICAL FITNESS**

### **2.1 Effects of endurance and strength training on physical fitness**

Adaptations to exercise training and the resultant performance improvements and training outcomes are highly specific to the mode of activity performed. The key components of a training program are the volume, intensity and frequency of exercise sessions. The sum of these inputs can term the training stimulus. (Hawley 2009). The initial signaling responses are likely to occur after each training session and the cumulative effect of repeated bouts of exercise will lead to chronic adaptations (Widegren et al. 2001).

*Endurance training.* Endurance training involves the performance of dynamic submaximal muscular contractions with large muscle groups, and is essentially aerobic (Gergley 2009). However, training at different intensity levels appears to produce different physiological adaptations or primary focus of change (Docherty & Sporer 2000). (Figure 1). Aerobic exercise, which involves prolonged muscular work, increases aerobic capacity through numerous adaptations at the cardiorespiratory and muscular levels (Chromiak & Mulvaney 1990). Changes in skeletal muscle include increases in mitochondrial content and capillary density, intramuscular myoglobin, and activities of key enzymes of citric acid cycle and mitochondrial electron transport chain with a concomitant increase in mitochondrial protein concentration (Gollnick et al. 1973, Holloszy & Coyle 1984, Tanaka & Swensen 1998). Increased capillary supply of blood to the skeletal muscle may play a vital role in determining aerobic metabolic function (Hepple et al. 1997). In addition, increases in the mitochondrial content and respiratory capacity of the trained muscle will result in a slower rate of utilization of muscle glycogen and blood glucose, a greater reliance on fat oxidation, and less lactate production during submaximal exercise (Hawley 2009). Repeated bouts of endurance exercise may cause increases in slow-twitch fiber area and possibly even elicit a conversion of fast-twitch fibers to slow-twitch fibers (Simoneau et al. 1985). Chronic adaptations in skeletal muscle are likely to be the result of the cumulative effect of repeated bouts of exercise, with the initial signaling responses leading to such adaptations occurring

after each training session (Hawley 2009). Changes in muscle bioenergetics and enhanced morphological, metabolic substrate and acid-base status will lead to increased maximal aerobic capacity (Gollnick et al. 1973, Holloszy & Coyle 1984, Tanaka & Swensen 1998). After the adaptation to endurance exercise the same work requires a smaller percentage of the muscles' maximum respiratory capacity and therefore results in less disturbance in homeostasis (Holloszy & Coyle 1984). Increased ability to perform repetitive high-intensity, low-resistance exercise such as cycling, running, and swimming, is mainly accomplished through an increase in maximal oxygen uptake and an increased ability of skeletal muscle to generate energy via oxidative metabolism without improvements in muscle strength (Nader 2006).

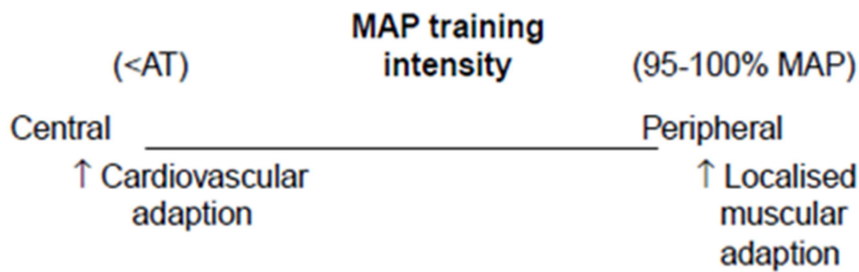


FIGURE 1. Intensity continuum of maximal aerobic power (MAP) training and the primary location of adaptation. AT= anaerobic threshold. (Docherty & Sporer 2000).

Muscular strength has been reported to increase a little or not at all as a result of endurance training (Gergley 2009, Sillanpää et al. 2008). A decrease in muscle fiber size may accompany endurance training, a change that could negatively impact muscle strength and power (Tanaka & Swensen 1998). In contrast to that, other studies have found that endurance training may promote improvements in leg press or knee extension strength in previously untrained subjects (Lo et al. 2011, Glowacki et al. 2004). Lo et al (2011) considered this to be because of sedentary lifestyle of the young adults who formed the sample. Since little force overload is placed on the upper-body musculature during lower-body endurance training (i.e., running), no great improvement in upper-body strength after run training would be anticipated (Glowacki et al. 2004).





identified type IIb fibers, a concomitant increase in the proportion of hybrid fibers expressing MCHIIa (Hostler et al. 2001, Kraemer et al. 1995), but no interconversion of fiber types has been noted after resistance-type of training (Costill et al. 1979). Accordingly, moderate-to-high intensity strength training can lead to marked gains in muscle strength and hypertrophy in men and women at all ages (Häkkinen et al. 1998, Häkkinen et al. 2003).

Factors which affect maximum voluntary strength include a cross-sectional area of the muscle or muscle groups, specific tension (force per unit CSA, which may be affected by the fiber type distribution and the amount of non-contractile tissue present in the muscle), ability of the subject to fully activate the motor units and possible anatomical differences in mechanical advantage of muscle acting across a joint (Miller et al. 1993). Rutherford and Jones (1986) suggested that with more complex exercises neural adaptations play a dominant role early in training and hypothesized reliance upon neural adaptations for strength increases may delay hypertrophy of the muscles used in these exercises. They further stated that with more complex exercises that involve movement at more than one joint (multi-joint exercises), fixator muscles used in support of the prime movers may have to increase in strength or improve their ability to activate and coordinate contractions before hypertrophy of the prime movers occurs (Fleck et al. 2006).

Improved strength-related performance is accomplished through neuromuscular learning and increased fiber-recruitment synchronicity, muscle cell hypertrophy, and, possibly, hyperplasia without changes in  $VO_2$ max or in the capacity to generate ATP via oxidative metabolism (McDonagh & Davies 1984). Usually it has been found that  $VO_2$ max changes are minimal or nonexistent after resistance training (Gergley 2009, Tanaka & Swensen 1998, Glowacki et al. 2004) . It has even been proposed that resistance training induces adaptations that could hinder improvements in aerobic performance (Nelson et al. 1990). Strength training has been reported to dilute mitochondrial volume in type IIa fibers due to hypertrophy and thereby possibly impairing aerobic performance (McDonagh & Davies 1984). On the other hand, circuit weight training using lighter resistances, a higher number of repetitions per set, and shorter rest periods may lead to improved endurance performance

and increases in  $VO_2\text{max}$  of approximately 5-10% have been observed (Chromiak & Mulvaney 1990). Research conducted by Hoff et al. (2002) showed that maximal strength training improved aerobic endurance performance by improving work economy in trained young athletes. Therefore, the key mechanism of the endurance performance ( $VO_2\text{max}$ ) increases may be the increase in muscular work economy, myofiber size, and the associated changes in myofiber contractile properties induced by resistance training (Lo et al. 2011).

## 2.2 Effects of combined training on physical fitness

From the perspective of promoting health, improvements in both strength and cardiorespiratory fitness are important and concurrent training seems to be the best strategy to enhance those variables (Cadore et al. 2010). Many of the combined strength and endurance training studies have investigated simultaneous strength and endurance training to assess whether it produces complementary or antagonistic adaptations in physical fitness (Cadore et al. 2011). Combined strength and endurance training studies have proposed divergent results, showing that it can lead to similar cardiovascular or musculoskeletal adaptations compared with either training regime alone (McCarthy et al. 2002, Izquierdo et al. 2005), increase endurance performance (Storen et al. 2008) or a diminished range of musculoskeletal and/or cardiovascular adaptation (Nelson et al. 1990, Izquierdo et al. 2005, Hickson 1980). Reasonable physiologic and metabolic evidence exists to support interference as aerobic endurance and resistance training represent the opposite ends of adaptation continuum (Figure 3) (Glowacki et al. 2004, Coffey & Hawley 2007).

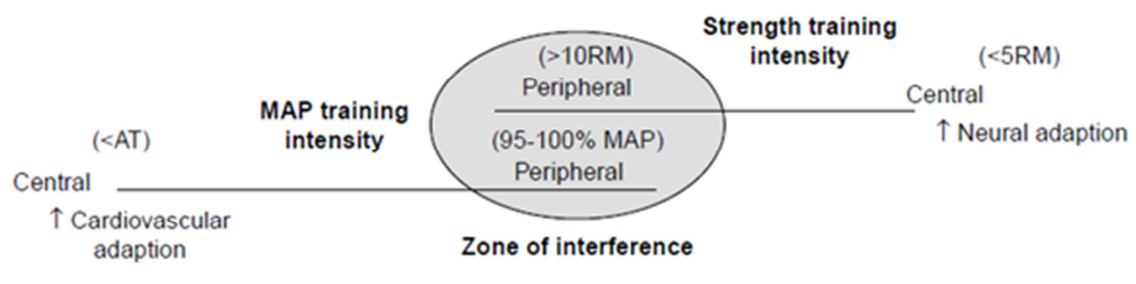


FIGURE 3. Primary location of adaptations for both maximal aerobic power and strength training, and the possible overlap. (Docherty & Sporer 2000) .

*Separate day combined training.* The results of several studies have shown that 10–12 weeks of concurrent training, with a weekly frequency between 4 and 11 sessions, with intensities ranging from 60% to 100% of  $\text{VO}_2\text{max}$  for endurance and from 40% to 100% of 1RM for resistance training, resulted in increases ranging from 6% to 23% in  $\text{VO}_2\text{max}$  and 22% to 38% of maximum strength (Kraemer et al. 1995, Hickson 1980). Whereas, in the majority of studies the increases in maximum strength were higher in the group that performed only strength training compared with the concurrent training group referring to “interference effect” reported already in 1980 by Hickson. Nevertheless, the majority of concurrent research supports the contention that concurrent training does not alter the ability to positively adapt to endurance training. (Garcia-Pallares & Izquierdo 2011).

Concurrent training studies have shown that added endurance training can reduce the adaptations to strength, especially to muscle power, when compared to the gains attained from the strength-only training (Kraemer et al. 1995, Häkkinen et al. 2003, Cadore et al. 2010, Sale et al. 1990, Bell et al. 2000, Karavirta et al. 2011). Häkkinen et al (2003) showed that after an extended training period of 21 weeks both combined strength and endurance as well as strength-only group resulted in large and similar gains in maximal lower body strength, but it was not the case in rapid force production. The strength/power training program used in that study resulted in significant increases in rapid force production of the trained leg extensors in the strength-only group. However, no increased maximal voluntary neural activation was observed when strength training was combined with endurance training (Figure 4) (Häkkinen et al. 2003). Those inversely affected gains in strength and power can be observed especially when high volumes, intensities, and/or frequencies are employed (Kraemer et al. 1995, Hickson 1980, Sale et al. 1990, Chtara et al. 2008).

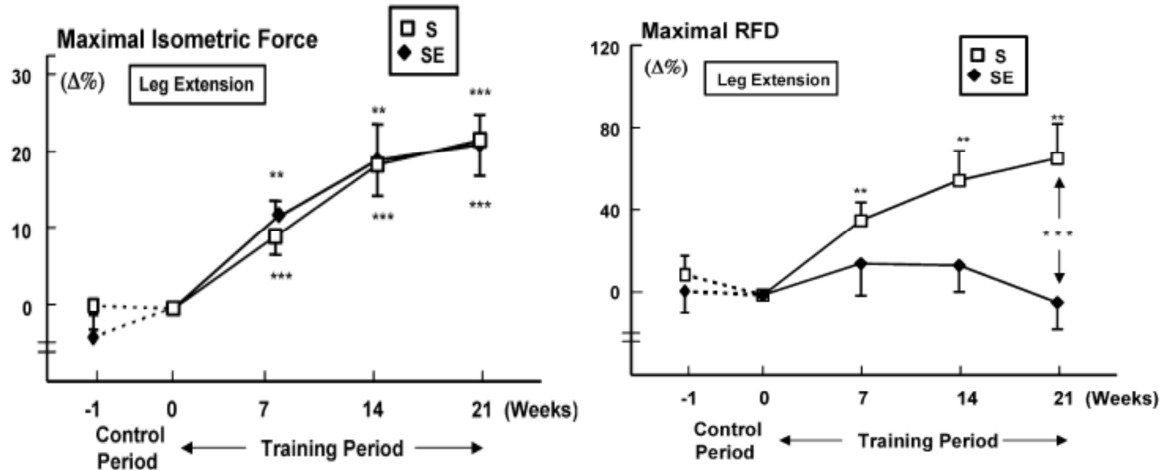


FIGURE 4. Changes in maximal voluntary bilateral isometric leg extension force (left) and changes in maximal rate of force development (RFD) in the rapidly produced voluntary bilateral isometric leg extension action (right) in the strength training group (S) and combined strength and endurance training group (SE) during the 1-week control and 21-week training periods. \*\* $p < 0.01$ ; \*\*\* $p < 0.001$ . (Häkkinen et al. 2003).

To achieve optimal adaptations in muscle strength and power, as well as to minimize interference phenomenon with endurance training, training frequency should not be in excess. Concurrent training has shown to be detrimental for strength gains only when training volume is high and frequency more than 3 days per week (Garcia-Pallares & Izquierdo 2011). In addition, interference in the improvement of physical fitness is usually observed only during longer (>7-8 weeks) training period (Hickson 1980, Izquierdo et al. 2003). In studies where the training frequency have not exceed 3 days per week, increases in maximum strength were detected following concurrent training periods between 8 and 16 weeks (McCarthy et al. 2002, Izquierdo-Gabarren et al. 2010) and  $\geq 20$  weeks (Häkkinen et al. 2003, Garcia-Pallares et al. 2010). This is in agreement with Glowacki et al (2004) and McCarthy et al (1995) who observed similar gains in maximum leg press or squat performance and bench press strength in the resistance training and combined training group. Similarly, study of Sillanpää et al (2008) stands for the proposition that large gains in muscle strength can be observed in the combined strength and endurance group. The magnitude of these increases did not differ from the corresponding changes observed in the group that performed either strength or endurance training alone (Sillanpää et al 2008).

Some endurance training programs have even shown increased strength (Rosler et al. 1986) and muscle fiber size (Gollnick et al. 1973, Lundberg et al. 2013). The data from Lo et al (2011) study support the notion that resistance and endurance training may interact to enhance rather than to hinder strength and endurance developments.

Muscle hypertrophy and changes in motor unit recruitment are two of the most salient factors associated with strength development (Häkkinen et al. 1985). Decreases in the cross-sectional area of muscle fibers and limited hypertrophy of type I fibers due to the reduction in total protein synthesis following the endurance exercise have been observed to interfere with strength development (Kraemer et al. 1995). Putman et al (2004) extend the findings of previous studies (Bell et al. 2000) by demonstrating that attenuated muscle strength development after separate day concurrent training was associated with greater fast-to-slow MHC-isoform transitions and preferential hypertrophy of IIa fibres (Figure 5). This study (Putman et al. 2004) is, however, the first to note further reductions in MHCIIB protein expression after concurrent application of strength and endurance training paradigms. The functional consequence of such conversion would appear to be lower rate and absolute amount of force development resulting in lower power output (Widrick et al. 2002).

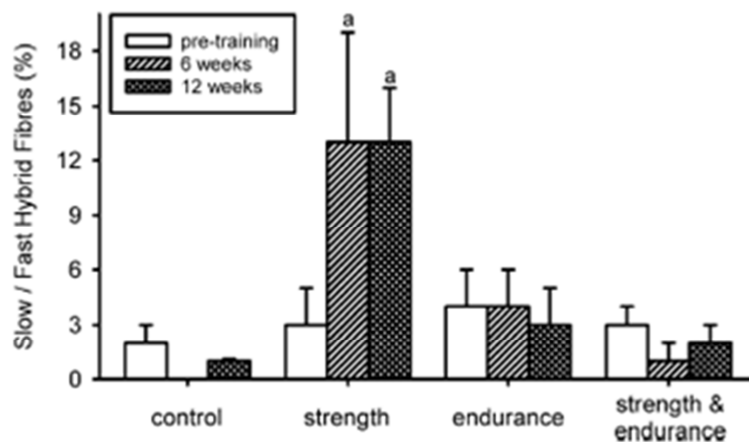


FIGURE 5. Proportion of slow/fast fibers in males throughout 12-week combined training. (Putman et al. 2004).

Interestingly, concurrent endurance and strength training diminishing or sometimes blunting the muscle hypertrophy that normally occurs with strength training, can still cause increases in maximal muscle strength (Kraemer et al. 1995, Bishop et al. 1999, Aagaard et al. 2011). The latter is proposed to happen as a result of neuromuscular adaptation (Aagaard 2003). However, there is a lack of evidence of interference on the neural component of strength development when evaluated by electromyography (EMG) measurements (Häkkinen et al. 2003, McCarthy et al. 2002). In addition to that, Häkkinen et al (2003) have proposed that a relatively high volume of strength training may be necessary to induce neuromuscular adaptations in response to concurrent training regimes. Thereby, it has been suggested that in addition to fiber type transitions, impairment in force development with concurrent training, as compared with strength-only training, can be related to altered neural activation associated with maximal voluntary contraction (Kraemer et al. 1995, McCarthy et al. 2002, Leveritt & Abernethy 1999).

With respect to aerobic performance, strength training does not seem to affect the gains in aerobic power (Figure 6) (Kraemer et al. 1995, Hickson 1980, Sale et al. 1990, Bell et al. 2000, Karavirta et al. 2011). Usually, it is believed that the changes in endurance performance with concurrent training increases are equal with those, achieved with endurance training alone. In the study of Sillanpää et al (2008) increases of the same magnitude were observed in  $\text{VO}_2\text{max}$  in the endurance-only (11%) and in the combined strength and endurance training group (11%) in middle-aged and older men. Similarly, Karavirta et al (2010), have shown that elderly men performing concurrent training have similar gains in aerobic power compared with aged-matched subjects performing only endurance training. The available data suggest that a high muscle loading intensity (85–95% 1RM) and/or a large volume of strength training need to be performed before a benefit on long-term endurance performance can be achieved (Aagaard & Andersen 2010). The results from other studies also suggest that increases in  $\text{VO}_2\text{max}$  are not impeded by combining resistance and aerobic training when compared with aerobic training alone in a sample of previously sedentary or untrained, apparently healthy males (Lo et al. 2011, Shaw & Shaw 2009, Chtara et al. 2005). Therefore, the study of Shaw & Shaw (2009) supports the concurrent use of resistance and aerobic training in the prevention of

cardiovascular disease, since this mode of training may not only increase  $VO_2\max$ , but also allows an individual to elicit the unique benefits of each mode of exercise.

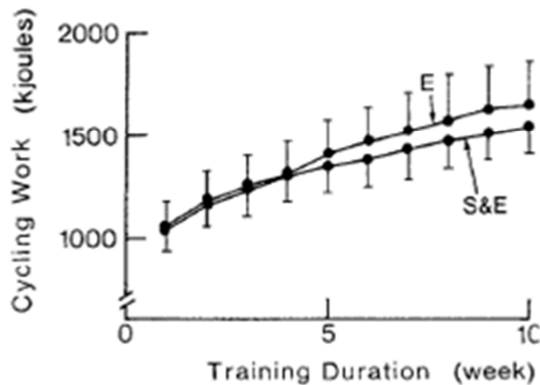


FIGURE 6. Increases in average total bicycle work per week during the 10 weeks of training in the endurance (E) and strength and endurance (S & E) groups.(Hickson 1980).

Combined strength and endurance training may improve endurance performance by increasing aerobic capacity and improving the economy of movement (Izquierdo et al. 2005). Muscular strength does not directly influence the cardiorespiratory system, but an improvement in the economy of movement can occur as a result of the increase in muscle strength (Izquierdo et al. 2001). Improvement in long-term endurance capacity comprise an increased proportion of type IIA muscle fibers (Aagaard et al. 2011) that are less fatigable and yet highly capable of producing high contractile power (Bottinelli et al. 1999). It should be noted that in previously untrained individuals, strength training per se appears to increase the number of capillaries per fiber (Lo et al. 2011, Tanaka & Swensen 1998) or result in unchanged capillarization (Bell et al. 2000). Stronger individuals can perform aerobic activity at a lower percentage of their relative strength and preferentially using fibers with a more oxidative metabolism and more resistance to fatigue. This all permits to commit aerobic activity with lower oxygen consumption at submaximal intensities. (Mikkola et al. 2007).

Nevertheless, Nelson et al (1990) have previously shown concurrent training to inhibit aerobic adaptations. In this case authors speculated that a dilution of mitochondrial volume



caused by resistance-training–induced hypertrophy in the combined strength and endurance training subjects might be responsible for the training interference (Nelson et al. 1990). In support of this contention, the activity of the mitochondrial oxidative enzyme citrate synthase increased only in the endurance- trained subjects (Nelson et al. 1990). Similarly, Glowacki et al (2004) found a significant increase (8.25%) in VO<sub>2</sub>peak with endurance training but not when resistance training was added.

*Single-session combined training.* The combination of strength and endurance training in the same-session training has been reported to be very common in physical fitness training programs because of time constraints and convenience (Vilacxa Alves et al. 2012). However, single-session strength and endurance training presents a specific challenge as the fatigue generated from one mode of exercise may negatively influence the quality and quantity of exercise in the other mode referring to possible interference effect (Davis et al. 2008). A number of researchers have shown that strength development during concurrent strength and endurance training is compromised when compared with training exclusively for increased strength development (Figure 7) (Hickson 1980, Dudley & Djamil 1985); (Dolezal & Potteiger 1998). In the study of Cadore et al (2010) strength training alone resulted in a 50% greater increase in the knee extensor strength than in the concurrent training group. Similar results have been observed also with circuit resistance training, where the strength-only group increased strength and power significantly further than the combined training group (Chtara et al. 2008). Gergley (2009) found also higher values in the resistance-only group, but innovatively showed the group where cycling was added to endurance training improved strength significantly more than the group where strength training was combined with running. Endurance training biomechanically specific to the concurrent resistance training may minimize adaptation interference when concurrently training.

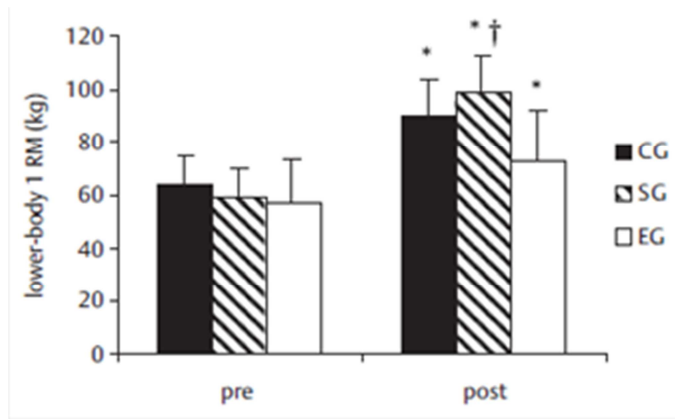


FIGURE 7. Lower-body one-repetition (1-RM) values (kg) before and after 12 weeks of training. CG=concurrent group; SG=strength group; EG=endurance group. \* significant difference from pre training values ( $p < 0.01$ ). † significant difference from EG. (Cadore et al. 2010).

Sale and colleagues (1990) have reported that the pattern of separate day strength and endurance training can be more effective for improving muscular strength than strength and endurance training on the same day (Figure 8). Supportively, Garcia-Pallares & Izquierdo (2011) found that, the strength gains were significantly higher in the group that performed the training sessions on different days. Performing endurance exercise immediately prior to strength exercise may result in a peripheral fatigue that consequently reduces performance during the strength training. If this were the case, the interference effect could be avoided by manipulating the intra-session exercise sequence (Cadore et al. 2012a).

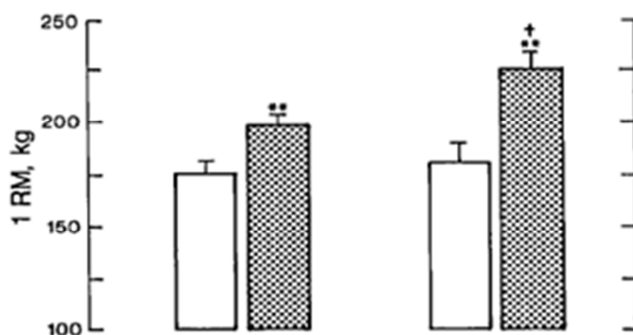


FIGURE 8. Leg press one-repetition maximum in single session (left) and separate day (right) combined training groups. Pre (open bars)- and post (hatched bars)- training values. \*\* $p < 0.001$  significant from pre- to post-measurements. † significant between groups. (Sale et al. 1990).

Though most of the studies have observed reduced strength development, the level of hypertrophy development may not be limited with single-session combined strength and endurance training. Sale et al (1990) and Hickson et al (1980) have presented impaired increases in voluntary strength but not in muscle size, in comparison to strength-only training. Perhaps in both studies the reduced voluntary strength development was caused by impaired central nervous system adaptation or by a decreased intrinsic contractile capacity of the muscles.

Not all studies have observed diminished strength improvement after single session combined training. Gravelle and Blessing (2000) found after eleven weeks of combined rowing and lifting, independent of the intra-session sequence, the improvements in the combined training groups to be almost identical of what observed in the lifting-only group. The difference from other studies may become because of different type of endurance training used in that study (Chtara et al. 2008).

Most studies that have investigated the effects of simultaneous strength and aerobic training on endurance performance demonstrate that strength training does not negatively interfere with the development of cardiorespiratory fitness (Izquierdo et al. 2005, Millet et al. 2002), especially when the endurance exercise occurs before strength exercise (Chtara et al. 2005). Data available suggest that in previously non-endurance-trained men (Hickson 1980, Dudley & Djamil 1985), or in previously resistance-trained subjects (Kraemer et al. 1995), combined training does not interfere with the development of  $VO_2max$  (Collins & Snow 1993). Maximal aerobic power ( $VO_2max$ ) has been reported to increase similarly in both separate day and same day concurrent training programs (Sale et al. 1990). Various studies have shown the benefits of adding strength training to improve endurance performance (Tanaka & Swensen 1998). The results from Chtara et al (2005) confirm the efficiency of single-session combined strength and endurance training, by increasing aerobic capacity. This study showed even larger increases in  $VO_2max$  in the combined training group where endurance precedes strength training when compared to endurance-only group. Cadore et al (2011) have supportively shown similar magnitude improvements in maximal aerobic

power in the combined training group where endurance preceded strength training and in the endurance-only group.

However, the improvement in  $\text{VO}_2\text{max}$  was compromised more than the improvements in lower-body strength for the concurrent training group in the study of Dolezal & Potteiger (1998). The attenuated improvements found in  $\text{VO}_2\text{max}$  of the concurrent training group, when compared with endurance training alone, could be explained by interferences found in strength training adaptations (Dolezal & Potteiger 1998). This may include muscle fiber hypertrophy and increases in contractile proteins with associated decreases in capillary and mitochondrial volume densities (McCarthy et al. 2002, Hickson 1980, Sale et al. 1990).

### **2.2.1 The interference effect**

As previously mentioned, combining resistance and endurance training may interfere with the training response induced by either type of training alone (Glowacki et al. 2004). Already in 1980, Hickson provided evidence for the existence of an “*interference phenomenon*” between resistance and endurance training by demonstrating that strength gains were hindered when the two types of training were performed concurrently (Figure 9). Thus, when the overall volume of training is high, simultaneous training for both strength and endurance may be associated with large gains during initial weeks of training but with only limited strength and/or power development later in the training period. This may finally lead to declined strength in the group where endurance training is added to the strength training, while the strength-only group is able to improve strength throughout the training period (Häkkinen et al. 2003, Hickson 1980). Similarly to Hickson (1980), some other studies have also shown the concurrent training to inhibit the development of strength and power but not to affect the development of aerobic fitness when compared with either mode alone (Nader 2006, Kraemer et al. 1995, Dudley & Djamil 1985). Reasonable physiological and metabolic evidence exists to support this principle (Glowacki et al. 2004) though the exact mechanisms causing the diminished strength and power improvements are not presently known. Craig et al (1991) have proposed that both acute and chronic factors may impair normal adaptive responses during concurrent training, while others have

proposed overtraining as a possible mechanism causing the interference when trying to adapt to strength and endurance training simultaneously (Nader 2006, Leveritt & Abernethy 1999, Dudley & Djamil 1985).

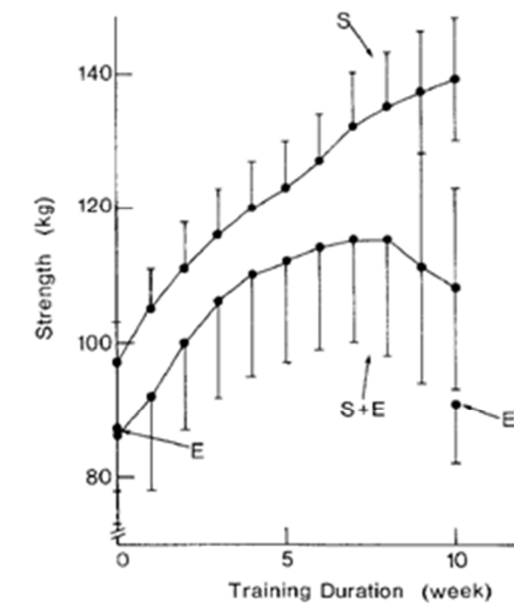


FIGURE 9. Strength changes in response to three types of training – endurance, strength and combined strength and endurance training. (Hickson 1980).

When considering acute effects, strength training may be compromised by the residual fatigue resulting from the endurance training. The residual fatigue from the first component of concurrent training compromises the ability to develop tension during the second portion of concurrent training (Craig et al. 1991). The degree of tension developed by the muscle during training is found to be a critical factor in producing optimal strength development (Atha 1981). If sufficient tension cannot be generated during the strength component of concurrent training, optimal strength development and adaptation may not occur (Leveritt & Abernethy 1999). Both central and peripheral factors are proposed to cause acute fatigue. A possible central mechanism is alteration to the excitation-contraction process (Leveritt & Abernethy 1999). Possible peripheral causes of acute fatigue include accumulation of metabolites (e.g. inorganic phosphate, lactic acid, ammonia) and depletion of energy

substrates such as ATP, creatine phosphate and muscle glycogen (Coffey et al. 2009, Bell et al. 2000). The acidosis during strength training, caused by the accumulation of the H<sup>+</sup>, may be lower when aerobic training is performed in advance, which may impair the effectiveness of the strength training programs addressed to promote muscle mass gains (Vilacxa Alves et al. 2012). Although these potential fatigue mechanisms have yet to be systematically investigated, the effect of residual fatigue is localized to the concurrently trained muscle (Leveritt & Abernethy 1999).

During concurrent training skeletal muscle is placed in the situation of conflict and it has been proposed that skeletal muscle may not be able to adapt metabolically or morphologically to both strength and endurance training simultaneously as strength or endurance training cause different or even opposing adaptations at the muscle level (Leveritt & Abernethy 1999). Resistance and endurance training cause distinct genetic and molecular adaptations, because each mode of exercise activates and (or) represses specific subsets of genes and cellular signaling pathways (Coffey et al. 2006). Endurance training may directly interfere with adaptation to strength training through activation of the AMPK pathway and inhibition of the insulin-like growth factor 1-AKT-mTOR pathway (Figure 10) (Nader 2006, Sillanpää et al. 2008). Recent findings of Lundberg et al (2012) will propose the opposite, as in their study concurrent exercise elicited greater mTOR and p70S6K phosphorylation compared with the resistance-only group. This indicates that translational capacity was reinforced rather than compromised by the combined strength and endurance (Lundberg et al. 2012).

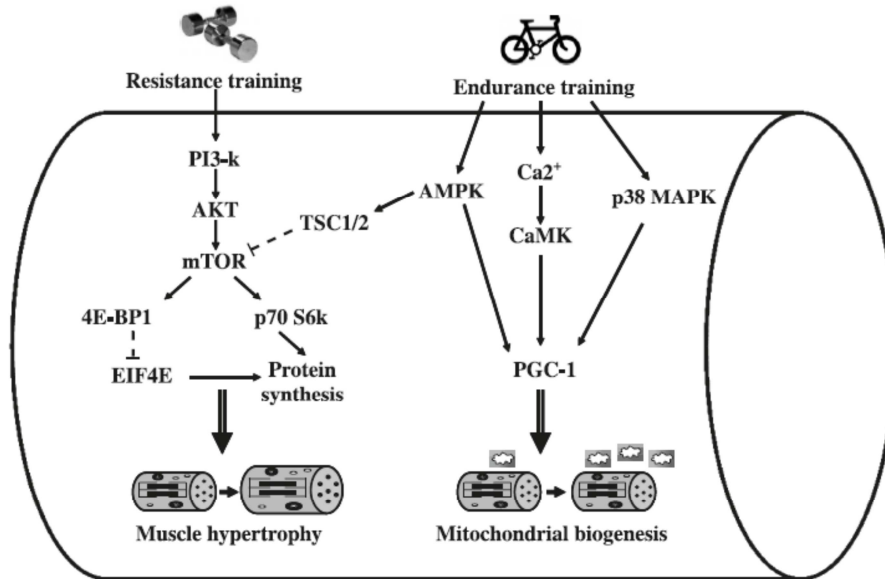


FIGURE 10. Intracellular signaling networks mediating strength and endurance exercise induced skeletal muscle responses. (Hawley 2009).

Concurrent training has the potential to elicit changes in the contractile character that is different from those associated with strength or endurance training (Costill et al. 1979). Shifts in skeletal muscle myosin isozymes may be a factor in the compromised strength gains with concurrent training (Chromiak & Mulvaney 1990). Those different alterations from fast to slow isoforms may hinder strength improvements. But not all concurrent training studies suggest transition of muscle fiber types as a potential mechanism causing interference as it has been found to be similar of what with strength-only training (Kraemer et al. 1995, Nelson et al. 1990, Sale et al. 1990).

Overlapping endurance exercise bouts with resistance exercise may result in impaired adaptive responses in protein synthesis and, therefore, a decrease in strength-related performance, in part, due to the suboptimal or lack of increase in muscle-fiber cross-sectional areas (Kraemer et al. 1995). Skeletal muscle hypertrophy after strength training occurs to a greater extent in fast-twitch than in slow twitch fibers (Häkkinen et al. 1985, Staron et al. 1990). Endurance training has shown to changes skeletal muscle fiber population by reducing the relative number of Type II fibers and thereby limiting the strength development during the concurrent training (Nader 2006). Hypertrophy in

different fiber type may also explain distinct strength improvements observed after strength or combined training (Leveritt & Abernethy 1999).

Strength interference during concurrent training cannot be wholly attributed to inhibition of fiber type transformations or fiber hypertrophy. This suggests that alterations in motor unit recruitment may be partly responsible for the inhibition in strength development observed during concurrent training (Leveritt & Abernethy 1999). The demand placed on the neuromuscular system during endurance and strength training requires different patterns of motor unit recruitment (Chromiak & Mulvaney 1990). Concurrent training may hinder organization of efficient motor unit recruitment patterns necessary for forceful muscular contraction at the level of the peripheral or central nervous system (Chromiak & Mulvaney 1990).

Acute responses and long term adaptations in serum testosterone concentrations as a result of endurance or strength training may result in compromised strength gains, since changes would ultimately affect muscle growth-related processes. Changes in the levels of other hormones (cortisol, thyroxine) may affect strength gains. These two types of training may activate various anabolic and catabolic processes to different degrees, which are modulated by endocrine response to exercise. (Chromiak & Mulvaney 1990). Concurrent training which alters the balance of anabolic to catabolic hormones may reduce fiber hypertrophy and consequently strength development. The endurance element of concurrent training could create a more catabolic environment, and this in turn may inhibit strength development (Leveritt & Abernethy 1999).

It has been suggested that individuals performing concurrent strength and endurance training may become overtrained because in comparison with strength- or endurance-only a concurrent training group needs to contend with the double of training load. Though higher training volume can cause overtraining it has been argued that if overtraining was a factor during concurrent training, then both strength and endurance measures would be inhibited (Dudley & Djamil 1985). However this argument presumes that the thresholds for the effects of overtraining to become apparent on strength and endurance measures are similar.



This may not be the case. There is insufficient evidence to preclude overtraining as a mechanism for the inhibited adaptive responses seen in some concurrent training studies (Leveritt & Abernethy 1999).

In addition, other authors have found that concurrent training compromised strength development only when both modes of exercise engaged the same muscle group, suggesting a local effect rather than a systemic one (Nader 2006). The closer the endurance exercise is biomechanically to the resistance exercise, the more likely an antagonistic or additive skeletal muscle adaptation will appear (Gergley 2009). Possibly there can be concurrent recruitment of motor units used in both types of training, resulting in lower gains in dynamic strength in the concurrent training group (Cadore et al. 2010). The same effects are not observed when aerobic training consists of running or jogging (McCarthy et al. 2002, Millet et al. 2002).

It has been suggested that the apparently conflicting findings might be reconciled based on different training frequencies (McCarthy et al. 2002, Izquierdo et al. 2004). When training frequency is high ( $\geq 5$  days per week), concurrent training may interfere with strength and/or aerobic endurance adaptations (Hickson 1980, Putman et al. 2004). When training frequency is low ( $\leq 3$  days per week), interference with strength and aerobic endurance adaptations is generally absent (Häkkinen et al. 2003, McCarthy et al. 2002, Izquierdo et al. 2004). In addition, interference between strength and aerobic endurance training in concurrent training protocols is proposed to be caused by combination of three variables: high intensity, poor physical condition, and timing and sequence of exercises (Davis et al. 2008). Discrepancies could be explained by different initial levels of physical fitness among the subjects (Ahtiainen et al. 2003). Trained individual seems to have greater resistance to high intensity exercise (Davis et al. 2008) compared to untrained or sedentary subjects (Baker & Newton 2006). It has also been suggested that the time required to give body sufficient recovery between training sessions may be the limiting factor when attempting to induce simultaneous adaptations to strength and endurance training (Leveritt & Abernethy 1999). Garcia-Pallares & Izquierdo (2011) concluded that insufficient recovery between training sessions might limit simultaneous adaptations to strength and

endurance training and suggested that the recovery periods between training periods should be under strict control.

### **2.3 Order effects of single-session combined training on physical fitness**

Since strength and endurance training are often performed concurrently, it is important to understand if there is an optimal training pattern or sequence for enhancing the physiological adaptations to exercise (Collins & Snow 1993). Along with the aerobic training volume and intensity, the intra-session exercise sequence might be an important variable in the concurrent training prescription (Garcia-Pallares & Izquierdo 2011, Chtara et al. 2005) and may determine the extent of impairment in strength (Leveritt & Abernethy 1999) or endurance (Chtara et al. 2005) development after concurrent strength and endurance training. However, a few studies have reported whether strength training should precede or follow endurance training when both are performed in the same session (Coffey et al. 2009, Chtara et al. 2008, Chtara et al. 2005, Vilacxa Alves et al. 2012, Collins & Snow 1993, Gravelle & Blessing 2000, Cadore et al. 2011).

One might hypothesize that the first activity performed would result in some residual fatigue experienced during the second activity, thereby reducing the quality of that session (Craig et al. 1991). However, Collins and Snow (1993) found that strength adaptations to combined strength and endurance training were independent of whether endurance training occurred prior to or following strength training. Two studies conducted with untrained subjects support that standpoint. Chtara et al (2008) found that the order of the sessions (i.e. first strength training and then endurance training or vice versa), produced no significant differences in training-induced adaptations between the groups, since both combinations allowed similar improvements in maximum strength and maximal aerobic power. Similar findings are observed for women showing that independent of the intra-session sequence women improved their strength after 11 weeks of training in the same magnitude. However, the authors proposed that the time course of strength adaptations may vary depending on the order of training, as the group where the lifting was performed before rowing had the

greatest strength improvement during the first half of the training and the least during the second half. (Gravelle & Blessing 2000).

Several other studies have highlighted the importance of the sequence and timing of the aerobic and strength sessions in order to minimize possible interference effects. Scheduling endurance training before strength may reduce strength training quality because of the residual fatigue from a previous endurance training session and may be responsible for causing impaired strength development (Leveritt & Abernethy 1999). However, strength development is not inhibited during concurrent single-session strength and endurance training in which strength training immediately precede endurance training sessions (Nelson et al. 1990). In the study of Cadore et al (2012) both concurrent training regimens resulted in enhanced lower-body dynamic strength and *quadriceps femoris* muscle quality, but greater improvement occurred when strength training was performed prior to endurance training (Figure 11). Supportively, Davis et al (2008) concluded in their literature based review that combining strength and aerobic endurance conditioning on the same day reduced training adaptations, particularly if aerobic endurance training preceded strength training. In addition, the study of Coffey et al (2009) provides a novel evidence of altered cell signaling and mRNA responses in an exercise order-dependent manner in skeletal muscle. Their results indicate that endurance activity undertaken before resistance training may diminish the anabolic response, whereas performing endurance after resistance exercise may exacerbate inflammation and protein degradation and (acute) concurrent training does not promote optimal activation of pathways to simultaneously promote both anabolic and aerobic responses.

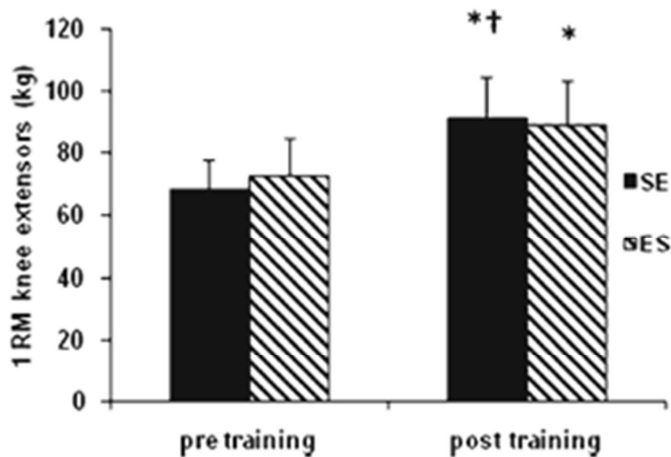


FIGURE 11. Lower body one-repetition maximum (1RM) values (kilogram), pre- and post- 12 weeks of concurrent training. SE=strength prior to endurance training; ES=endurance prior to strength training. \* $p < 0.001$ , significant difference from pretraining values. †  $p < 0.001$ , significant time vs. group interaction. (Cadore et al. 2012a).

Only few authors have studied the order effect on endurance development, since strength performance immediately prior to endurance training may compromise the endurance gains (Chtara et al. 2005). Interestingly, Chtara et al (2005) found that significantly greater increase were observed in the endurance markers of young men performing endurance training prior to strength training when compared with the inverse intra-session order. Not in agreement with Chtara et al (2005), Gravelle and Blessing (2000) investigating young women observed greater  $VO_2\text{max}$  increases in the subjects performing strength prior to endurance training. Additionally, the primary finding of the study of Cadore et al (2012b) showed that intra-session exercise orders during concurrent training resulted in the same magnitude of maximal endurance performance increases. The differences among different studies can be explained with different endurance training intensities and subject populations.

### **3 EFFECTS OF PHYSICAL TRAINING ON BODY COMPOSITION**

The loss in fat mass and increase in lean mass are favorable and desired effects of exercise training programs and contribute to an enhanced level of fitness and health (Nindl et al. 2000). Resistance and endurance training has long been known to increase functional abilities and health status, primarily by changing body composition (Nindl et al. 2000, Sipila & Suominen 1995). Physical activity provides stimuli that promote specific and varied adaptations according to the type, intensity and duration of exercise performed. Combined training seems to share the benefits from both strength (increased lean mass) and endurance training (decreased fat mass) and thereby providing the most effective exercise program strategy (Dolezal & Potteiger 1998).

#### **3.1 Effects of endurance and strength training on body composition**

*Endurance training.* Typically, endurance exercise has been undertaken to promote reduction in body weight due to its ability to increase energy expenditure and fat utilization. It is believed that both fat mass and total body mass are generally reduced with endurance exercise. (Dolezal & Potteiger 1998). High and low intensity exercise has similar effects on the percentage of weight loss as fat loss is a function of energy expended rather than exercise intensity (Grediagin et al. 1995). At the same time the plasticity of tissue mass to training or is known to be influenced by anatomic location (Nindl et al. 2002) e.g., the lipolytic response to exercise is more pronounced in abdominal than in peripheral tissue (Nindl et al. 2000). The health risks associates with fat mass are more related to regional placement rather than overall adiposity.

There exists some evidence that aerobic training can be associated with small or moderate increases in skeletal muscle mass (Marti & Howald 1990). Previous studies have also proved that both high-intensity cycling (Harber et al. 2009) and walking/jogging training (Coggan et al. 1992) have been shown to be effective in increasing muscle mass in

previously untrained individuals. Other factors, such as baseline body composition and fitness level, may also affect weight changes during the exercise period (Sillanpää et al. 2008, Sillanpää et al. 2009). However, endurance training even without weight loss results in changes in body composition. In several studies, aerobic training without weight loss has resulted in reductions in total body fat, as well as in visceral and adipose tissue both in obese and lean individuals (Ross et al. 2004).

*Strength training.* High-intensity strength training does increase fat free mass, muscle cross-sectional area and muscle fiber area. A strength training intervention for a couple of months in duration has been shown to produce increases in lean body mass at least 1-2 kg (Sillanpää 2011) and muscle cross-sectional area (CSA) 5-10 % (Häkkinen et al. 1998). Heavy resistance-training stimulates the myofibrillar proteins responsible for muscle hypertrophy (Fry 2004) and activates both low- and high-threshold motor units inducing hypertrophy of all fiber types (McCarthy et al. 2002). Both fast and slow twitch fibers have shown to adapt to strength training by increasing size.

Increased lean body mass produced by strength training can translate into clinically important increases in daily energy expenditure and associated losses in body fat (Strasser & Schobersberger 2011). Energy expenditure increases due to increased lean body mass, increased requirements of metabolically active lean tissue (Campbell et al. 1994) and increased energy needed to accomplish physical activity during the training. Especially the total body strength training with progressive training load seems to be effective in modifying body composition (Sillanpää 2011). These findings are consistent with previous studies showing that strength training can improve body composition and decrease abdominal obesity in the absence of changes in body weight (Kay & Fiatarone Singh 2006). Strength training, however, is less frequently associated with decreased body weight as weight training is associated with increase in lean mass and concomitant decrease in fat mass (Campbell et al. 1994).

Although prior research has demonstrated that resistance training can augment strength, physical performance, fat-free mass, and muscle fiber hypertrophy, information is lacking

regarding regional (upper body vs. lower body) changes in soft tissue composition (fat and lean mass). Fleck et al (2006) have reported the lack of significant increase in leg lean soft tissue, but significant increases in arm and trunk lean soft tissue, suggesting that it may take longer for the leg musculature to hypertrophy. An emphasis on complex, multijoint exercises has been postulated to delay hypertrophic responses of neuromuscular system due to prolonged neural adaptations (Chilibeck et al. 1998). This might be an indication of greater reliance on neural adaptations and (or) longer duration for “fixator” muscles of the leg musculature to become strong enough to support the resistance necessary for the prime movers involved in the leg press to hypertrophy. The differential hypertrophy of the leg region over the arm and trunk regions can be attributed to specific stresses placed by the training program.

### **3.2 Effects of combined training on body composition**

*Separate day combined training.* Both endurance and strength training and especially their combination seem to be effective in modifying body composition. Usually slight increases (Glowacki et al. 2004) or no significant changes (Häkkinen et al. 2003, Cadore et al. 2010, Shaw & Shaw 2009) has been observed in body weight after combined strength and endurance training studies and thereby following the similar trend with resistance training only (Glowacki et al. 2004). Percentage fat mass and total fat mass has shown to decrease (Glowacki et al. 2004, Shaw & Shaw 2009, Sillanpää et al. 2009) or stay unchanged (Sillanpää et al. 2008, Häkkinen et al. 2003, Cadore et al. 2010) with concurrent strength and endurance training in non-obese subjects. Thereby, changes in fat mass followed similar changes with the endurance-only group, although the training volume might have been different between the groups (Sillanpää et al. 2008). Thus, combined training may elicit advantageous changes in the body composition (Glowacki et al. 2004).

Several studies have proposed that hypertrophy is not attenuated when combining strength and endurance exercises and similar increases in total body lean mass can be observed for the strength-only as well as for the combined training group (Figure 12) (Sillanpää et al.

2008, Glowacki et al. 2004, McCarthy et al. 2002, Sale et al. 1990). McCarthy et al (2002) and Häkkinen et al (2003) did not observe also any restriction in the myofiber level. Häkkinen et al (2003) observed significant enlargements in the CSA of the quadriceps femoris muscle and in the size of individual muscle fibers (type I and types IIa, IIb) when the training frequency is low. The magnitudes of these increases did not differ from the corresponding changes observed in the group that performed strength training only. McCarthy et al (2002) observed substantial and similar levels of hypertrophy occurred in type II fibers in both strength and combined group. Although significant type I fiber hypertrophy occurred only in the strength training group, this change was not different than the non-significant increase observed in the combined training group (McCarthy et al. 2002). It can be speculated that 3-d·wk<sup>-1</sup> concurrent training for both strength and endurance, in sedentary subjects, does not impair the magnitude of muscle hypertrophy induced by strength training alone (McCarthy et al. 2002).

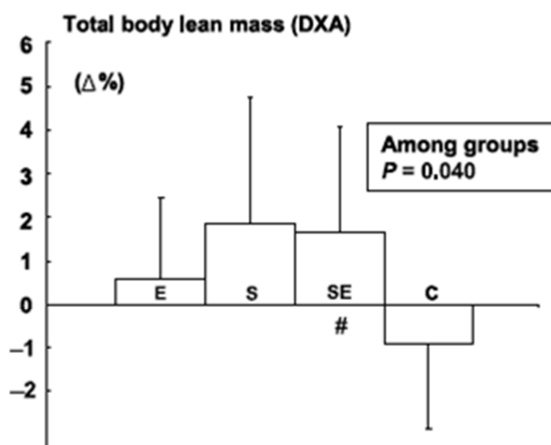


FIGURE 12. Changes in total body lean mass during the 21-wk training period. E=endurance training; S=strength training; SE=combined strength and endurance training group, and C=control group. # p<0.05 significant difference within group from week 0 to week 21. (Sillanpää et al. 2009).

Others have proposed that when adding endurance to strength training a limitation in muscle hypertrophy can be observed (Kraemer et al. 1995, Bell et al. 2000, Izquierdo-Gabarren et al. 2010, Sillanpää et al. 2009). Recent studies have shown that distinct cell



signaling events involving the Akt/mTOR or AMPK pathways appear to become activated by resistance or endurance training, respectively (Atherton et al. 2005), and that inhibitory cross-talk exists from one pathway to the other (Nader 2006). In the microscopic level concurrent strength and endurance training resulted in greater fast-to-slow fiber type transitions and attenuated hypertrophy of the type I fibers compared with strength training alone (Putman et al. 2004). Concurrent training induced 18% increase in the cross-sectional area of only type IIA fibers, while strength training induced increases in both type I (17%) and IIA (13%) fibers. Thus, the differential hypertrophic responses of type I and fast type IIA fibers between the strength and concurrent training appear to also underlie some of the interference effects on knee extensor muscle strength development. Similar differential hypertrophic response of type I and type IIA fibers between the strength and combined training have been reported also by Kraemer et al (1995). Karavirta et al (2011) observed that the CSA of type II muscle fibers increased only with strength training, but no increases in the CSA of any of the fiber types were observed with prolonged strength training program when strength training was combined with two weekly sessions of cycling at high intensities (Karavirta et al. 2011). It seems plausible that greater recruitment of the type I fibers in the combined training group, in the presence of elevated serum cortisol level (Kraemer et al. 1995) enhanced the rate of catabolic events within this fiber population. This observation implies that muscle hypertrophy might be compromised when combining the two different training modes (Kraemer et al. 1995, Bell et al. 2000, Karavirta et al. 2011).

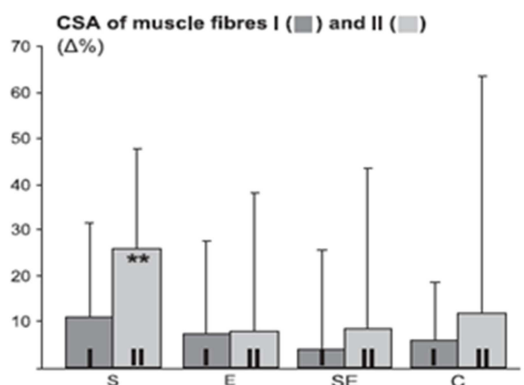


FIGURE 13. Changes (%) in the mean CSA of type I and II muscle fibers in vastus lateral muscle after 21 weeks of strength (S), endurance (E) and combined (SE) training or control (C) period. \*\*p<0.01 significantly different from the baseline measurements. (Karavirta et al. 2011).

*Single-session combined training.* Single session combined strength and endurance training has shown to cause small but significant (2%) increase in body weight similar of what observed after separate day combined training (Sale et al. 1990, Chtara et al. 2008). Others have observed decreases in body weight (Nindl et al. 2000, Gergley 2009, Dolezal & Potteiger 1998) which can be even larger of what observed after strength- or endurance-only training due to a greater amount of work done (Dolezal & Potteiger 1998). In the case where single session combined training caused similar decreases in fat mass and increases in lean mass, the changes in body composition results in no significant change in total body mass. (Fleck et al. 2006, Gravelle & Blessing 2000).

Combining strength and endurance training into the same training session have been reported to lead to positive changes in total body fat percentage. Many studies (Fleck et al. 2006, Nindl et al. 2000, Dolezal & Potteiger 1998, Kang et al. 2009) support the use of combined aerobic and resistance exercise in a single session training to augment fat utilization though not all have observe a significant changes in fat percentage (Gravelle & Blessing 2000). Changes in fat mass have been similar of what observed in the endurance-only group (Dolezal & Potteiger 1998). With respect to body compositional changes Nindl et al (2000) found positive changes in fat mass but brought to attention the regional differences. Women involved to that intervention significantly lost fat mass from the arm and trunk region but not from the legs after military training. The findings of this study showed the importance of considering regional body composition changes rather than whole body changes alone (Nindl et al. 2000).

When endurance and resistance training were performed on the same day increases in lean mass have been observed (Sale et al. 1990, Dolezal & Potteiger 1998, Nindl et al. 1996), at least when strength training precedes endurance training (Dolezal & Potteiger 1998, Nindl et al. 1996). Increased lean mass and concomitant increases in basal metabolic rate have been shown to aid in weight management (Dolezal & Potteiger 1998). It has been proposed that gains in soft tissue lean mass can be attributed mainly to a gain in soft tissue lean mass of the legs (Nindl et al. 2000) though it was not the case in the study of Fleck et al (2006). In the study of Fleck et al (2006) the body compositional changes indicate that the training

program performed resulted in small but significant changes in total lean soft tissue, and regional lean soft tissue in all regions but the legs. It is possible that the inconsistencies concerning regional body compositional changes in the studies are due to differences in the populations studied or training programs used (Fleck et al. 2006).

Previous studies have shown that endurance training may ultimately degrade myofibrillar protein (Hickson et al. 1988) and the physiological environment evoked by aerobic training might attenuate the maximal muscle fiber growth (Babcock et al. 2012). In fact, it has been previously shown that high-intensity endurance training may significantly reduce muscle type I fibers and thereby whole muscle area (Koenig 1995). Similarly, Babcock et al (2012) reported diminished growth adaptations to concurrent training, particularly in MHC I muscle fibers. Given that only 10-15 minutes recovery was implemented between the different modes, the hampered molecular response could have been attributed to residual fatigue (Coffey et al. 2009, Babcock et al. 2012). Certainly, the time course for recovery is critical to avoid residual fatigue and allow for glycogen repletion and normalization of other metabolic changes resulting from previous exercise (Lundberg et al. 2012). Lundberg et al (2012) have observed enhanced skeletal muscle anabolic environment by observing greater mTOR and p70S6K phosphorylation and suppressed myostatin when endurance cycling and strength were performed in the same day, when separated by six hours. Lundberg et al (2012) proposed that complete recovery before resistance exercise may be critical for prolonged enhanced signaling favoring increased muscle protein synthesis. This enhanced skeletal muscle anabolic environment caused greater increases in muscle and muscle fiber CSA after combined strength and endurance training than after strength-only training (Figure 14) (Lundberg et al. 2013). These novel results suggest that aerobic cycling could offer a synergistic hypertrophic stimulus to resistance exercise training. Authors suggested that one reason for that can be increased content of muscle water/hydrogen content rather than accretion of contractile material.

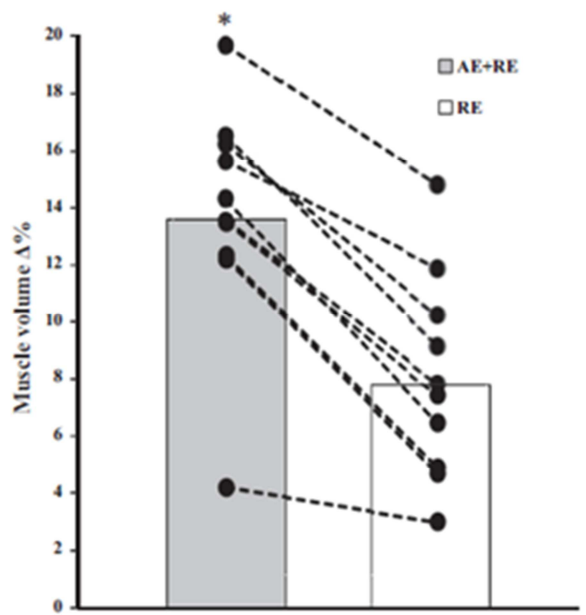


Figure 14. Individual and group mean increase in m. quadriceps muscle volume following combined strength and endurance (AE+RE) and strength (RE) exercise. \* Greater increase after AE+RE. (Lundberg et al. 2013).

### 3.3 Order effect on body composition

There are a limited number of combined training studies which have examined the order effect on body composition. Cadore et al (2012b) focused on the effects of different intra-session exercise orders on muscle morphological adaptations in elderly subjects during concurrent strength and endurance training program for 12 weeks. In that study lower and upper body muscle thickness increased to a similar amplitude and no between-group differences were observed in muscle thickness variables (Cadore et al. 2012b).

Chtara et al (2008) who looked at the changes in body weight observed similar increases for both E+S (1.6%) and S+E (1.5%). Gravelle and Blessing (2000) did not find any changes in body weight or in the calculated percentages of body fat over the time and between the groups (E+S vs. S+E). However, older men significantly decreased percent of body fat in both E+S and S+E with no differences between groups (Cadore et al 2012b). This is in accordance with Vilacxa Alves et al (2011) who showed that the sequence of the aerobic and the strength training exercise does not interfere in energy expenditure during

the training sessions. Cutts et al (2010) in turn suggested that aerobic exercise followed by resistance training may expend the most kilocalories. Kang et al (2009) in turn have recommended a training approach that combines both aerobic and resistance exercise, but the resistance exercise should be performed first in the training session and the aerobic exercise should commence after no more than 5 minutes of rest. Authors speculated that this effect was mediated by an increased lipolysis that was brought about by preceding resistance exercise. They suggested that the intensity of preceding resistance exercise is a more important determinant of the fat oxidation rate than the volume of exercise completed. (Kang et al. 2009).

## **4 PURPOSE OF THE STUDY**

The main purpose of the present study was to examine the order effect after 24 weeks of single session combined endurance and strength training on the changes in total and regional body composition in male subjects. In addition, the study was designed to evaluate the order effect on maximal lower and upper body strength as well as on endurance performance.

### **Research questions**

- 1) Does the order of the strength and endurance training when performed during the same training session influence the changes in regional and whole body soft tissue lean and fat mass?
- 2) Are there differences in strength and endurance performance development between the E+S and S+E group?

## 5 RESEARCH HYPOTHESIS

The hypothesis to the proposed research questions are as follows:

*Hypothesis 1.* Combined single session strength and endurance training will elicit gains in total body lean mass which can be mainly attributed to the hypertrophy of the lower body muscles. Gains in lean mass will be independent of the training session sequence (Cadore et al. 2012b). In addition, total body soft tissue fat mass will decrease (Vilacxa Alves et al. 2012, Cadore et al. 2012b), however, changes of a similar magnitude will be observed for both groups (E+S and S+E).

*Hypothesis 2.* Performing endurance training before the strength training will cause diminished strength gains when compared to the group where the strength training will be performed first in the training session (Coffey et al. 2009, Davis et al. 2008, Leveritt & Abernethy 1999, Cadore et al. 2012a). However, the intra-session exercise order during the concurrent strength and endurance training will result in the same magnitude of maximal endurance performance increases (Cadore et al. 2012b).

## 6 METHODS

### 6.1 Subjects

A total of 64 untrained men were recruited for the current study from the Jyväskylä region. Untrained was defined as not being involved regularly in either endurance or resistance training for at least one year. All subjects were recruited by advertisements in e-mailing lists and newspapers as well as from public places. The acceptable age range was 18 – 40 years of age. The target group had to be free of acute illnesses and injuries as well as pronounced overweight (BMI <31 kg/m<sup>2</sup>). Additional exclusion criteria were impaired glucose tolerance or metabolic syndrome as well as any form of cardiovascular, obstructive pulmonary or musculoskeletal diseases which may restrict their participation in prolonged physical training. General health status and resting electrocardiogram (ECG) were examined by a qualified physician before the participation. All subjects were informed verbally and in a written form about the study design and the conducted measurements as well as about possible risks before the beginning of the study. Before the study, all subjects signed the informed consent for participating in the study. Methodological considerations, conducted in this study were approved by the Ethical Committee at the University of Jyväskylä.

Not all the subjects recruited for the training study completed the intervention period successfully. Drop outs occurred due to the minor injuries or medical issues. Motivational and personal issues also decreased the number of men completing the study. A total of 56 subjects completed the entire 24-week training intervention.

The anthropometric characteristics of the subjects completing the 24-week training period are shown in Table 1. Subject height was measured with wall-mounted tape measurer (accuracy 0.1 cm) and weight with a digital scale (accuracy 0.1 kg). Before the scaling subjects were asked to be fasted for 12 hours and remove heavy clothes and shoes when scaled. BMI was calculated as body weight in kilograms divided by the square of the height in meters (kg/m<sup>2</sup>).



**Table 1.** Anthropometric data for two intervention groups (E+S and S+E) and control group before the training period.

Group	E+S	S+E	Control
n	14	18	24
Age (yrs)	28.7 ± 5.5	29.8 ± 4.4	29.2 ± 6.0
Height (m)	1.8 ± 0.1	1.8 ± 0.1	1.8 ± 0.1
Weight (kg)	78.0 ± 9.3	75.2 ± 8.5	79.5 ± 10.0
BMI (kg/m <sup>2</sup> )	24.6 ± 2.7	23.5 ± 2.1	24.6 ± 3.3

E+S=endurance preceding strength training; S+E=strength preceding endurance training.

## 6.2 Study design

The study was designed as longitudinal, taking into consideration training adaptations attained during a 24-week training period. In the autumn 2011 a total of 40 men were recruited to participate in a training intervention study. The intervention period for the training groups was conducted between the Autumn of 2011 and Spring of 2012 over a six-month period. Subjects for the control group were recruited and measured during the Fall of 2012 over a three-month period. All the subjects were familiarized with the measurement protocol before conduction of the pre-measurements. After the basal measurements for strength and endurance subjects recruited in Autumn of 2011 were matched according to the baseline performance values and assigned either to the training group where endurance (E) preceded strength (S) training (E+S) or to the group where trainings were performed in the opposite order (S+E). The 24-week training period consisted of two 12-week periods which were separated by mid-measurements. During the first part of the intervention period (period I) subjects trained two times per week (2x 1E+1S or 2x 1S+1E) and during the second part of the intervention (period II) subjects had 5 trainings in a 2-week period (5x 1E+1S/ 14 days or 5x 1S+1E/ 14 days). All subjects, including controls, were instructed to continue their habitual physical activities throughout the intervention period. The overview of the study design is presented in Figure 15.

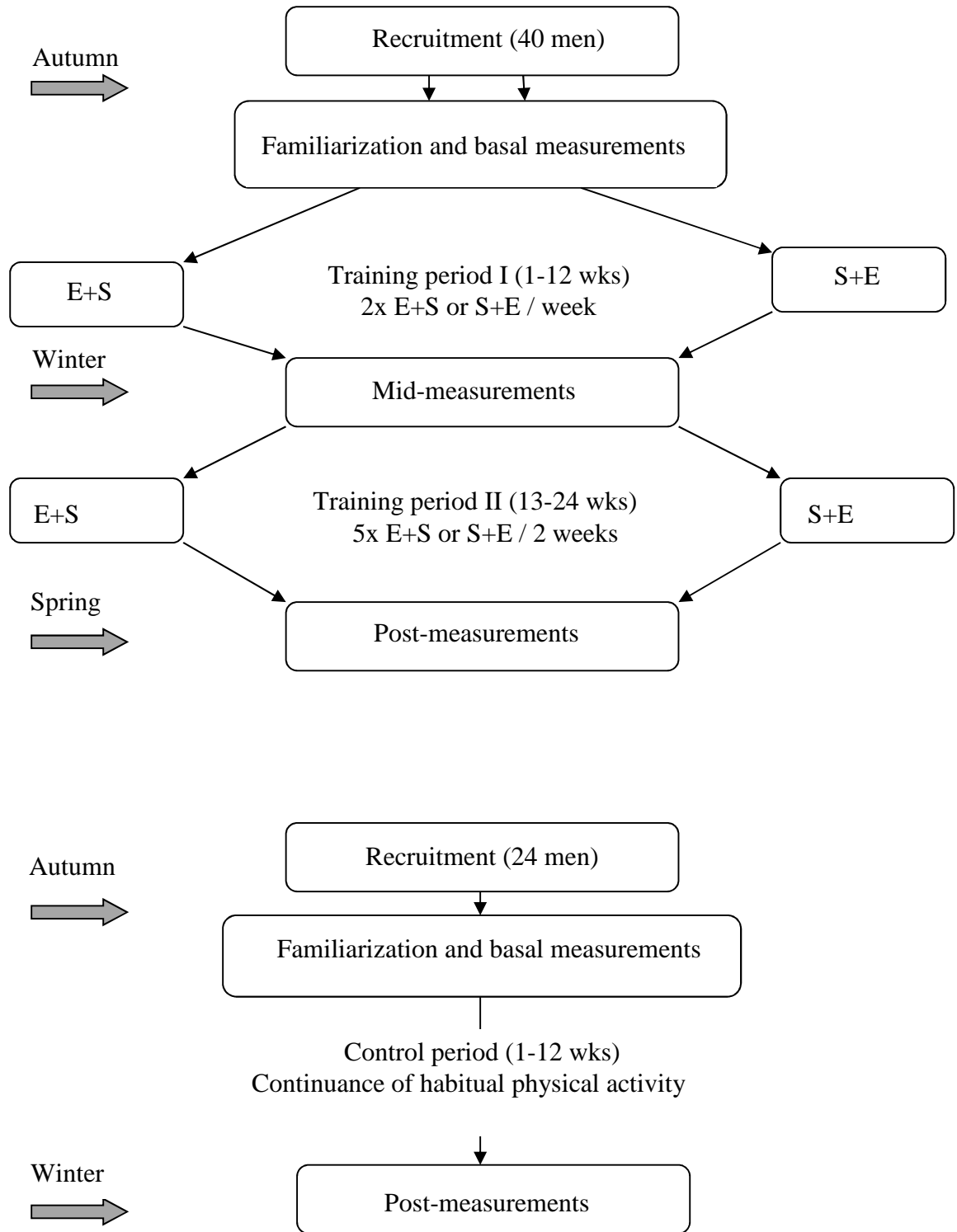


FIGURE 15. Overview of the study design.

## 6.3 Training protocols

Training consisted of two 12-week periods of progressive combined single session strength and endurance training (E+S or S+E). All subjects completed a familiarization session to acquaint themselves with training procedures, equipment and loads. Training programs were identical for the E+S and S+E group, only the sequence of strength and endurance training was reversed. Endurance and strength training were combined into the one training session so that no more than a 5-10 minute break was allowed during two training sections. A maximum of half a litre water was allowed to consume during the training sessions. To avoid the fatigue and glycogen depletion from the first training session subjects were encouraged to consume glucose tablets, provided by the research team, during the break between the two training sections. The combined endurance and strength training sessions averaged from 60 to 120 minutes in length. All the training sessions were supervised by qualified instructors. Missed workouts were made up, so that each subject achieved at least 90% of the prescribed number of training sessions assigned.

### 6.3.1 Endurance training protocol

The endurance training program was performed on a cycle ergometer. The intensity of cycle training was based heart rate zones which were calculated based on the subject's aerobic and anaerobic thresholds, determined during the maximal aerobic performance tests and controlled by Polar® heart rate monitors. Heart rate zones were reassessed during the mid-measurements in order to adjust the endurance training for weeks 13-24. Endurance training sessions averaged from 30-50 minutes. A more detailed description of the progression of the endurance-training program is presented in Table 2.

Table 2. Endurance training periodization for training period I and II (1-12/13-24 wks)

Weeks	1-3	4-7	8-9/13-15	10-12/16-24
Intensity	< AT	<AT - >AT	<AT - AnT	<AT - >AnT
Mode	Continuous	Continuous	Interval	Interval (10-12/20-24 wks) Continuous (16-19 wks)

AT - aerobic threshold; AnT- anaerobic threshold

### 6.3.2 Strength training protocol

The total body strength training program consisted of exercises for the lower and upper extremities and trunk, but was focused on knee extensors and flexors. Each training session consisted of three leg exercises: two leg extensor exercises (bilateral leg press and seated knee extension) and one exercise for knee flexors (seated knee flexion). Knee extensors and flexors were trained bilaterally as well as unilaterally (during the last 5 weeks of training period I and II). Four to five exercises were performed for other main muscle groups (lateral pull down, standing bilateral triceps push down, bilateral biceps curl, seated military press, or bilateral dumbbell fly, trunk flexors and extensors). Training intensity was progressive throughout the two 12-week periods. First 3 weeks of strength training was performed as circuit training and acted as a general preparation phase to develop toleration to the resistive exercise stress, verify proper exercise techniques, and accustom the subjects to strength training. Next 4 weeks (week 4-7) were designed to produce muscle hypertrophy and were followed by 2 weeks of mixed hypertrophic and maximal strength training (each performed once in a week). During the last two weeks one maximal strength and one mixed maximal strength and explosive strength session was carried out in a week. A similar strength training progression was carried out also during the second training period. A more detailed description of the progression of the resistance-training program is presented in Table 3 and 4. The rest periods between the sets and exercises of hypertrophic exercises were two minutes and between sets and exercises of maximal and explosive strength three minutes.

Table 3. Strength training periodization for training period I (1-12 wks)

	1-3 wks	4-7 wks	8-9 wks	10-12 wks
	Strength- endurance	Hypertrophy	Hypertrophy/Maximal	Maximal/Explosive
Intensity	40-50%	70-85%	70-80% / 85-90%	80-95% / 30-40%
Repetitions	15-20	8-12	8-10/3-5	3-4/8-10
Sets	2-3	2-4	2-3/2-4	4-5/3

Table 4. Strength training periodization for training period II (13-24 wks)

	13-15wks	16-19 wks	20-22 wks	23-24 wks
	Endurance/Hypertrophy	Hypertrophy	Maximal	Maximal/Explosive
Intensity	45-60% / 65-80%	70-85%	70-80/85-90%	80-95% / 30-40%
Repetitions	12-20/10-12	8-12	8-10/3-5	3-4/8-10
Sets	2-3	2-4	2-3/3-4	4-5/3

## 6.4 Pre-, mid-, and post-training measurements

In order to determine prolonged training adaptations, the measurements were conducted prior to the start of the training period (after preparatory sessions), repeated in the middle of the study (after the first 12-week training period) and the final measures were conducted after 24 weeks of training (after the second 12-week training period). The control group was tested only before and after their control period (12 weeks). All the physical tests were separated by two days of recovery. All the subjects, regardless of group assignment, were tested for each of the following dependent variables described in the following chapters.

### 6.4.1 Body Composition

Dual-energy X-ray absorptiometry (DXA) measurements were performed in the postabsorptive state after a 12-hour overnight fast. The day preceding the measurement day was a rest day from training. Total body fat and lean mass as well as regional body composition (arms, legs, trunk) were measured using dual energy X-ray absorptiometry (DXA, LUNAR Prodigy, GE Healthcare, Madison, WI). DXA scanner was calibrated always in the morning before the measurements. Body composition of individual subjects was determined at the approximate same (within one hour) time of the day. Soft tissue distribution was analyzed separately for the trunk and the upper and lower extremities. The system software was enCore 2005, version 9.30 was used (Kim et al. 2002). Lean mass was calculated as the fat-free body mass without including bone mineral mass. Subjects were asked to wear only underwear with no metallic accessories and lay supine on a DXA-scanner table. The body was carefully positioned so that it was laterally centred on the

table, palms facing to the thighs. Legs were strapped together at the upper part of the calves and above the toes. Scanning was in 1-cm slices from head to toe by using the 6-min scanning speed. Appendages were isolated from the trunk and head by using DXA regional computer-generated default lines with manual adjustments. Bony landmarks were determined for the regional analysis (arms, legs, and trunk). The vertical line bisecting the glenoid fossa was used to separate the arms from the trunk (A). A horizontal line across the top of iliac crests (B) and angled line passing through femoral neck (C) was used to separate the legs from the trunk. The superior end of the trunk region was set at a level just below the chin (D) (Figure 16). Fat and lean mass in the head region was included into respective total body composition calculations.

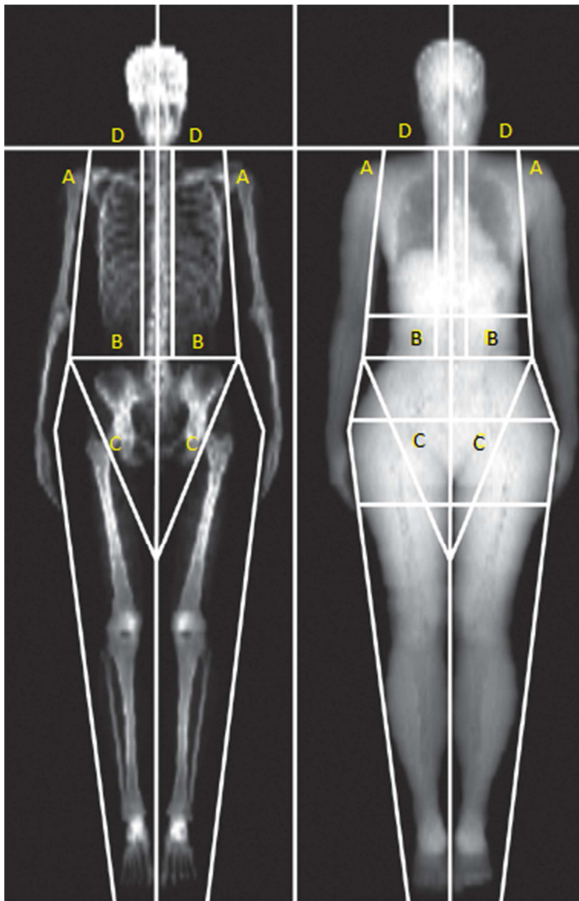


FIGURE 16. Dual-energy x-ray absorptiometry scan illustrating cut points for arm, trunk, and leg regions. A= line bisecting the glenoid fossa to separate the arms from the trunk; B= horizontal line across the top of iliac crests and C=angled line passing through femoral neck to separate the legs from the trunk; D=line below the chin separates head from the body.

## 6.4.2 Cardiorespiratory measures

The graded maximal aerobic cycling test to volitional exhaustion was performed on a mechanically braked bicycle ergometer (Ergonomic 839E, Monark Exercise AB, Sweden). The exercise intensity was increased by 25W every two min starting with 50W. Pedalling frequency was sustained at 70 rpm throughout the test. The subjects were encouraged by the tester to continue cycling until exhaustion. Maximal aerobic cycling power ( $W_{\max}$ ) was calculated with the following formula:  $W_{\max} = W_{\text{com}} + t/120\Delta W$ , where  $W_{\text{com}}$  is the last cycling power completed,  $t$  is the time in seconds the non-completed power was maintained and  $\Delta W$  is the increment in watts (Kuipers et al. 1985). Aerobic and anaerobic thresholds were determined from the respiratory gas analysis and blood lactate values. Blood samples were taken from the fingertip and analyzed with Lactata Pro LT.1710 analyzer (Arkray Inc., Kyoto, Japan). Oxygen uptake was measured by breath-by-breath continuously (SensorMedics® Vmax229, SensorMedics Corporation, Yorba Linda, California, USA).

## 6.4.3 Force measurements

*One repetition maximum (1 RM):* Maximal bilateral concentric strength (1RM) of the leg extensors was measured using horizontal leg press (David 210, David Sports Ltd., Helsinki, Finland) (Häkkinen et al. 1998). The subject was in a seated position so that the knee angle was less than 60 degrees. Before the real 1 RM testing a short warm-up was performed. Subjects were instructed to grasp from the handles and keep the contact with seat and backrest. On verbal command, the subject performed a concentric leg extension to a full extension of 180 degrees against the resistance determined by the loads chosen on the weight stack. Verbal encouragement was given to evoke the maximal performance. Each trial was separated with one minute of rest. The testing was continued until the subject was unable to extend the leg in full range of motion. Usually three but no more than five trials were used.

*Isometric leg press:* Maximal bilateral isometric strength (N) was measured using a horizontal dynamometer (designed and manufactured by the Department of Biology of Physical Activity, University of Jyväskylä, Finland) at the knee angle of 107° (Häkkinen et al. 1998).

Subjects were instructed to generate maximum force as rapidly as possible against the force plate for a duration of 2-4 sec. Subjects were verbally encouraged to perform their maximal. A minimum of three up to five trails were used to determine the maximal isometric leg extension with one minute break separating the trials. The trial with the highest peak force was selected for further analysis. The force signal was low-pass filtered (20 Hz) and analysed (Signal software Version 2.6, Cambridge Electronic Design Ltd., Cambridge, UK).

*Isometric military press:* Maximal bilateral isometric strength (N) for the upper extremities was measured using a seated military shoulder press. Subject sat on the dynamometer and pushed with arms against a horizontal bar with their elbows at 90 degrees (Häkkinen et al. 1998). Subjects were instructed to generate maximum force as rapidly as possible against the fixed bar for duration of 2-4 sec. During the tension subjects were verbally encouraged to perform their maximal. A minimum of three up to five trails were used to determine maximal isometric upper body force. The trial with the highest peak force was selected for further analysis. The force signal was low-pass filtered (20 Hz) and analysed (Signal software Version 2.6, Cambridge Electronic Design Ltd., Cambridge, UK).

## **6.5 Statistical analysis**

Before the analysis the normality test was carried out to check the normal distribution of the data. A one-way ANOVA analysis of variance was used to analyse differences between the two intervention groups (E+S and S+E) and the control group for pre- and mid-measurements. At post-measurements independent-samples T-test was used to analyse between group differences as data was present only for two intervention groups (E+S and S+E). Within group differences were analysed by using repeated measures ANOVA for pre-, mid-, and post-measurement values for all dependent variables. The relationship between body composition measurements and physical fitness was studied with the Pearson's correlation test. The level of significance for all tests was set at \* $p \leq 0.05$ , \*\* $p \leq 0.01$ , and \*\*\* $p \leq 0.001$ . Statistical analyses were performed using SPSS Statistics version 20 software (SPSS, Chicago, IL).



## 7. RESULTS

### 7.1 Body composition

At baseline there were no differences between the groups in body weight. No significant between-group difference was found in the changes of body weight and body mass index (BMI) during the 24-week training period between the two intervention groups. In within-group analysis only the S+E group significantly increased body weight during the 24-week period (Figure 17), while E+S and the control group showed no changes. An increase in body weight in the S+E group from  $75.2\pm 8.5$  kg to  $76.8\pm 8.3$  kg ( $2.3\pm 3.9\%$ ;  $p=0.013$ ) was assessed after 24 weeks of training, whereas, most of the change occurred during the first 12 weeks ( $1.7\pm 2.4\%$ ;  $p=0.007$ ). There was significant between-group difference between S+E and the control group at mid-measurements, when relative changes were compared.

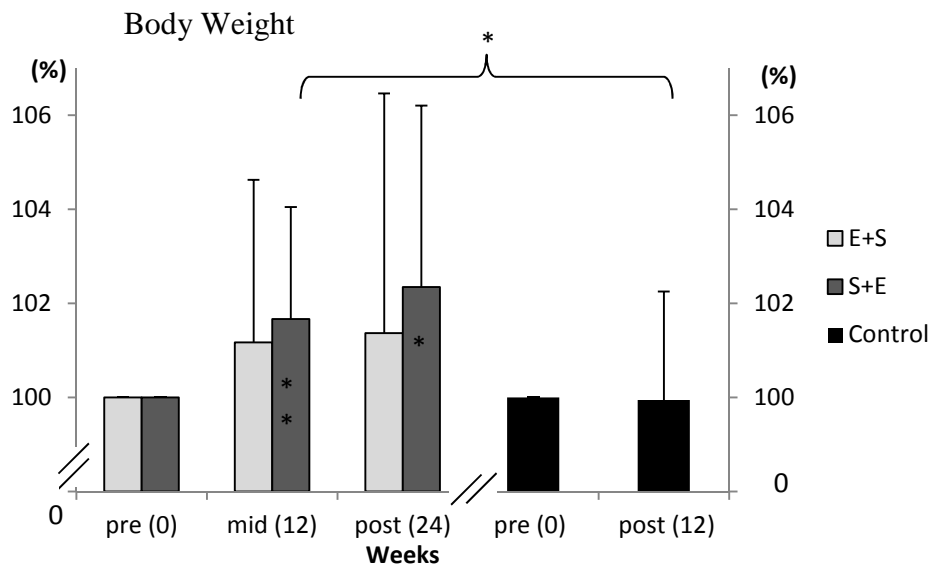


FIGURE 17. Changes in body weight over 24 weeks of periodized training. E+S=endurance training followed by strength training. S+E=strength training followed by endurance training. %=percent change from pre-values \*= significant from pre-measurements or as indicated.  $*p<0.05$ ;  $**p<0.01$

### 7.1.1 Body lean mass

The overall training period led to increases in lean mass. No significant between-group difference was found in any measurement point between the two intervention groups. In within-group analysis, both E+S and S+E increased total body lean mass during the 24-week training period by 3.3% ( $p=0.001$ ) or 1.9 kg and 2.6% ( $p\leq 0.001$ ) or 1.1 kg, respectively (Figure 18). Whereas, the E+S group increased lean body mass during the first 12 weeks by 1.6% ( $p=0.027$ ) and S+E 2.1% ( $p=0.002$ ). Statistically significant between-group difference was observed between the S+E and control group in changes in total lean mass ( $p=0.020$ ) which took place during the first 12-week period. The absolute values of whole body and regional lean soft tissue mass over the 24-week training period are given in Table 5.

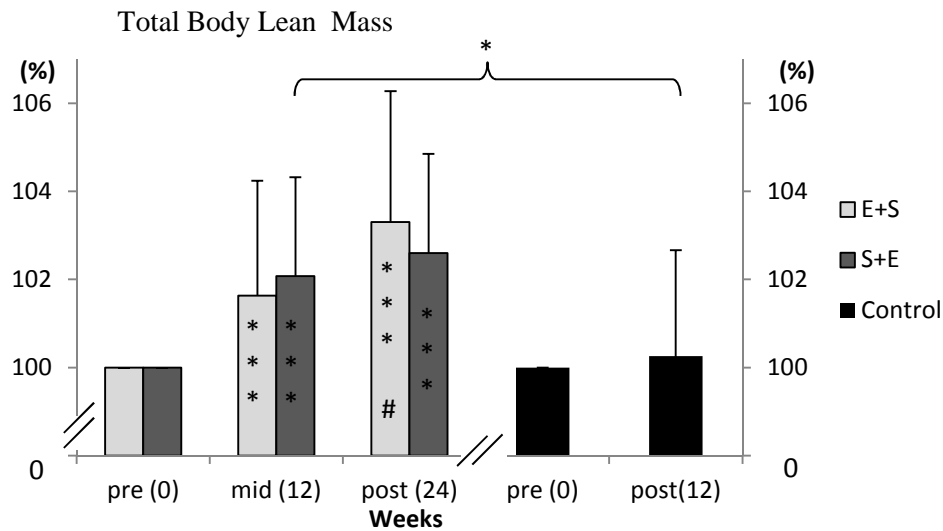


FIGURE 18. Changes in total body lean mass after 24 weeks of training. E+S=endurance training followed by strength training. S+E=strength training followed by endurance training. %=percent change from pre-values \*=significant from pre-measurements or as indicated #=significant from mid-measurements. \* $p<0.05$ ; \*\* $p<0.01$ ; \*\*\* $p>0.001$ ; # $p<0.05$

These increases in total lean mass were mainly due to changes in the leg region. The changes in total lean mass and leg lean mass correlated well throughout the training period in both E+S ( $r=0.735$ ,  $p=0.003$ ) and S+E ( $r=0.747$ ,  $p<0.000$ ). The E+S group significantly increased soft tissue lean mass in the leg region during both the first and last 12-week

periods by 3.6% ( $p=0.001$ ) and 2.4% ( $p=0.007$ ), respectively. The S+E group increased leg lean mass significantly during the first 12 weeks by 3.3% ( $p=0.018$ ) and over the 24-week period by 4.9% ( $p<0.000$ ). An overall increase of 1.4 kg and 1.1 kg or  $6.0\pm 4.4\%$  ( $p<0.000$ ) and  $4.9\pm 3.7\%$  ( $p<0.000$ ) were observed for the E+S and S+E group, respectively (Figure 19). The absolute values over the 24-week period are presented in Table 5. Changes during the first 12-week period in leg lean mass in the E+S and S+E group significantly differed from the changes in the control group ( $p=0.009$  and  $p=0.011$ ), respectively.

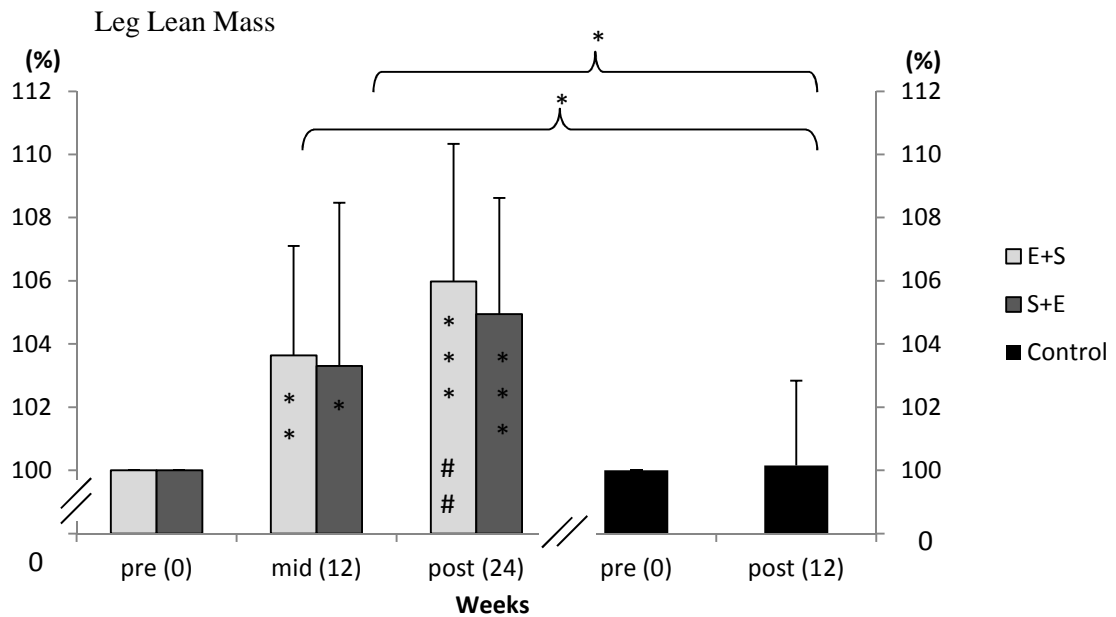


FIGURE 19. Relative changes in leg lean mass after 24 weeks of training. E+S=endurance training followed by strength training. S+E=strength training followed by endurance training. %=percent change from pre-values \*=significant from pre-measurements or as indicated #=significant from mid-measurements. \* $p<0.05$ ; \*\* $p<0.01$ ; \*\*\* $p>0.001$ ; ## $p<0.01$

Minor changes were observed in arm and trunk lean mass. Whereas, arm lean mass increased significantly only in the E+S group by 2.8% from  $6.61\pm 1.01$  kg to  $6.80\pm 1.07$  kg ( $p=0.029$ ). No significant changes in soft tissue lean mass were apparent for the trunk regions. There was a significant  $1.4\pm 3.0\%$  ( $p=0.028$ ) increase in percentage of lean mass from the mid- to post-measurements for the E+S group, whereas no significant differences were observed in the S+E and control group during the 24-week training period.

TABLE 5. Summary of the absolute values of lean mass over 24 weeks of periodized single-session combined strength and endurance training. (E+S n=14; S+E n=18).

Body region	Week 0	Week 12	Week 24
Total body (kg) E+S	57.1±4.3	58.1±5.2*	59.1±5.2***#
Total body (kg)S+E	56.7±4.8	57.9±4.7**	58.1±4.6***
Lean% E+S	74.0±7.5	74.29±7.2	75.4±7.1#
Lean% S+E	75.34±5.4	75.71±5.6	75.75±5.6
Legs (kg) E+S	23.9±2.5	24.8±2.7***	25.3±2.6***##
Legs (kg) S+E	23.5±2.2	24.2±2.5*	24.6±2.3***
Arms (kg) E+S	6.6±1.0	6.6±0.9	6.8±1.1#
Arms (kg) S+E	6.3±0.8	6.3±0.8	6.4±0.9
Trunk (kg) E+S	22.7±1.4	22.8±1.9	22.95±1.8
Trunk (kg) S+E	23.0±2.1	23.3±2.1	23.09±1.7

E+S=endurance training followed by strength training. S+E=strength training followed by endurance training. \*=significant with-in group difference from pre-measurement; #=significant with-in group difference from mid-measurements. \*p<0.05, \*\*p<0.01,\*\*\* p<0.001, #p<0.05, ##p<0.01

### 7.2.2 Body fat mass

There was a statistically significant between-group difference between the S+E and control group in the pre- and mid-measurements in leg, arm, trunk and total fat absolute values and fat percentage. Whole body and regional fat tissue absolute values over the 24-week training period are given in Table 6. Total body fat mass did not change significantly from pre- to post-training in any of the groups.

Percent of body fat measured by DXA was significantly higher in the control group than in S+E at pre- (p=0.018) and mid-measurement (p=0.014) time points (Figure 20). Only the E+S group showed a significant decrease from mid- to post-measurements by 1.4±3.17% (p=0.034).

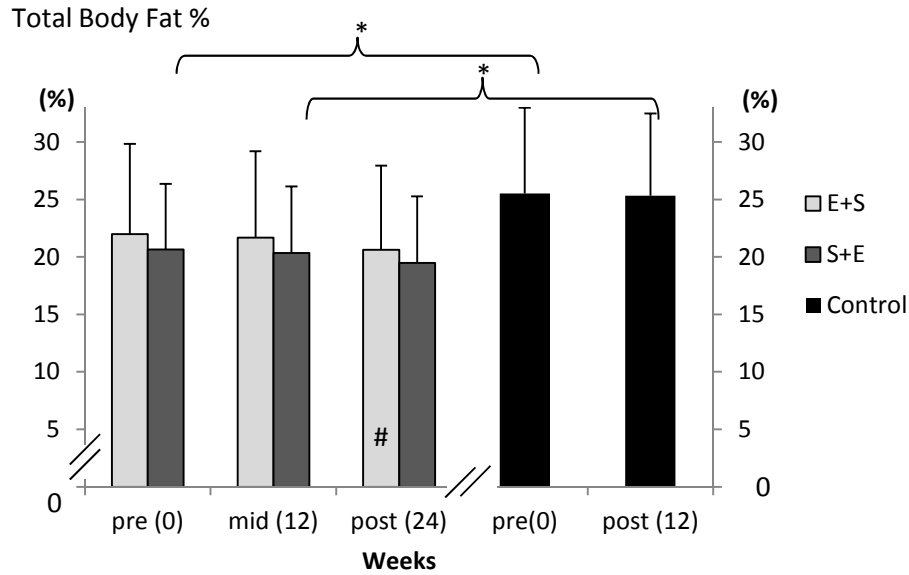


FIGURE 20. Values of total body fat% after 24 weeks of training. E+S=endurance training followed by strength training. S+E=strength training followed by endurance training. \*=significant from pre-measurements or as indicated; #=significant from mid-measurements. \* $p < 0.05$  # $p < 0.05$

Arm fat mass decreased in the S+E group by  $5.5 \pm 18.6\%$  ( $p = 0.045$ ) from  $1.10 \pm 0.47$  kg to  $1.01 \pm 0.40$  kg over the 24-week intervention period, while there were no statistically significant changes in the E+S group or control group. No significant changes were observed in leg and trunk fat mass for any of the groups at any time point.

No significant changes were observed in the control group at any time point for any body composition variable.

TABLE 6. Summary of the absolute values of fat mass over 24 weeks of periodized single-session combined strength and endurance training. (E+S n=14; S+E n=18).

Body region	Week 0	Week 12	Week 24
Total body (g) E+S	17.6±8.2	17.4±7.5	16.6±7.6
Total body (g) S+E	15.5±5.6	15.5±5.7	15.2±5.5
Fat% E+S	22.0±7.9	21.7±7.5	20.6±7.3#
Fat% S+E	20.7±5.7	20.3±5.8	19.5±5.8
Legs (g) E+S	7.2±3.2	7.1±3.0	6.8±2.9
Legs (g) S+E	6.5±1.8	6.1±2.0	6.2±1.7
Arms (g) E+S	1.3±0.7	1.2±0.6	1.2±0.6
Arms (g) S+E	1.1±0.5	1.1±0.5	1.0±0.4*
Trunk (g) E+S	8.5±4.5	8.5±4.0	7.9±4.0
Trunk (g) S+E	7.4±3.5	7.7±3.6	7.5±3.7

E+S=endurance training followed by strength training, S+E=strength training followed by endurance training.\*=significant with-in group difference from pre-measurement; #=significant with-in group difference from mid-measurements. \*p<0.05, #p<0.05

## 7.3 Physical performance

### 7.3.1 Strength measurements

Lower body strength increased in both training groups but remained unchanged in the control group. Dynamic leg press increased by 13% (p=0.000) or 18.8 kg and 17% (p=0.000) or 22.6 kg respectively in E+S and S+E during the 24-week training period (Figure 21). No significant between group differences at any time point were found in E+S and S+E (p>0.05). Training induced changes in the E+S and S+E group during the first half of training period significantly differed from the changes in the control group (p<0.000). Summary of absolute values of lower and upper body strength and aerobic power are presented in Table 7.

Dynamic 1 RM Leg Press

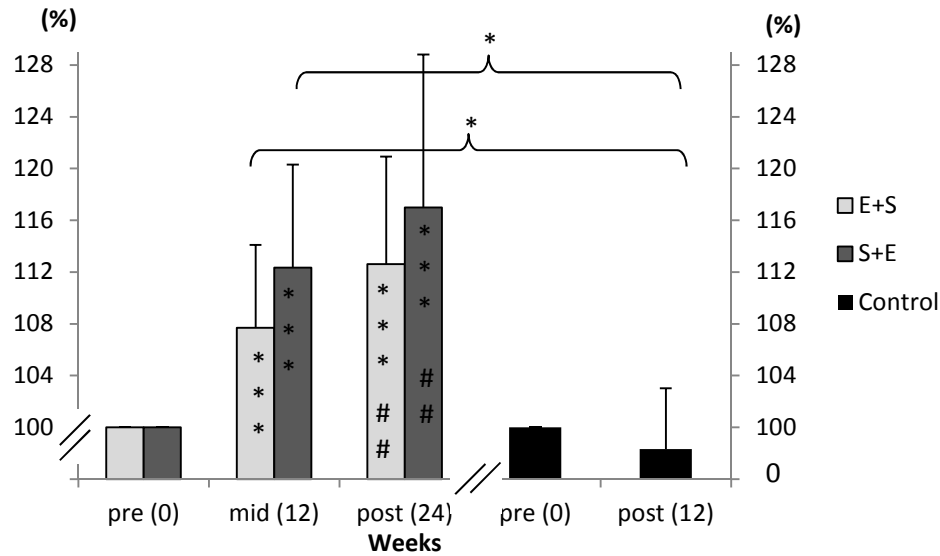


FIGURE 21. Relative changes in dynamic leg press 1 RM after 24 weeks of training. E+S=endurance training followed by strength training. S+E=strength training followed by endurance training. %=percent change from pre-values \*=significant from pre-measurements or as indicated #=significant from mid-measurements. \*p<0.05; \*\*p<0.01; \*\*\*p>0.001; ##p<0.01

TABLE 7. Summary of the lower and upper body strength and aerobic power during the 24-week training period ( $\pm$  SD). (E+S n=14; S+E n=18).

	E+S			S+E		
	Pre	Mid	Post	Pre	Mid	Post
1RM leg press (kg)	160.±28	171±26***	178±27***##	142±23	159.6±21***	165±20***##
Isometric leg press (N)	2772±738	3044±775**	3078±824***	2337±540	2517±522**	2603±563**
Military press (N)	742±212	755±174	799±157*#	661±148	682±126	703±133*#
maxWatts	265±42	281±40*	293±39***##	245±35	268±38**	284±37**

E+S=endurance training followed by strength training. S+E=strength training followed by endurance training.\*=significant with-in group difference from pre-measurement; #=significant with-in group difference from mid-measurements. \*=significant with-in group difference from pre-measurement; #=significant with-in group difference from mid-measurements. \*p<0.05; \*\*p<0.01; \*\*\*p<0.001; #p<0.05; ##p<0.01; ###p<0.001.

Isometric leg press force increased from pre- to post-measurements by  $11.6 \pm 9.8\%$  ( $p=0.000$ ) and  $13.2 \pm 3.5\%$  ( $p=0.008$ ) in both E+S and S+E group, respectively (Figure 22). Changes in the control group significantly differed from the changes in the E+S and S+E group during the first 12 weeks. There was no significant between-group difference between two training groups. The changes in the control group were not significant in any measurement time point in any of the lower strength variable measured.

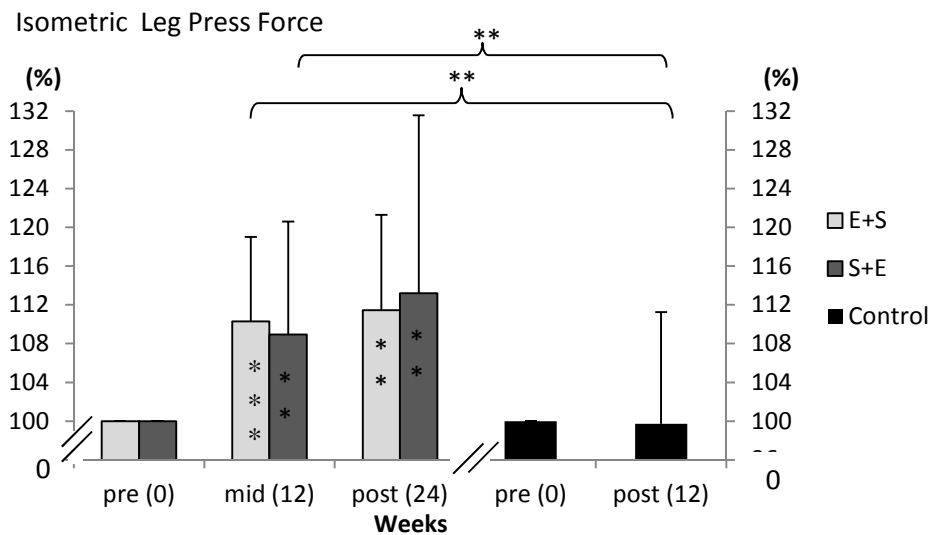


FIGURE 22. Relative changes in isometric leg press force after 24 weeks of training. E+S=endurance training followed by strength training. S+E=strength training followed by endurance training. %=percent change from pre-values \*=significant from pre-measurements or as indicated. \*\* $p < 0.01$ ; \*\*\* $p < 0.001$ ;

Upper body strength increased in both training groups. During the whole training period isometric military press force increased from  $742 \pm 212$  N to  $799 \pm 157$  N (10%) ( $p=0.043$ ) and from  $661 \pm 147.9$  N to  $703 \pm 133$  N (8%) ( $p=0.015$ ) in E+S and S+E, respectively (Figure 23). The changes in the control group were not significant in any measurement time point.



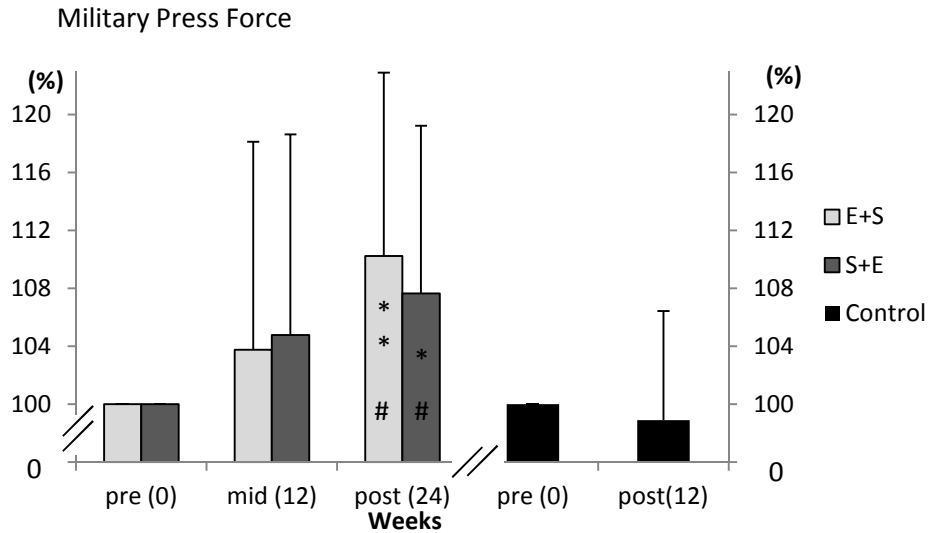


FIGURE 23. Relative changes in isometric military press force after 24 weeks of training. E+S=endurance training followed by strength training. S+E=strength training followed by endurance training. %=percent change from pre-values \*=significant from pre-measurements or as indicated #=significant from mid-measurements. \* $p < 0.05$ ; \*\* $p < 0.01$ ; # $p < 0.05$

### 7.3.2 Endurance performance

Endurance performance increased in both intervention groups.  $W_{max}$  increased by 11% ( $p=0.000$ ) in the E+S and 16.2% ( $p=0.000$ ) in the S+E group (Figure 24). There were no between-group differences between the E+S and S+E group. Changes in the control group values, significantly differed from the changes in the E+S ( $p=0.004$ ) and S+E ( $p < 0.000$ ) group. The changes in the control group were not significant in any measurement time point.

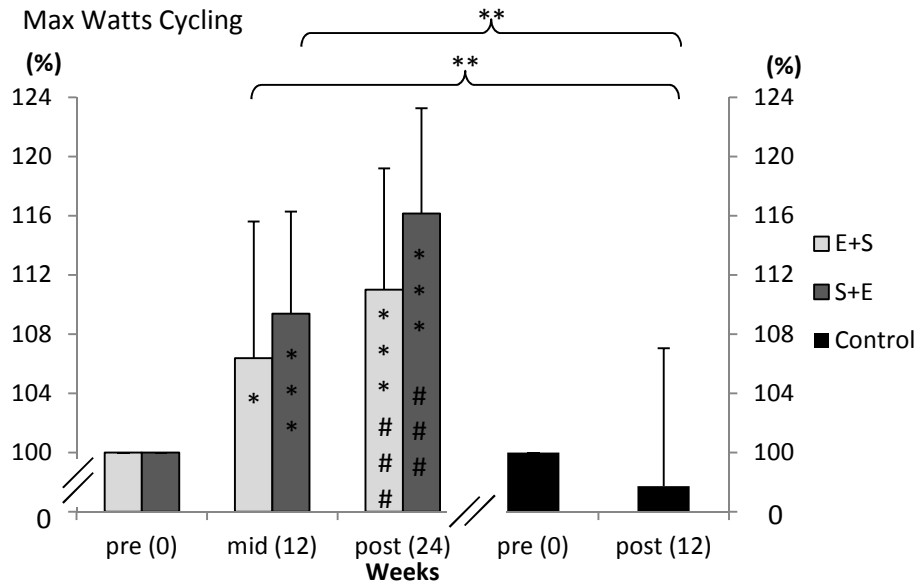


FIGURE 24. Relative changes in maximum watts in the cycling test after 24 weeks of training. E+S=endurance training followed by strength training. S+E=strength training followed by endurance training. %=percent change from pre-values \*=significant from pre-measurements or as indicated #=significant from mid-measurements. \*p<0.05; \*\*\*p>0.001; ###p<0.001

## 7.4 Correlations between body composition and physical fitness

When the two training groups were combined and the relative changes in physical fitness parameters and lean mass were analyzed, there was a significant correlation between the changes in leg lean mass and isometric leg press force from pre- to mid measurements ( $r=0.441$ ,  $p=0.012$ ). When the changes throughout the training period were analyzed each group separately a positive significant correlation in leg lean mass and isometric leg press force changes was observed only in the S+E group ( $r=0.516$ ,  $p=0.028$ ) from pre- to post-measurements. In the E+S group a significant correlation was present between in arm lean mass and isometric military press force ( $r=0.541$ ,  $p=0.046$ ) from pre- to mid-measurements.

Significant correlations between strength and lean soft tissue were observed when the absolute values were compared in the total group of E+S and S+E. Significant correlations were observed between leg lean mass and lower body dynamic leg press 1 RM at pre- ( $r=0.379$ ;  $p<0.05$ ), mid- ( $r=0.491$ ;  $p<0.05$ ), and post-measurements ( $r=0.545$ ;  $p\leq 0.001$ ). Similarly, leg lean mass significantly correlated with aerobic power in every measurement time point (pre:  $r=0.599$ ,  $p\leq 0.000$ ; mid:  $r=0.641$ ,  $p\leq 0.000$ ; post:  $r=0.713$ ,  $p\leq 0.000$ ). At every measurement point, upper body isometric military press significantly correlated with arm lean mass (pre:  $r=0.650$ ,  $p\leq 0.000$ ; mid:  $r=0.543$ ,  $p\leq 0.001$ ; post:  $r=0.525$ ,  $p\leq 0.002$ ).

When absolute values were compared in two training groups separately, leg lean mass correlated with dynamic leg press 1 RM in the E+S group in mid- measurement ( $r=0.546$ ,  $p=0.043$ ) and post-measurement ( $r=0.026$ ,  $p=0.026$ ) time point. A positive correlation between lower body strength and lean mass was present also in the S+E group at post-measurements ( $r=0.470$ ,  $p=0.049$ ). Significant correlations between upper body lean mass and military press force were observed in the E+S group at every measurement time point (pre:  $r=0.881$ ,  $p\leq 0.000$ ; mid:  $r=0.772$ ,  $p<0.05$ ; post:  $r=0.766$ ,  $p<0.001$ ). Aerobic power and lower body lean mass correlated in both training groups. In E+S there was a significant correlation in every measurement time point (pre:  $r=0.676$ ,  $p<0.05$ ; mid:  $r=0.903$ ,  $p\leq 0.000$ ; post:  $r=0.867$ ,  $p\leq 0.000$ ) and in S+E only in the pre- ( $r=0.519$ ;  $p<0.05$ ) and post-measurements ( $r=0.569$ ;  $p<0.05$ ).

## **8 DISCUSSION**

The purpose of the present thesis was to examine the effect of intra-session sequence on body composition as well as on lower and upper body strength and endurance performance after 24 weeks of single session combined strength and endurance training. The primary findings of this study showed that in subjects not accustomed to regular resistance or endurance training the intra-session order had no influence on the changes in body composition. Independent of the intra-session sequence 24 weeks of single session combined strength and endurance training led to significant increases in total body and leg lean mass. Large training-specific improvements were also observed in muscle strength and aerobic performance after 24 weeks of single session combined strength and endurance training. Irrespective of the strength and endurance training sequence no differences were observed in the magnitude of strength or aerobic performance improvements.

### **8.1 Changes in body composition**

The endurance-first training protocol has been often proposed to impair the strength performance committed later in the same session (Coffey et al. 2009, Chtara et al. 2005) and thereby impair the effectiveness of strength training programs addressed to promote muscle mass gains (Vilacxa Alves et al. 2012). In the current study the magnitude of changes in soft tissue lean mass was similar for both intervention groups (E+S and S+E), whereas most of the changes took part in total lean mass (3.3% in E+S and 2.6% in S+E) and leg lean mass (3.6% in E+S and 2.4% in S+E). Supportively to our results, Cadore and his colleagues (2012a, 2012b) have reported that in the elderly the intra-session concurrent exercise sequence had no influence on quadriceps femoris thickness gains (9.0% in E+S and 9.3% in S+E). They interpreted that even when performing strength training with a lower relative loading intensity, maximal effort per set allows the E+S group to stimulate

its optimal contractile protein synthesis, which results in the same level of morphological adaptation.

Increases in total body lean mass observed in our study seem to be in agreement with previous literature (Fleck et al. 2006, Nindl et al. 2000, Dolezal & Potteiger 1998). Though the study of Nindl et al (2000) was with the same duration as the current study, others have observed similar gains with only the half of the time (Fleck et al. 2006, Dolezal & Potteiger 1998). Differences in hypertrophy development between studies could be explained with different training intensities, volumes and frequencies used. Strength training program used in the current study was not designed to maximize hypertrophy but to produce overall improvements in skeletal muscle hypertrophy, maximal strength, and power. Only one fourth of the whole strength training program included loads of 70-85% of maximum which should promote muscle hypertrophy (American College of Sports Medicine 2009). In the studies of Dolezal and Potteiger (1998) and Fleck et al (2006) hypertrophic loadings were used throughout the training period for all the main muscle groups. Unlike in the present study, Dolezal and Potteiger (1998) and Fleck et al (2006) used jogging in their endurance training. Though high intensity cycling has shown to increase lower body skeletal muscle mass (Harber et al. 2009), the intensities used the present study might have been too low to elicit muscle hypertrophy.

Others have observed larger muscle mass increases with single session combined strength and endurance training, exceeding 10% (Sale et al. 1990, Lundberg et al. 2013, Cadore et al. 2012a). Those greater improvements may come from the different methods used to assess changes in body composition. Methods estimating muscle thickness or cross-sectional area (CSA) (Sale et al. 1990, Lundberg et al. 2013, Cadore et al. 2012a) have shown much larger skeletal muscle mass gains (>10%) compared to the lean tissue values observed with DXA (Fleck et al. 2006, Nindl et al. 2000) (<5%). The differences in the CSA data compared with the volume data, combined with the fact that muscle hypertrophy has been shown not to occur uniformly throughout each individual muscle or region of the body in response to strength training (Abe et al. 2003) provides support for the

recommendation that muscle volume rather than CSA should be studied in investigations where muscle mass or hypertrophy are primary variables of interest (Roth et al. 2001).

Strength training in our study targeted foremost the thigh muscles, especially the knee extensors. This likely resulted in a lower absolute change in total lower body lean mass (Delmonico et al. 2008). The DXA-method is unable to differentiate between muscles within limb and thereby leg lean mass measurements included lower limb area consisting of whole thigh and calf (Menon et al. 2012). This increased the possibility that the measurement error may have had some role in the findings by reducing the percent muscle mass change observed. The increases of the similar magnitude were observed for both total and leg lean mass. Thereby, it can be concluded that total lean mass increases were observed mainly due to the positive lean mass changes in the leg region. Nindl et al (2000) have supportively shown that after 24 weeks of total body periodized military-specific strength and endurance training increases in total body lean mass could mainly be attributed to a gain in leg lean mass. In the present study, arm lean mass had a tendency to increase in both groups but only in the E+S group a significant 2.8% increase was observed. Larger improvements in leg lean mass can be explained with the higher training intensity/volume for the thigh muscles than for upper body used in the current study. The current results and those from Nindl et al (2000) show the importance to consider the regional changes in body composition rather than whole body changes alone.

No significant changes in total body fat mass were observed in the present study. Percentage of fat mass decreased only in the E+S group which was mostly due to an overall increase in lean body mass. Though this is in agreement with Gravelle and Blessing (2000), literature usually suggests decreases in fat mass and/or percentage of fat mass after combined training (Sillanpää et al. 2008, Glowacki et al. 2004, Vilacxa Alves et al. 2012, Dolezal & Potteiger 1998). There can be some explanations why men in the current study did not lose fat mass. First, though all the subjects were encouraged to eat healthfully and participate in the nutrition lecture in the beginning of the intervention period, nutrition in the current study was not controlled. Physical exercise alone without dieting has shown to have only a modest effect on total body mass and fat mass loss. Second, the magnitude of

the expected adipose tissue loss has been shown to be related to the initial values of adipose tissue (Doucet et al. 2002) but the male subjects participating in the current training intervention study were all in normal weight category ( $BMI \leq 25 \text{ kg/m}^2$ ;  $\text{fat}\% \leq 21\%$ ) (Madeira et al. 2013). Third, in order to observe an increase in fat utilization and augmented energy expenditure, both the resistance and endurance exercise protocol needs to be of sufficiently high intensity as secretion of lipolytic hormones has found to be intensity dependent (Kang et al. 2009). According to that it can be speculated that the intensities used in our study were too low to elicit significant fat utilization and hence a decrease in fat mass. In addition to possibly low endurance training intensity, the training frequency in the current training program was also less than suggested for weight loss. The current training frequency was two times a week during the first training period and even though training frequency increased during the last 12 weeks it still may have been too low, as training programs should be conducted at least  $3 \text{ d}\cdot\text{wk}^{-1}$  to elicit total body or fat mass loss. Last, the training programs used in the current study were designed to elicit changes in lower body. Resistance of thigh fat to mobilization and utilization has been reported previously (Rognum et al. 1982), which can be attributed to a number of possible factors, including lipoprotein lipase activity, local blood flow, receptor agonist-to-antagonist ratio, sympathetic nervous stimulation, tissue morphology, and lipolytic responsiveness to endocrine stimuli (Rognum et al. 1982, Schoenfeld 2010).

As lean mass increased and fat mass did not decrease during the 24-week period the total body weight had a tendency to increase during the 24-week period, whereas the increase was significant only in the S+E group (2.3%). Increased body weight is usually observed after a resistance training program (Donnelly et al. 2009). According to those results strength training seemed to be superior to endurance training in terms of changes in body composition. Even without changes in fat mass, this can be considered as a favorable change in body composition, because the increase in lean mass is associated with increases in resting metabolic rate (RMR) (Dolezal & Potteiger 1998). This in turn is relevant in terms of body composition, because RMR represents about 50% of daily energy expenditure (Vilacxa Alves et al. 2012).

## 8.2 Changes in muscle strength performance

In the current study, both E+S and S+E group increased lower body dynamic and isometric maximal strength during the 6-month training period and no between group differences were observed. The current findings indicate that performing low- to moderate intensity strength and endurance training over a prolonged period of time does not interfere with maximal strength gains in healthy young men. Supportively, Collins and Snow (1993), Chtara et al (2008) and Gravelle and Blessing (2000) have not found that the sequence of training sections had had specific influence on the development of lower body strength. Though it has been demonstrated that a cycle ergometer exercise session can induce an acute decrease in lower-body force development due to the local fatigue (Leveritt & Abernethy 1999) and by compromising neuromuscular function (Garcia-Pallares & Izquierdo 2011, Collins & Snow 1993), this seems to be not the case in the current study. Low- to moderate cycling did not probably cause fatigue which would have limited strength training for young healthy men as no between group difference was observed or might have served as a warm up before the strength training (Gergley 2009). Those findings are also in agreement with de Souza et al (2007), who showed that low-intensity continuous endurance exercise does not interfere with maximal strength.

The present results are not in agreement with Cadore et al (2012a) who observed different strength improvements according to the intra-session order. Concurrent training regimens in the study by Cadore et al (2012a) resulted in enhanced lower-body dynamic strength and *quadriceps femoris* muscle quality in both E+S and S+E group, but greater improvement occurred when strength training was performed prior to endurance training. Possible reasons for conflicting results can be explained with different endurance and strength training intensities, and volumes employed in various studies can lead to diverse training specific adaptations. In addition to that, the training status of subject, their gender and age as well as tests used to measure the dependent variables can influence the final results. (Glowacki et al. 2004).



The magnitude of the lower body strength improvements in the present study are in accordance with previous studies (Chtara et al. 2008, Dolezal & Potteiger 1998, Collins & Snow 1993, Gravelle & Blessing 2000). However, many studies have observed similar or even larger improvements within half a shorter time (Fleck et al. 2006, Dolezal & Potteiger 1998, Collins & Snow 1993, Gravelle & Blessing 2000). A study using similar duration intervention period (22 weeks) observed 20-35% improvements in maximal strength in previously untrained young male subjects (Sale et al. 1990).

The extent of interference might also be related to the endurance training type used in training. There has been evidence that strength development can be maximized when strength exercise is combined with biomechanically specific endurance training mode. In both leg press resistance exercise and cycle ergometer endurance exercise, the quadriceps femoris produce movement primarily concentrically which in turn can lead to larger strength gains. (Gergley 2009). Even though the training load is significantly lower in bicycle training than in strength training, the high amount of repetitions and high intensity of cycling with rather high loads has been shown to cause some hypertrophy in knee extensors (McCarthy et al. 2002). Subjects in the current study were informed to keep the pedaling rate close to 70 rpm, but they were not equipped with electronic values and the training protocol was controlled only by the heart rate monitor. The ones who were pedaling slower than 70 rpm might have imposed a form of high repetition resistance training. The extent that cycling rpm effects strength development in concurrent training remains unclear and requires further inquiry. (Gergley 2009). Contrary to that, isometric and concentric force production has been reported to be impaired if aerobic exercise is performed on a cycle ergometer at anaerobic intensity (Lepers et al. 2001).

In the literature it has been shown that the optimal strength development stimulus is not necessarily the same as the optimal muscle hypertrophy stimulus (Schoenfeld 2010). Increases in the muscle quality after strength training suggest that despite the increases in muscle size, neural factors, such as increases in motor unit recruitment or firing rate capacity, are the primary mechanisms that explain strength increases in elderly people (Cadore et al. 2012b). In agreement with previous literature (Ahtiainen et al. 2003) the

improvements in strength were larger than the gains in soft tissue lean mass also in the present study.

### **8.3 Changes in endurance performance**

Along with the aerobic training volume and intensity the intra-session exercise sequence might be an important variable in the adaptations to the concurrent training program (Garcia-Pallares & Izquierdo 2011, Chtara et al. 2005). In the current study different intra-session exercise orders resulted in the increases of the same magnitude in maximal aerobic power (11% and 16.2%, respectively in the E+S and S+E group) over the 24-week training period. Similarly to our results, Cadore et al (2012b) and Collins and Snow (1993) demonstrated that different intra-session order during concurrent training resulted in the same magnitude of maximum endurance performance. Most of the studies investigating the effects of simultaneous strength and aerobic training on endurance performance demonstrate that strength training does not negatively interfere with the development of cardiorespiratory fitness (Kraemer et al. 1995, Bell et al. 2000, Cadore et al. 2012b). Unlike others, Chtara et al (2005) observed compromised endurance gains in young men when strength training was performed immediately before endurance. Possibly the volume, intensity, and frequency of the concurrent training performed in the current study minimized interference of the intra-session sequence in the endurance performance (Cadore et al. 2012a). Similarly to the Cadore et al (2012a), subjects in the present study performed periodized strength and endurance training for health promotion, starting at lower intensities and gradually achieving the intensities close to the maximum.

The increases in aerobic power in the single session combined training group have been proposed to be of lesser magnitude than those induced by endurance training alone (Dolezal & Potteiger 1998). Conversely to that, Cadore and his colleagues (2011) observed the same magnitude increases in the concurrent training and endurance only group (20.4% and 22.0%, respectively). They concluded that combining strength and endurance into the same training session does not interfere with the development of maximal aerobic power in the

elderly. The enhancement of the efficiency pattern after a concurrent training period may be explained, in part, by neuromuscular adjustments (Cadore et al. 2012b). It has been shown a positive association between neuromuscular performance and maximum endurance capacity (Izquierdo et al. 2003) as well as muscular economy during aerobic exercise (Cadore et al. 2011). The increase in maximum aerobic power may be at least in part due to improved lower body strength (Cadore et al. 2012b). Enhanced endurance performance has been observed after combining strength training with endurance training because of increases in the size of type I fibers and changes in type II subtype ratios and myofibril contractile properties (Chtara et al. 2005). It has been suggested that when interference is observed in muscle hypertrophy, strength gains may be maintained by neural mechanisms (Leveritt & Abernethy 1999).

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

The limitation of this thesis was the limited dietary energy intake observations. Incomplete and missing data from food diaries and physical activity logs made it impossible to follow the everyday activities which may have influenced the changes in body composition. Changes in food intake or habitual physical activity which may have occurred with the enrollment to the study can potentially explain the increase instead of decrease in the body weight. Though subjects were asked to participate in the nutrition lecture about the adequate and optimal food intake before and after the training, the detailed data about the food consumed is missing. Data about energy expenditure during the training sessions was not collected. The strengths of the present thesis are the long supervised training period, controlled and repeated measurements of body composition, muscle strength and aerobic performance.

Although DXA is reported to be a valid and reliable technique to estimate changes in soft tissue composition (Nindl et al. 2000, Sillanpää 2011, Houtkooper et al. 2000), unlike in many other studies (Sillanpää 2011, Santos et al. 2010, Williams et al. 2006), several persons were carrying out DXA measurements in the current project. Nevertheless, before

body composition measurements all the subjects were asked to follow a similar pattern by avoiding physical activities 48 hours and fasting for 12 hours before the measurement. This will make the measurements more reliable. DXA allowed assessing changes in total body as well as in regional fat and lean soft tissue mass.

Since no strength-only or endurance-only training was included in the present study it remains unknown if there was interference effect between strength and endurance training even though no order effect was observed. It is possible to speculate only according to the existing literature that the values observed during single session combined training were less than during strength-only or endurance-only training. Finally, those results are applicable only to sedentary, apparently healthy males. Whether those results can be applied to women at the same age, weight and physical fitness status remains out of the scope of this thesis.

## **8.5 Conclusions and practical applications**

The present data expand the knowledge of previous findings related to the importance of intra-session exercise sequence during the single session combined strength and endurance training when optimizing the training outcome. The current findings suggest that a 24-week single session combined strength and endurance training program significantly increases total body and leg soft tissue lean mass in young previously untrained men, independent of the training sequence. In addition to whole body measurements, regional body composition changes should be observed, as the total body lean mass increases were present due to the changes in leg lean mass. Training in the same volume and intensity as used in our study did not cause significant decreases in fat mass which led to increased body weight. Perhaps a significant decline in these variables may have occurred if the subjects had been engaged in higher endurance training intensity.

Training sequence of the present concurrent training program had also little influence on strength and endurance adaptations as the magnitude of improvements were similar for both E+S and S+E groups. According to these results the first training session may not have

caused fatigue which could have limited the subsequent training session. Health and fitness professionals who need to make recommendations and advise clients can suggest single session strength and endurance training to cause positive changes in body composition as well as in physical fitness and hence maintain long term health. The present results showed that when emphasizing lower body strength training the largest improvements can be observed in lean mass and dynamic strength of the same region. From a health perspective, strength training should evenly cover all big muscle groups in the upper and lower body as well as in the trunk region.

Based on the present findings it can be concluded that when young, apparently healthy men combine strength and endurance into the same training session the personal preferences of the practitioner in terms of exercise sequence can be taken into account. The possibility to freely change the strength and endurance training sequence can improve space and time management as well as provide an additional way to reduce the monotony of training. It is well known that the adaptations to physical training are attenuated when the training program design remains unchanged over a long period of time. Therefore, it is beneficial to know that the order of combination of strength training with endurance training can be varied without compromising the overall outcome.

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## 9. REFERENCES

- Aagaard, P. 2003. Training-induced changes in neural function. *Exercise and sport sciences reviews* 31 (2), 61-67.
- Aagaard, P. & Andersen, J. L. 2010. Effects of strength training on endurance capacity in top-level endurance athletes. *Scandinavian Journal of Medicine & Science in Sports* 20 Suppl 2, 39-47.
- Aagaard, P., Andersen, J. L., Bennekou, M., Larsson, B., Olesen, J. L., Crameri, R., Magnusson, S. P. & Kjaer, M. 2011. Effects of resistance training on endurance capacity and muscle fiber composition in young top-level cyclists. *Scandinavian Journal of Medicine & Science in Sports* 21 (6), e298-307.
- Abe, T., Kojima, K., Kearns, C. F., Yohena, H. & Fukuda, J. 2003. Whole body muscle hypertrophy from resistance training: distribution and total mass. *British journal of sports medicine* 37 (6), 543-545.
- Ahtiainen, J. P., Pakarinen, A., Alen, M., Kraemer, W. J. & Häkkinen, K. 2003. Muscle hypertrophy, hormonal adaptations and strength development during strength training in strength-trained and untrained men. *European journal of applied physiology* 89 (6), 555-563.
- American College of Sports Medicine 2009. American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. *Medicine and science in sports and exercise* 41 (3), 687-708.
- Atha, J. 1981. Strengthening muscle. *Exercise and sport sciences reviews* 9, 1-73.
- Atherton, P. J., Babraj, J., Smith, K., Singh, J., Rennie, M. J. & Wackerhage, H. 2005. Selective activation of AMPK-PGC-1alpha or PKB-TSC2-mTOR signaling can explain specific adaptive responses to endurance or resistance training-like electrical muscle stimulation. *FASEB journal : official publication of the Federation of American Societies for Experimental Biology* 19 (7), 786-788.
- Babcock, L., Escano, M., D'Lugos, A., Todd, K., Murach, K. & Luden, N. 2012. Concurrent aerobic exercise interferes with the satellite cell response to acute resistance exercise. *American journal of physiology. Regulatory, integrative and comparative physiology* 302 (12), R1458-65.
- Baker, D. G. & Newton, R. U. 2006. Adaptations in upper-body maximal strength and power output resulting from long-term resistance training in experienced strength-

- power athletes. *Journal of strength and conditioning research / National Strength & Conditioning Association* 20 (3), 541-546.
- Bell, G. J., Syrotuik, D., Martin, T. P., Burnham, R. & Quinney, H. A. 2000. Effect of concurrent strength and endurance training on skeletal muscle properties and hormone concentrations in humans. *European journal of applied physiology* 81 (5), 418-427.
- Bishop, D., Jenkins, D. G., Mackinnon, L. T., McEniery, M. & Carey, M. F. 1999. The effects of strength training on endurance performance and muscle characteristics. *Medicine and science in sports and exercise* 31 (6), 886-891.
- Bottinelli, R., Pellegrino, M. A., Canepari, M., Rossi, R. & Reggiani, C. 1999. Specific contributions of various muscle fibre types to human muscle performance: an in vitro study. *Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology* 9 (2), 87-95.
- Broeder, C. E., Burrhus, K. A., Svanevik, L. S. & Wilmore, J. H. 1992. The effects of either high-intensity resistance or endurance training on resting metabolic rate. *The American Journal of Clinical Nutrition* 55 (4), 802-810.
- Cadore, E. L., Izquierdo, M., Alberton, C. L., Pinto, R. S., Conceicao, M., Cunha, G., Radaelli, R., Bottaro, M., Trindade, G. T. & KrueL, L. F. 2012a. Strength prior to endurance intra-session exercise sequence optimizes neuromuscular and cardiovascular gains in elderly men. *Experimental gerontology* 47 (2), 164-169.
- Cadore, E. L., Izquierdo, M., Pinto, S. S., Alberton, C. L., Pinto, R. S., Baroni, B. M., Vaz, M. A., Lanferdini, F. J., Radaelli, R., Gonzalez-Izal, M., Bottaro, M. & KrueL, L. F. 2012b. Neuromuscular adaptations to concurrent training in the elderly: effects of intrasession exercise sequence. *Age (Dordrecht, Netherlands)* .
- Cadore, E. L., Pinto, R. S., Alberton, C. L., Pinto, S. S., Lhullier, F. L., Tartaruga, M. P., Correa, C. S., Almeida, A. P., Silva, E. M., Laitano, O. & KrueL, L. F. 2011. Neuromuscular economy, strength, and endurance in healthy elderly men. *Journal of strength and conditioning research / National Strength & Conditioning Association* 25 (4), 997-1003.
- Cadore, E. L., Pinto, R. S., Lhullier, F. L., Correa, C. S., Alberton, C. L., Pinto, S. S., Almeida, A. P., Tartaruga, M. P., Silva, E. M. & KrueL, L. F. 2010. Physiological effects of concurrent training in elderly men. *International Journal of Sports Medicine* 31 (10), 689-697.
- Cadore, E. L., Pinto, R. S., Pinto, S. S., Alberton, C. L., Correa, C. S., Tartaruga, M. P., Silva, E. M., Almeida, A. P., Trindade, G. T. & KrueL, L. F. 2011. Effects of strength, endurance, and concurrent training on aerobic power and dynamic neuromuscular



- economy in elderly men. *Journal of strength and conditioning research / National Strength & Conditioning Association* 25 (3), 758-766.
- Campbell, W. W., Crim, M. C., Young, V. R. & Evans, W. J. 1994. Increased energy requirements and changes in body composition with resistance training in older adults. *The American Journal of Clinical Nutrition* 60 (2), 167-175.
- Chilibeck, P. D., Calder, A. W., Sale, D. G. & Webber, C. E. 1998. A comparison of strength and muscle mass increases during resistance training in young women. *European journal of applied physiology and occupational physiology* 77 (1-2), 170-175.
- Chromiak, J. A. & Mulvaney, D. R. 1990. A Review: The Effects of Combined Strength and Endurance Training on Strength Development. *Journal of Applied Sport Science Research* 4 (2), 55-60.
- Chtara, M., Chamari, K., Chaouachi, M., Chaouachi, A., Koubaa, D., Feki, Y., Millet, G. P. & Amri, M. 2005. Effects of intra-session concurrent endurance and strength training sequence on aerobic performance and capacity. *British journal of sports medicine* 39 (8), 555-560.
- Chtara, M., Chaouachi, A., Levin, G. T., Chaouachi, M., Chamari, K., Amri, M. & Laursen, P. B. 2008. Effect of concurrent endurance and circuit resistance training sequence on muscular strength and power development. *Journal of strength and conditioning research / National Strength & Conditioning Association* 22 (4), 1037-1045.
- Coffey, V. G. & Hawley, J. A. 2007. The molecular bases of training adaptation. *Sports medicine (Auckland, N.Z.)* 37 (9), 737-763.
- Coffey, V. G., Pilegaard, H., Garnham, A. P., O'Brien, B. J. & Hawley, J. A. 2009. Consecutive bouts of diverse contractile activity alter acute responses in human skeletal muscle. *Journal of applied physiology (Bethesda, Md.: 1985)* 106 (4), 1187-1197.
- Coffey, V. G., Zhong, Z., Shield, A., Canny, B. J., Chibalin, A. V., Zierath, J. R. & Hawley, J. A. 2006. Early signaling responses to divergent exercise stimuli in skeletal muscle from well-trained humans. *FASEB journal : official publication of the Federation of American Societies for Experimental Biology* 20 (1), 190-192.
- Coggan, A. R., Spina, R. J., King, D. S., Rogers, M. A., Brown, M., Nemeth, P. M. & Holloszy, J. O. 1992. Skeletal muscle adaptations to endurance training in 60- to 70-year-old men and women. *Journal of applied physiology (Bethesda, Md.: 1985)* 72 (5), 1780-1786.

- Collins, M. A. & Snow, T. K. 1993. Are adaptations to combined endurance and strength training affected by the sequence of training? *Journal of sports sciences* 11 (6), 485-491.
- Costill, D. L., Coyle, E. F., Fink, W. F., Lesmes, G. R. & Witzmann, F. A. 1979. Adaptations in skeletal muscle following strength training. *Journal of applied physiology: respiratory, environmental and exercise physiology* 46 (1), 96-99.
- Craig, B. W., Lucas, J., Pohlman, R. & Stelling, H. 1991. The Effects of Running, Weightlifting and a Combination of Both on Growth Hormone Release. *Journal of strength and conditioning research / National Strength & Conditioning Association* 5 (4), 198-203.
- Davis, W. J., Wood, D. T., Andrews, R. G., Elkind, L. M. & Davis, W. B. 2008. Concurrent training enhances athletes' strength, muscle endurance, and other measures. *Journal of strength and conditioning research / National Strength & Conditioning Association* 22 (5), 1487-1502.
- Delmonico, M. J., Kostek, M. C., Johns, J., Hurley, B. F. & Conway, J. M. 2008. Can dual energy X-ray absorptiometry provide a valid assessment of changes in thigh muscle mass with strength training in older adults? *European journal of clinical nutrition* 62 (12), 1372-1378.
- Docherty, D. & Sporer, B. 2000. A proposed model for examining the interference phenomenon between concurrent aerobic and strength training. *Sports medicine (Auckland, N.Z.)* 30 (6), 385-394.
- Dolezal, B. A. & Potteiger, J. A. 1998. Concurrent resistance and endurance training influence basal metabolic rate in nondieting individuals. *Journal of applied physiology (Bethesda, Md.: 1985)* 85 (2), 695-700.
- Donnelly, J. E., Blair, S. N., Jakicic, J. M., Manore, M. M., Rankin, J. W., Smith, B. K. & American College of Sports Medicine 2009. American College of Sports Medicine Position Stand. Appropriate physical activity intervention strategies for weight loss and prevention of weight regain for adults. *Medicine and science in sports and exercise* 41 (2), 459-471.
- Doucet, E., St-Pierre, S., Almeras, N., Imbeault, P., Mauriege, P., Pascot, A., Despres, J. P. & Tremblay, A. 2002. Reduction of visceral adipose tissue during weight loss. *European journal of clinical nutrition* 56 (4), 297-304.
- Dudley, G. A. & Djamil, R. 1985. Incompatibility of endurance- and strength-training modes of exercise. *Journal of applied physiology (Bethesda, Md.: 1985)* 59 (5), 1446-1451.

- Fleck, S. J., Mattie, C. & Martensen Iii, H. C. 2006. Effect of resistance and aerobic training on regional body composition in previously recreationally trained middle-aged women. *Applied physiology, nutrition, and metabolism = Physiologie appliquee, nutrition et metabolisme* 31 (3), 261-270.
- Fry, A. C. 2004. The role of resistance exercise intensity on muscle fibre adaptations. *Sports medicine (Auckland, N.Z.)* 34 (10), 663-679.
- Garcia-Pallares, J. & Izquierdo, M. 2011. Strategies to optimize concurrent training of strength and aerobic fitness for rowing and canoeing. *Sports medicine (Auckland, N.Z.)* 41 (4), 329-343.
- Garcia-Pallares, J., Sanchez-Medina, L., Perez, C. E., Izquierdo-Gabarren, M. & Izquierdo, M. 2010. Physiological effects of tapering and detraining in world-class kayakers. *Medicine and science in sports and exercise* 42 (6), 1209-1214.
- Gergley, J. C. 2009. Comparison of two lower-body modes of endurance training on lower-body strength development while concurrently training. *Journal of strength and conditioning research / National Strength & Conditioning Association* 23 (3), 979-987.
- Glowacki, S. P., Martin, S. E., Maurer, A., Baek, W., Green, J. S. & Crouse, S. F. 2004. Effects of resistance, endurance, and concurrent exercise on training outcomes in men. *Medicine and science in sports and exercise* 36 (12), 2119-2127.
- Gollnick, P. D., Armstrong, R. B., Saltin, B., Saubert, C. W., 4th, Sembrowich, W. L. & Shepherd, R. E. 1973. Effect of training on enzyme activity and fiber composition of human skeletal muscle. *Journal of applied physiology* 34 (1), 107-111.
- Gravelle, B. L. & Blessing, D. L. 2000. Physiological Adaptation in Women Concurrently Training for Strength and Endurance. *Journal of strength and conditioning research / National Strength & Conditioning Association* 14 (1), 5-13.
- Grediagin, A., Cody, M., Rupp, J., Benardot, D. & Shern, R. 1995. Exercise intensity does not effect body composition change in untrained, moderately overfat women. *Journal of the American Dietetic Association* 95 (6), 661-665.
- Häkkinen, K., Alen, M. & Komi, P. V. 1985. Changes in isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of human skeletal muscle during strength training and detraining. *Acta Physiologica Scandinavica* 125 (4), 573-585.
- Häkkinen, K., Alen, M., Kraemer, W. J., Gorostiaga, E., Izquierdo, M., Rusko, H., Mikkola, J., Hakkinen, A., Valkeinen, H., Kaarakainen, E., Romu, S., Erola, V., Ahtiainen, J. & Paavolainen, L. 2003. Neuromuscular adaptations during concurrent

- strength and endurance training versus strength training. *European journal of applied physiology* 89 (1), 42-52.
- Häkkinen, K., Kallinen, M., Izquierdo, M., Jokelainen, K., Lassila, H., Malkia, E., Kraemer, W. J., Newton, R. U. & Alen, M. 1998. Changes in agonist-antagonist EMG, muscle CSA, and force during strength training in middle-aged and older people. *Journal of applied physiology* (Bethesda, Md.: 1985) 84 (4), 1341-1349.
- Harber, M. P., Konopka, A. R., Douglass, M. D., Minchev, K., Kaminsky, L. A., Trappe, T. A. & Trappe, S. 2009. Aerobic exercise training improves whole muscle and single myofiber size and function in older women. *American journal of physiology. Regulatory, integrative and comparative physiology* 297 (5), R1452-9.
- Hawley, J. A. 2009. Molecular responses to strength and endurance training: are they incompatible? *Applied physiology, nutrition, and metabolism = Physiologie appliquee, nutrition et metabolisme* 34 (3), 355-361.
- Hepple, R. T., Mackinnon, S. L., Goodman, J. M., Thomas, S. G. & Plyley, M. J. 1997. Resistance and aerobic training in older men: effects on VO<sub>2</sub>peak and the capillary supply to skeletal muscle. *Journal of applied physiology* (Bethesda, Md.: 1985) 82 (4), 1305-1310.
- Hickson, R. C. 1980. Interference of strength development by simultaneously training for strength and endurance. *European journal of applied physiology and occupational physiology* 45 (2-3), 255-263.
- Hickson, R. C., Dvorak, B. A., Gorostiaga, E. M., Kurowski, T. T. & Foster, C. 1988. Potential for strength and endurance training to amplify endurance performance. *Journal of applied physiology* (Bethesda, Md.: 1985) 65 (5), 2285-2290.
- Holloszy, J. O. & Coyle, E. F. 1984. Adaptations of skeletal muscle to endurance exercise and their metabolic consequences. *Journal of applied physiology: respiratory, environmental and exercise physiology* 56 (4), 831-838.
- Hostler, D., Schwirian, C. I., Campos, G., Toma, K., Crill, M. T., Hagerman, G. R., Hagerman, F. C. & Staron, R. S. 2001. Skeletal muscle adaptations in elastic resistance-trained young men and women. *European journal of applied physiology* 86 (2), 112-118.
- Houtkooper, L. B., Going, S. B., Sproul, J., Blew, R. M. & Lohman, T. G. 2000. Comparison of methods for assessing body-composition changes over 1 y in postmenopausal women. *The American Journal of Clinical Nutrition* 72 (2), 401-406.

- Hunter, G. R., Chandler-Laney, P. C., Brock, D. W., Lara-Castro, C., Fernandez, J. R. & Gower, B. A. 2010. Fat distribution, aerobic fitness, blood lipids, and insulin sensitivity in African-American and European-American women. *Obesity* (Silver Spring, Md.) 18 (2), 274-281.
- Izquierdo, M., Häkkinen, K., Anton, A., Garrues, M., Ibanez, J., Ruesta, M. & Gorostiaga, E. M. 2001. Maximal strength and power, endurance performance, and serum hormones in middle-aged and elderly men. *Medicine and science in sports and exercise* 33 (9), 1577-1587.
- Izquierdo, M., Häkkinen, K., Ibanez, J., Anton, A., Garrues, M., Ruesta, M. & Gorostiaga, E. M. 2003. Effects of strength training on submaximal and maximal endurance performance capacity in middle-aged and older men. *Journal of strength and conditioning research / National Strength & Conditioning Association* 17 (1), 129-139.
- Izquierdo, M., Häkkinen, K., Ibanez, J., Kraemer, W. J. & Gorostiaga, E. M. 2005. Effects of combined resistance and cardiovascular training on strength, power, muscle cross-sectional area, and endurance markers in middle-aged men. *European journal of applied physiology* 94 (1-2), 70-75.
- Izquierdo, M., Ibanez, J., Häkkinen, K., Kraemer, W. J., Larrion, J. L. & Gorostiaga, E. M. 2004. Once weekly combined resistance and cardiovascular training in healthy older men. *Medicine and science in sports and exercise* 36 (3), 435-443.
- Izquierdo-Gabarron, M., Gonzalez De Txabarri Exposito, R., Garcia-pallares, J., Sanchez-medina, L., De Villarreal, E. S. & Izquierdo, M. 2010. Concurrent endurance and strength training not to failure optimizes performance gains. *Medicine and science in sports and exercise* 42 (6), 1191-1199.
- Kang, J., Rashti, S. L., Tranchina, C. P., Ratamess, N. A., Faigenbaum, A. D. & Hoffman, J. R. 2009. Effect of preceding resistance exercise on metabolism during subsequent aerobic session. *European journal of applied physiology* 107 (1), 43-50.
- Karavirta, L., Häkkinen, A., Sillanpää, E., Garcia-Lopez, D., Kauhanen, A., Haapasaari, A., Alen, M., Pakarinen, A., Kraemer, W. J., Izquierdo, M., Gorostiaga, E. & Häkkinen, K. 2011. Effects of combined endurance and strength training on muscle strength, power and hypertrophy in 40-67-year-old men. *Scandinavian Journal of Medicine & Science in Sports* 21 (3), 402-411.
- Kay, S. J. & Fiatarone Singh, M. A. 2006. The influence of physical activity on abdominal fat: a systematic review of the literature. *Obesity reviews : an official journal of the International Association for the Study of Obesity* 7 (2), 183-200.

- Kim, J., Wang, Z., Heymsfield, S. B., Baumgartner, R. N. & Gallagher, D. 2002. Total-body skeletal muscle mass: estimation by a new dual-energy X-ray absorptiometry method. *The American Journal of Clinical Nutrition* 76 (2), 378-383.
- Koening, J. M. 1995. The effect of bench step aerobics on muscular strength, power, and endurance. *J.Strength Cond Res.* 9 (1), 43-46.
- Koutoubi, S. & Huffman, F. G. 2005. Body composition assessment and coronary heart disease risk factors among college students of three ethnic groups. *Journal of the National Medical Association* 97 (6), 784-791.
- Kraemer, W. J., Patton, J. F., Gordon, S. E., Harman, E. A., Deschenes, M. R., Reynolds, K., Newton, R. U., Triplett, N. T. & Dziados, J. E. 1995. Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. *Journal of applied physiology (Bethesda, Md.: 1985)* 78 (3), 976-989.
- Kuipers, H., Verstappen, F. T., Keizer, H. A., Geurten, P. & van Kranenburg, G. 1985. Variability of aerobic performance in the laboratory and its physiologic correlates. *International Journal of Sports Medicine* 6 (4), 197-201.
- Lepers, R., Millet, G. Y. & Maffiuletti, N. A. 2001. Effect of cycling cadence on contractile and neural properties of knee extensors. *Medicine and science in sports and exercise* 33 (11), 1882-1888.
- Leveritt, M. & Abernethy, P. J. 1999. Acute Effects of High-Intensity Endurance Exercise on Subsequent Resistance Activity. *J.Strength Cond Res.* 13 (1), 47-51.
- Lo, M. S., Lin, L. L., Yao, W. J. & Ma, M. C. 2011. Training and detraining effects of the resistance vs. endurance program on body composition, body size, and physical performance in young men. *Journal of strength and conditioning research / National Strength & Conditioning Association* 25 (8), 2246-2254.
- Lundberg, T. R., Fernandez-Gonzalo, R., Gustafsson, T. & Tesch, P. A. 2013. Aerobic exercise does not compromise muscle hypertrophy response to short-term resistance training. *Journal of applied physiology (Bethesda, Md.: 1985)* 114 (1), 81-89.
- Lundberg, T. R., Fernandez-Gonzalo, R., Gustafsson, T. & Tesch, P. A. 2012. Aerobic exercise alters skeletal muscle molecular responses to resistance exercise. *Medicine and science in sports and exercise* 44 (9), 1680-1688.
- Madeira, F. B., Silva, A. A., Veloso, H. F., Goldani, M. Z., Kac, G., Cardoso, V. C., Bettiol, H. & Barbieri, M. A. 2013. Normal weight obesity is associated with metabolic syndrome and insulin resistance in young adults from a middle-income country. *PLoS one* 8 (3), e60673.

- Marti, B. & Howald, H. 1990. Long-term effects of physical training on aerobic capacity: controlled study of former elite athletes. *Journal of applied physiology* (Bethesda, Md.: 1985) 69 (4), 1451-1459.
- McCarthy, J. P., Pozniak, M. A. & Agre, J. C. 2002. Neuromuscular adaptations to concurrent strength and endurance training. *Medicine and science in sports and exercise* 34 (3), 511-519.
- McDonagh, M. J. & Davies, C. T. 1984. Adaptive response of mammalian skeletal muscle to exercise with high loads. *European journal of applied physiology and occupational physiology* 52 (2), 139-155.
- Menon, M. K., Houchen, L., Harrison, S., Singh, S. J., Morgan, M. D. & Steiner, M. C. 2012. Ultrasound assessment of lower limb muscle mass in response to resistance training in COPD. *Respiratory research* 13, 119-9921-13-119.
- Mikkola, J. S., Rusko, H. K., Nummela, A. T., Paavolainen, L. M. & Häkkinen, K. 2007. Concurrent endurance and explosive type strength training increases activation and fast force production of leg extensor muscles in endurance athletes. *Journal of strength and conditioning research / National Strength & Conditioning Association* 21 (2), 613-620.
- Miller, A. E., MacDougall, J. D., Tarnopolsky, M. A. & Sale, D. G. 1993. Gender differences in strength and muscle fiber characteristics. *European journal of applied physiology and occupational physiology* 66 (3), 254-262.
- Millet, G. P., Jaouen, B., Borrani, F. & Candau, R. 2002. Effects of concurrent endurance and strength training on running economy and  $\dot{V}O_2$  kinetics. *Medicine and science in sports and exercise* 34 (8), 1351-1359.
- Nader, G. A. 2006. Concurrent strength and endurance training: from molecules to man. *Medicine and science in sports and exercise* 38 (11), 1965-1970.
- Nelson, A. G., Arnall, D. A., Loy, S. F., Silvester, L. J. & Conlee, R. K. 1990. Consequences of combining strength and endurance training regimens. *Physical Therapy* 70 (5), 287-294.
- Nindl, B. C., Friedl, K. E., Marchitelli, L. J., Shippee, R. L., Thomas, C. D. & Patton, J. F. 1996. Regional fat placement in physically fit males and changes with weight loss. *Medicine and science in sports and exercise* 28 (7), 786-793.
- Nindl, B. C., Harman, E. A., Marx, J. O., Gotshalk, L. A., Frykman, P. N., Lammi, E., Palmer, C. & Kraemer, W. J. 2000. Regional body composition changes in women after 6 months of periodized physical training. *Journal of applied physiology* (Bethesda, Md.: 1985) 88 (6), 2251-2259.

- Nindl, B. C., Scoville, C. R., Sheehan, K. M., Leone, C. D. & Mello, R. P. 2002. Gender differences in regional body composition and somatotrophic influences of IGF-I and leptin. *Journal of applied physiology* (Bethesda, Md.: 1985) 92 (4), 1611-1618.
- Putman, C. T., Xu, X., Gillies, E., MacLean, I. M. & Bell, G. J. 2004. Effects of strength, endurance and combined training on myosin heavy chain content and fibre-type distribution in humans. *European journal of applied physiology* 92 (4-5), 376-384.
- Rognum, T. O., Rodahl, K. & Opstad, P. K. 1982. Regional differences in the lipolytic response of the subcutaneous fat depots to prolonged exercise and severe energy deficiency. *European journal of applied physiology and occupational physiology* 49 (3), 401-408.
- Rosler, K., Conley, K. E., Howald, H., Gerber, C. & Hoppeler, H. 1986. Specificity of leg power changes to velocities used in bicycle endurance training. *Journal of applied physiology* (Bethesda, Md.: 1985) 61 (1), 30-36.
- Ross, R., Janssen, I., Dawson, J., Kungl, A. M., Kuk, J. L., Wong, S. L., Nguyen-Duy, T. B., Lee, S., Kilpatrick, K. & Hudson, R. 2004. Exercise-induced reduction in obesity and insulin resistance in women: a randomized controlled trial. *Obesity research* 12 (5), 789-798.
- Roth, S. M., Ivey, F. M., Martel, G. F., Lemmer, J. T., Hurlbut, D. E., Siegel, E. L., Metter, E. J., Fleg, J. L., Fozard, J. L., Kostek, M. C., Wernick, D. M. & Hurley, B. F. 2001. Muscle size responses to strength training in young and older men and women. *Journal of the American Geriatrics Society* 49 (11), 1428-1433.
- Sale, D. G., Jacobs, I., MacDougall, J. D. & Garner, S. 1990. Comparison of two regimens of concurrent strength and endurance training. *Medicine and science in sports and exercise* 22 (3), 348-356.
- Santos, D. A., Silva, A. M., Matias, C. N., Fields, D. A., Heymsfield, S. B. & Sardinha, L. B. 2010. Accuracy of DXA in estimating body composition changes in elite athletes using a four compartment model as the reference method. *Nutrition & metabolism* 7, 22-7075-7-22.
- Santtila, M., Kyrolainen, H., Vasankari, T., Tiainen, S., Palvalin, K., Hakkinen, A. & Häkkinen, K. 2006. Physical fitness profiles in young Finnish men during the years 1975-2004. *Medicine and science in sports and exercise* 38 (11), 1990-1994.
- Schoenfeld, B. J. 2010. The mechanisms of muscle hypertrophy and their application to resistance training. *Journal of strength and conditioning research / National Strength & Conditioning Association* 24 (10), 2857-2872.



- Shaw, B. S. & Shaw, I. 2009. Compatibility of concurrent aerobic and resistance training on maximal aerobic capacity in sedentary males. *Cardiovascular journal of Africa* 20 (2), 104-106.
- Sillanpää, E. 2011. Adaptations in Body Composition, Metabolic Health and Physical Fitness during Strength or Endurance Training or Their Combination in Healthy Middle-Aged and Older Adults. University of Jyväskylä.
- Sillanpää, E., Häkkinen, A., Nyman, K., Mattila, M., Cheng, S., Karavirta, L., Laaksonen, D. E., Huuhka, N., Kraemer, W. J. & Häkkinen, K. 2008. Body composition and fitness during strength and/or endurance training in older men. *Medicine and science in sports and exercise* 40 (5), 950-958.
- Sillanpää, E., Laaksonen, D. E., Häkkinen, A., Karavirta, L., Jensen, B., Kraemer, W. J., Nyman, K. & Häkkinen, K. 2009. Body composition, fitness, and metabolic health during strength and endurance training and their combination in middle-aged and older women. *European journal of applied physiology* 106 (2), 285-296.
- Simoneau, J. A., Lortie, G., Boulay, M. R., Marcotte, M., Thibault, M. C. & Bouchard, C. 1985. Human skeletal muscle fiber type alteration with high-intensity intermittent training. *European journal of applied physiology and occupational physiology* 54 (3), 250-253.
- Sipila, S. & Suominen, H. 1995. Effects of strength and endurance training on thigh and leg muscle mass and composition in elderly women. *Journal of applied physiology* (Bethesda, Md.: 1985) 78 (1), 334-340.
- Staron, R. S., Malicky, E. S., Leonardi, M. J., Falkel, J. E., Hagerman, F. C. & Dudley, G. A. 1990. Muscle hypertrophy and fast fiber type conversions in heavy resistance-trained women. *European journal of applied physiology and occupational physiology* 60 (1), 71-79.
- Storen, O., Helgerud, J., Stoa, E. M. & Hoff, J. 2008. Maximal strength training improves running economy in distance runners. *Medicine and science in sports and exercise* 40 (6), 1087-1092.
- Strasser, B. & Schobersberger, W. 2011. Evidence for resistance training as a treatment therapy in obesity. *Journal of obesity* 2011, 10.1155/2011/482564. Epub 2010 Aug 10.
- Tanaka, H. & Swensen, T. 1998. Impact of resistance training on endurance performance. A new form of cross-training? *Sports medicine (Auckland, N.Z.)* 25 (3), 191-200.
- Vilacxa Alves, J., Saavedra, F., Simao, R., Novaes, J., Rhea, M. R., Green, D. & Machado Reis, V. 2012. Does aerobic and strength exercise sequence in the same session affect

the oxygen uptake during and postexercise? *Journal of strength and conditioning research / National Strength & Conditioning Association* 26 (7), 1872-1878.

- Widegren, U., Ryder, J. W. & Zierath, J. R. 2001. Mitogen-activated protein kinase signal transduction in skeletal muscle: effects of exercise and muscle contraction. *Acta Physiologica Scandinavica* 172 (3), 227-238.
- Widrick, J. J., Stelzer, J. E., Shoepe, T. C. & Garner, D. P. 2002. Functional properties of human muscle fibers after short-term resistance exercise training. *American journal of physiology. Regulatory, integrative and comparative physiology* 283 (2), R408-16.
- Williams, J. E., Wells, J. C., Wilson, C. M., Haroun, D., Lucas, A. & Fewtrell, M. S. 2006. Evaluation of Lunar Prodigy dual-energy X-ray absorptiometry for assessing body composition in healthy persons and patients by comparison with the criterion 4-component model. *The American Journal of Clinical Nutrition* 83 (5), 1047-1054.