CHRONIC NEUROMUSCULAR ADAPTATIONS TO SINGLE SESSION VS. SEPARATE DAY COMBINED STRENGTH AND ENDURANCE TRAINING IN PREVIOUSLY UNTRAINED MEN

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ABSTRACT

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Combined strength (S) and endurance (E) training has drawn increasingly more interest due to its use for practical purposes (e.g. time management) and the necessity of both S and E in certain athletic events (e.g. soccer). However, there is very little literature on the differences among combined training protocols, specifically single-session, S before E (S+E), and separate day (SD) combined training and the potential differences in long-term neuromuscular adaptations. Hence, the aim of this study was to examine the possible differences in chronic neuromuscular adaptations to performing S+E compared to SD.

39 previously untrained young adult males completed 24-weeks of progressively periodized combined strength and endurance training. Subjects were from two different periods of training and were assigned to either a single-session, S before E (S+E; n=18), or a separate day (SD; n=21) combined training protocol. All subjects were tested three times (0, 12 and 24 weeks), with the SD group also having a fourth measurement (-12 weeks).

The 24 weeks of combined training resulted in significant increases in maximal strength. Specifically, maximal bilateral concentric 1RM leg press increased 13% ($p<0.001$) and 17% ($p<0.001$), maximal bilateral isometric leg press force increased 11% ($p<0.001$) and 13% ($p<0.01$), maximal unilateral isometric knee extension force increased 6% ($p<0.05$) and 14% ($p<0.01$), and maximal unilateral isometric knee flexion force increased 15% ($p<0.001$) and 14% ($p<0.01$) in the SD and S+E training groups, respectively. Additionally, significant increases in: voluntary activation (VA) of 4.2% ($p<0.001$) and 3.6% ($p\leq0.01$), vastus lateralis (VL) maximal iEMG (during max. bilateral isometric leg press) of 26% ($p<0.001$) and 42% ($p<0.001$), maximal VL rms EMG (during max. unilateral isometric knee extension) of 22% ($p<0.05$) and 26% ($p<0.01$), maximal BF iEMG (during max. unilateral isometric knee flexion) of 36% ($p<0.01$) and 34% ($p<0.05$), and M-wave maximum of 22% ($p<0.05$) and 17% (non-significant; $p=0.051$) occurred in the SD and S+E training groups, respectively. Lastly, maximal oxygen consumption (VO_2max) significantly increased 17% ($p<0.001$) and 6% ($p<0.01$) in the SD and S+E training groups, respectively, while no significant differences were found between SD and S+E in any of the variables.

The findings support the notion that both training protocols induce significant increases in neuromuscular adaptations to a similar (non-significant difference) degree. Hence, both protocols can be performed to equal effect regarding S and E gains, and S+E can be used to exercise in a more time-efficient manner.

Keywords: combined training, single-session, separate day, neuromuscular adaptations

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LIST OF ABBREVIATIONS

1RM – one-repetition maximum

AD – analog-to-digital

BF – biceps femoris

E – endurance

iEMG – integrated surface electromyography

GTO – Gogli tendon organ

Kg – kilograms

M_{max} – maximal peak-to-peak M-wave amplitude

MNP – motor neuron pool

MU – motor unit

mV – millivolt

MVC – maximal voluntary contraction

N – newton

QF – quadriceps femoris

RF – rectus femoris

rms EMG – root-mean-square electromyography

S – strength

S+E – single-session combined strength and endurance training, strength before endurance

SD – separate day combined strength and endurance training

sEMG – surface electromyography

SENIAM – surface electromyography for the non-invasive assessment of muscles

VA – voluntary activation

VL – vastus lateralis

VM – vastus medialis

VO_2max – maximal oxygen consumption

1 INTRODUCTION

There are various intended outcomes or objectives to exercise, but its general purpose is to bring about adaptations in the body. Many different factors affect which specific adaptations occur, one of those factors being the training stimulus or type of exercise performed (i.e. endurance-, resistance-, strength-, hypertrophic- or explosive- training) (Hickson 1980). For example, different training stimuli have been suggested to influence force-time characteristics and maximal strength increases. In regards to improving maximal force, high-intensity concentric/eccentric contraction combinations characterize the training stimuli (Häkkinen & Komi 1983). The training adaptations that occur from performing strength exercises that involve heavy-resistance and low-repetition (e.g. weight lifting) are different than those induced by endurance exercises that incorporate a lighter amount of resistance with higher repetitions (e.g. cycling, running and swimming) (Hickson 1980). Strength training has resulted in strength and power increases, muscle cell hypertrophy (Hickson 1980; Kraemer & Häkkinen 2002), and changes in motor unit and antagonistic muscle co-activation (Kraemer & Häkkinen 2002). Increases in maximal oxygen consumption, muscle mitochondria and myoglobin, and prolonged work capacity are outcomes of endurance exercise (Hickson 1980). In short, strength- and endurance- training cause different neuromuscular adaptations.

Some studies have shown that suppressed strength adaptations may occur when performing combined strength and endurance training with high volumes over prolonged periods rather than strength training alone (Hickson 1980; Kraemer et al. 1995; Bell et al. 2000). However, endurance variables are not usually found to be lessened by concurrently training strength and endurance (Chtara et al. 2005; Izquierdo et al. 2004). Additionally though, Hickson (1980) and Häkkinen at el. (2003) have shown that some neuromuscular adaptations are not inhibited by concurrently training strength and endurance. While the topic of combined training has received increased attention, there has only been a limited amount of research focused on the combined training protocols used and the relationship of the timing that strength and endurance training are performed. Thus, this thesis assessed the chronic neuromuscular adaptations to combined strength and endurance training with a focus on potential differences between groups trained either in a single session or on separate days.

2 STRENGTH TRAINING

Strength is measured by ones ability to perform physically demanding tasks (e.g. moving heavy weights). The types of physiological mechanisms that are stimulated by strength training are defined by the specific type of exercise protocol performed (i.e. heavy resistance, explosive). Performing a specific type of exercise stimulus repeatedly will initiate training specific physiological adaptations. Kraemer et al. (1996) described five acute resistance protocol variables to be; exercise choice; exercise order; prescribed intensity or resistance; amount of sets; and rest intervals. Specific exercise demands or intended adaptations determine the configuration or combination of these five acute protocol variables. Resistance exercises and their combinations involve the nervous system and require specific and varying neuromuscular activation patterns, which in turn, cause other systems (e.g., endocrine) to become more active in ways that support the neuromuscular system's changes (Kraemer et al 1996). The type and number of motor units recruited are dependent on the activity being performed. For example, a strength test that requires maximal force production for a short duration recruits a greater number and different types of motor units (MU) and motor neurons than a submaximal jogging test (figures 1 & 2) (Enoka 2002). Strength training protocols must be progressive in order to increase muscular size and strength, and as strength increases, less muscle is activated to perform a task that previously required more muscle (Kraemer et al. 1996).

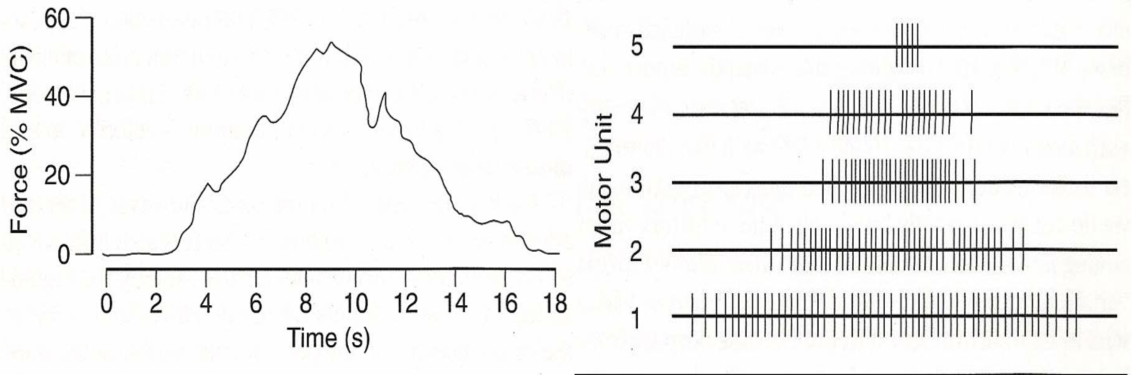

FIGURE 1. Side-by-side view of the change in force production (from 0 to 50% MVC) and the motor unit recruitment and discharge patterns of five motor units (Enoka 2002).

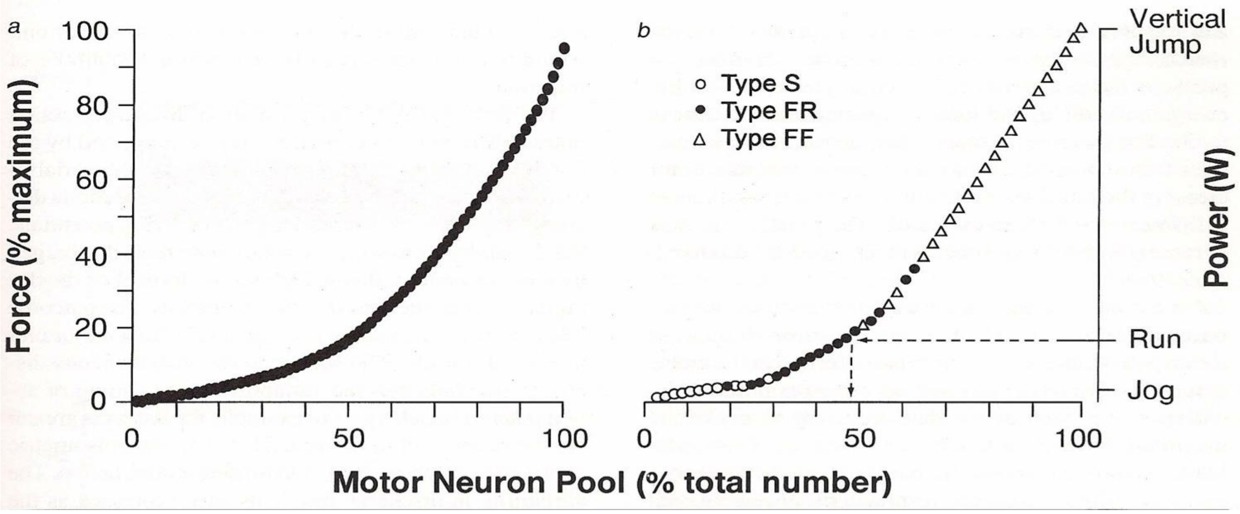

FIGURE 2. Motor unit order recruitment. (a) The increase in force as total number of motor neuron recruitment increased in the cat peroneous longus muscle. (b) Hypothetical model of motor unit recruitment, which starts with the smallest motor neuron and increases until sufficient power is produced for movement (Enoka 2002).

2.1 Types of strength training protocols

There are multiple strength training protocols, which are each thought to induce varying physiological effects. Some of the more common protocols are referred to as strength or maximal strength training, hypertrophic strength training, strength endurance training and explosive strength training. The intensity or load of the exercise, the number of repetitions per set, the number of sets, the rest intervals and the amount of muscle mass involved are all determinants of the hormonal response that is due to heavy resistance strength training (Ahtiainen et al. 2005).

Ahtiainen et al. (2005) explains that the general recommendations for strength training with the primary adaptive goal being hypertrophy are to have multiple (3 to 5) sets per exercise, 8 to 12 repetitions maximum per set and rest intervals of 60 to 120 seconds. Additionally, muscular hypertrophy has been elicited in men and women who performed 16 weeks of progressively periodized strength training at 70 to 90 percent of their 1RM while completing as many repetitions per set of exercise as possible (Cureton et al. 1988).

Campos et al. (2002) describes multiple studies that used high resistance with low repetitions (3 sets, 6 to 8 reps maximum), medium resistance and medium repetitions (2 sets of 15 to 20 repetitions), and low resistance with high repetitions (one set of 30 to 40 repetitions). The high resistance and low repetitions was shown to result in the greatest gains in muscular strength, while the low resistance and high repetitions was shown to induce the least muscular gains (hypertrophy) (Campos et al. 2002). Additionally, the low repetition group improved the most in maximal dynamic strength. Muscular endurance improved the most for the high repetition group. The intermediate intensity and repetition and the low intensity and high repetition training both had similar hypertrophic adaptations (Campos et al. 2002).

Explosive strength can be trained by performing exercises that employ the stretch-shortening cycle (SSC) and/or with lighter loads and maximal effort in an aim to develop explosive force production. Performing exercises such as jump squats with 30 to 60 percent of the squat 1RM, drop jumps, hurdle jumps and hopping exercises with 5 to 10 repetitions per set falls within the category of explosive strength training (Kyröläinen et al. 2005).

2.2 Neuromuscular adaptations to strength training

Strength training causes neuromuscular adaptations. Moritani and deVries (1979) examined how hypertrophy and neural factors contributed to the time course of strength gains in subjects performing an isotonic strength training protocol. They found that initial strength gains were caused primarily by neural factors, with a smaller portion of the gains coming from hypertrophy. However, after three to five weeks, hypertrophy became the dominant contributor to strength gains in their experimental design.

Similar results were found when subjects underwent a heavy-resistance strength training protocol that incorporated combined concentric and eccentric contractions. They significantly improved maximal peak isometric bilateral leg extension force and maximal peak isometric unilateral knee extension force during the first eight weeks of a training program. Average maximal iEMG for the rectus femoris (RF), vastus lateralis (VL) and a three-muscle average [RF, VL and vastus medialis (VM)] also significantly increased during the bilateral leg extension movement during this time. The second eight weeks of training were accompanied by an increase in muscle fiber diameter but a slight decrease in maximal integrated EMG (iEMG). (Häkkinen & Komi 1983).

When examining the relationship between force production and iEMG, linear and curvilinear relationships were found between the two, respectively, when using unipolar lead and bipolar lead systems (Moritani & deVries 1978). Results from Häkkinen and Komi (1983) agree with this and can be seen in figure 3.

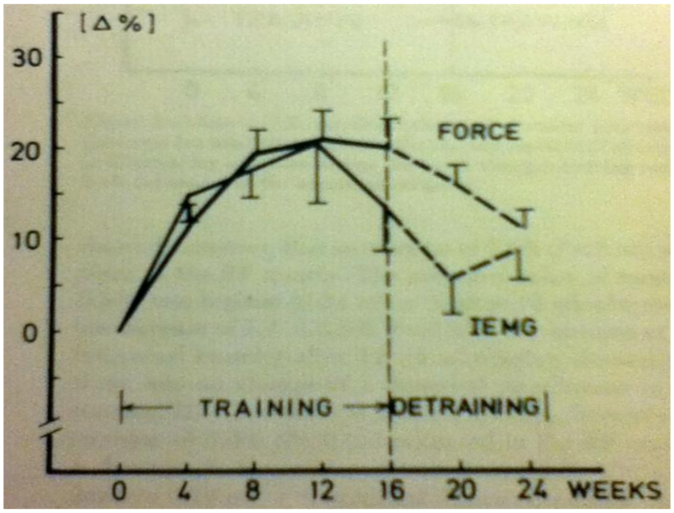

FIGURE 3. Changes in integrated EMG (iEMG) (averaged for the vastus lateralis, vastus medialis and the rectus femoris muscles) and maximal isometric quadriceps force during a bilateral leg extension during 16 weeks of strength training followed by 8 weeks of detraining (Häkkinen & Komi 1983).

One explanation that describes the mechanisms of the neuromuscular adaptations of strength training is a reduction of the inhibition caused by the Golgi tendon organ (GTO) and Renshaw cells. This inhibition would allow an increased inflow of activation in muscle, allowing a higher force production (Häkkinen & Komi 1983). Along with an increased flow of activation, neural adaptations like increased motor unit firing rate and recruitment can occur, typically during the initial weeks of strength training (Sale 1988).

Another adaptation to strength training involves the endocrine system. The acute anabolic hormonal response of testosterone and growth hormone and increases in muscle cell protein synthesis are greatest in response to hypertrophic strength training (Ahtiainen et al. 2005). These hormonal and cellular responses are important to muscle growth, and strength training primarily causes muscle fiber hypertrophy that is associated with an increase in contractile proteins. The increase in contractile proteins contributes to an increase in voluntary strength (Sale et al. 1990a). Hence, the hormonal responses are important for increases in voluntary strength gains.

10 weeks of strength training led to significant increases in; maximal force; average iEMG of the VL and VM muscles; cross-sectional area of the VL, VM, vastus intermedius, RF and the total quadriceps femoris (QF) muscle group (figure 4); trained muscles' voluntary neural activation; and type I and IIa muscle fiber area. Agonist muscle activation increased due to the strength training, which may be due to training-induced learning effects (i.e. a reduction in coactivation of antagonist muscles and/or synergist muscle activation optimization) (Häkkinen et al. 1998a).

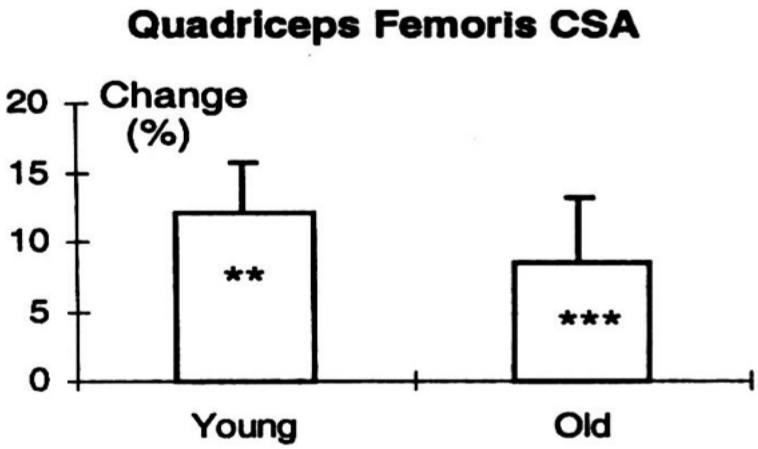

FIGURE 4. Change in quadriceps femoris CSA after 10 weeks of strength training in young (29.2 ± 5.0 years old) and old (60.8 ± 4.0 years old) subjects (**p<0.01 & ***p<0.001; Häkkinen et al. 1998a).

In addition, resting metabolic rate increases due to two factors involving strength training. The first mechanism is the chronic adaptation of increases in lean muscle mass.

Maintaining a higher amount of muscle mass requires a greater amount of energy at rest. On an acute level, strength training causes microtrauma that requires higher levels of energy in order for the muscle to recover. Results have shown that a single session of strength training can increase resting metabolic rate by 5 to 9 percent for up to three days after the training session (Westcott, 2012).

3 ENDURANCE TRAINING

Aerobic training is typically performed to increase maximal oxygen uptake (VO_2max) and other aerobic fitness indices like lactate threshold, ventilatory threshold and economy (Baquet et al. 2003). Measuring VO_2max is important because it provides information about an individual's maximal work power and the functional capacity of the oxygen-transport system. According to McKenzie (2012), the most significant contributor to VO_2max is the transport of oxygen to the working muscle, while the peripheral muscles oxygen-extracting ability is also important. The principal components to VO_2max are maximal stroke volume and cardiac output (McPhee et al. 2009).

Maximal aerobic power is very important when high-intensity work is performed by large muscle groups for longer than one minute, and low maximal oxygen uptake values can hardly be compensated for by factors like technique and motivation (Astrand 1967). The mass of the working muscles and the load on the muscle affects the volume of oxygen consumed during exercise. In essence, there is typically more muscle mass in the legs, so metabolism is higher when performing exercise with the legs than compared to exercising with arms. This means that skiers have reported higher VO_2max values than runners or cyclists. However, it has been reported that the limit for oxygen uptake appears to be independent of working muscle mass as soon as it exceeds are certain mass (Astrand & Saltine 1961).

During continuous exercises, the lactate threshold is the point when the VO_2 or work intensity gradually starts to increase. The ratio between work output and oxygen expenditure is work economy, while running economy is the running cost per meter (Helgerud et al. 2007). Häkkinen et al. (2003) explains that performing endurance training for a prolonged period of time will improve VO_2max and increase muscle aerobic enzyme activities, intramuscular glycogen stores, and the density of capillaries and mitochondria in the muscle, which will all enhance aerobic performance.

Sustaining muscular exercise requires the body to have the ability to transport oxygen from the atmosphere to the mitochondrial electron transport chain, where it is used as the terminal oxidant (Caputo et al. 2003). During very strenuous exercise, respiratory and circulatory systems became unable to supply the working muscles with a sufficient amount of oxygen, which causes oxygen debt due to lactic acid building up in the blood and muscle. Oxygen uptake eventually levels off and is unable to increase after a certain high workload is reached (Karlsson et al. 1967).

3.1 Endurance training adaptations

McKenzie (2003) compiled a large list of adaptations to general endurance training. He included an increase in left ventricle cavity size, left ventricle wall, heart mass, left ventricular compliance and left atrial dimensions as structural cardiovascular adaptations. Functional cardiovascular adaptations included increases in cardiac contractility, stroke volume, cardiac output, diastolic function and venous return, and decreases in total peripheral resistance and pericardial constraint.

Endurance training causes an increase in rate of energy production, rate of force production in muscle and mean power output (McKenzie 2003; Gibala et al. 2006). Structurally, the muscles increase their mitochondrial density, capillary to fiber ratio, type 1 fibers, neural recruitment, and mitochondrial oxidative enzymes (McKenzie 2003).

Functional respiratory changes to endurance training include an increase in respiratory muscle endurance, respiratory muscle strength and ventilatory equivalents for oxygen (Ve/VO_2), while functional haemotological adaptations include an increase in total blood volume and oxygen carrying capacity (McKenzie 2003). In addition, buffering capacity improves, and resting muscle glycogen levels increase while the rate of muscle glycogen depletion decreases (Gibala et al. 2006; Holloszy & Coyle 1984). Glycogen depletion is slowed by the improved ability to oxidize fats, due to endurance training (Holloszy & Coyle, 1984). Structurally, red cell mass and plasma volume increase (McKenzie 2003).

3.2 Training at different intensities, frequencies and volumes

Training intensity, duration and frequency are directly related to improvement in VO_2max, with 55-65% of maximal heart rate being the approximate minimum training intensity to improve lactate threshold or VO_2max (Helgerud et al. 2007). Previously, high-intensity sprint interval training was believed to be less effective for training endurance performance, muscle oxidative capacity and substrate utilization (Kubukeli et al. 2002), however, recently there have been results to support the theory that high-intensity interval training is actually better at improving VO_2max than continuous, low-intensity exercise (Helgerud et al. 2007). Exercising above maximal lactate steady state or at a high intensity causes blood lactate and oxygen uptake to progressively increase biexponentially. Anaerobic systems end up contributing more as exercise intensity becomes more severe (Helgerud et al. 2007).

Helgerud et al. (2007) compared training protocols of different intensities that were matched for energy consumption. Four training protocols were used: a 45-minute, continuous, long slow distance at 70% of the subjects' maximal heart rates: a 24.25 minute, continuous run at lactate threshold, which was deemed to be 85% of the subjects' maximal heart rates: 47 repetitions of 15-s intervals at 90 to 95% maximal heart rate and 15-s of active rest at 70% maximal heart rate: and 4 by 4 minute intervals at 90 to 95% maximal heart rate with active rest periods for 3 minutes at 70% maximal heart rate. (Helgerud et al. 2007).

VO_2max was found to increase significantly when training with the 15/15 intervals or the 4 by 4 intervals rather than the lactate threshold or long slow distance training. Running economy significantly improved with all training groups with no difference found between groups. No groups significantly improved their lactate threshold, however they significantly increased the velocity at which lactate threshold was reached (Helgerud et al. 2007). In addition, Gibala et al. (2006) compared low volume sprint interval training with high volume endurance training and found there to be no significant differences in performance time decreases, oxidative enzyme increases, muscle buffering capacity increases and muscle glycogen content increases. This means that low volume, high intensity sprint training is a time-efficient way to induce similar muscle and performance adaptations to high volume endurance training (Coyle 2005; Gibala et al. 2006).

3.3 Endurance training by cycling

Previously, lower VO_2max levels were reported to occur during cycling tests than compared to running tests. However, Astrand (1967) found no difference in oxygen uptake values between subjects tested and measured during maximal cycling and running. Also, it is easier to measure ECG and blood pressure when a subject is cycling rather than running due to the amount of limb and torso movement. Comparatively, if a subject’s arm is supported while running, in order to take blood pressure more easily, the subject’s oxygen uptake may decrease (Astrand 1967).

One study contained a group of subjects that performed only endurance training via cycling. This endurance-trained group had a significant increase in hypertrophy in the quadriceps femoris muscle group (Mikkola et al. 2012). Endurance running on the other hand, is not typically associated with muscular hypertrophy.

Caputo et al. (2003) reported data that supports that endurance training via cycling might result in different effects on maximal exercise duration than endurance training via running. One possible reason for this difference is the mechanical efficiency of running. Running has a greater eccentric muscle action, which may reduce type II motor unit recruitment and/or delay peripheral fatigue onset when compared to cycling at the same relative intensity. Another possible reason is that during cycling, high intramuscular pressure develops, which may cause the femoral artery to become partially occluded, reducing oxygen supply and causing an increase in type II muscle fiber recruitment (Caputo et al. 2003).

Cycling for longer than 30 minutes has shown to cause significant knee extensor muscle fatigue (Lepers et al. 2000). Reduction in maximal voluntary contractions (MVC) or power can originate due to fatigue that is proximal (central) or distal (peripheral) to the neuromuscular junction. Theurel and Lepers (2008) found that having subjects cycle at variable power outputs caused a greater reduction of the knee extensor muscles' maximal strength capacity than when subjects cycle at a constant power output. Larger changes of central and peripheral fatigue mechanisms resulted in a greater reduction in MVC torque after subjects cycled at variable power outputs, while a decrease in voluntary activation levels was found to be significantly greater after performing variable cycling than after performing constant cycling (Theurel & Lepers 2008).

4 COMBINED STRENGTH AND ENDURANCE TRAINING

Multiple studies have been conducted with the focus of determining the adaptations and effects of concurrent strength and endurance training programs, and not all of them have found similar results. One of the main focuses of these studies is the interference effect. The interference effect is based on the idea that strength training produces adaptations whose nature is divergent to the adaptations that result from endurance training or vice versa. This is suggested to occur because of conflicting neuromuscular adaptations. Sale et al. (1990a) explains that performing endurance training concurrently with strength training has been shown to impair strength development when compared to strength training alone, while strength training has not impaired maximal aerobic power. Cross-sectional area of skeletal muscle has been found to be suppressed (Bell et al. 1991) and individual muscle fibers have hypertrophied to a lesser degree (Kraemer et al. 1995; Bell et al. 2000). Mikkola et al. (2012) explains that the chronic interference hypothesis suggests that optimal adaptations of trained muscles to both strength and endurance training stimulus may not be morphologically or metabolically possible. For example, training mode, intensity and duration influence serum hormone concentrations, which in turn, affect adaptations. Strength training causes an acute increase in serum testosterone in men, while long duration endurance exercise causes a decrease in serum testosterone and/or an increase in serum cortisol (Taipale et al. 2013).

Concurrent training resulting in addition or antagonism of strength gains probably depends on the initial state of training of the subjects; the modes of training; and the way the strength and endurance training are integrated together (Sale et al. 1990a; Taipale et al. 2013). The duration, frequency, and volume of the training protocols, and the type of resistance training (i.e., whether it is power training or maximal strength training) used in the different studies could be determinants of the studies' results (Häkkinen et al. 2003). Mikkola et al. (2012) states that strength inhibition may occur if the concurrent training period is too long and the frequency (4-6 days per week), volume and/or intensity too high because strength and endurance training often induce divergent and distinct physiological adaptations. Development of residual fatigue in the neuromuscular system is a potential resultant of the high training frequency and volume, possibly causing this interference (Mikkola et al. 2012).

However, alone, strength training has also been shown to affect cardiovascular health. It does so by decreasing resting systolic and/or diastolic blood pressure, positively affecting blood lipid profiles, and improving the ability of the arteries to accommodate blood flow. In regards to improving blood lipid profiles, strength training has been shown to increase high-density lipoproteins and decrease low-density lipoproteins and triglycerides (Westcott, 2012). Related to cardiovascular health, aerobic indices like VO_2max, economy and maximal cycling performance have been shown to slightly improve with strength training alone (Mikkola et al. 2012). This allows for the possibility of strength training to be helpful to endurance training.

4.1 Neuromuscular and cardiorespiratory adaptations

In one study, subjects performed strength training twice a week with a periodized progression of sets and repetitions. A combined group additionally performed endurance training twice a week. The strength training only group and the concurrently trained group both significantly increased their maximal strength without any significant difference between the groups in this measure. As can be seen in figure 5, strength was gradually gained over a 21-week training period, showing that performing endurance training concurrently with strength training did not result in adverse or lessened strength adaptations. (Häkkinen et al. 2003).

However, the strength training only group significantly increased its maximal rate of force development and average force produced during the first 500 ms of the contraction. Neither the rate of force development nor the average force during the first 500 ms changed significantly for the concurrent group, and there was a significant difference between the groups as is seen in figure 6. Also, the strength trained group and the concurrent group significantly increased the cross-sectional area of the QF (figure 7) and the mean cross-sectional area of type I, IIa, and IIb fibers with no significant differences between the groups (Häkkinen et al. 2003).

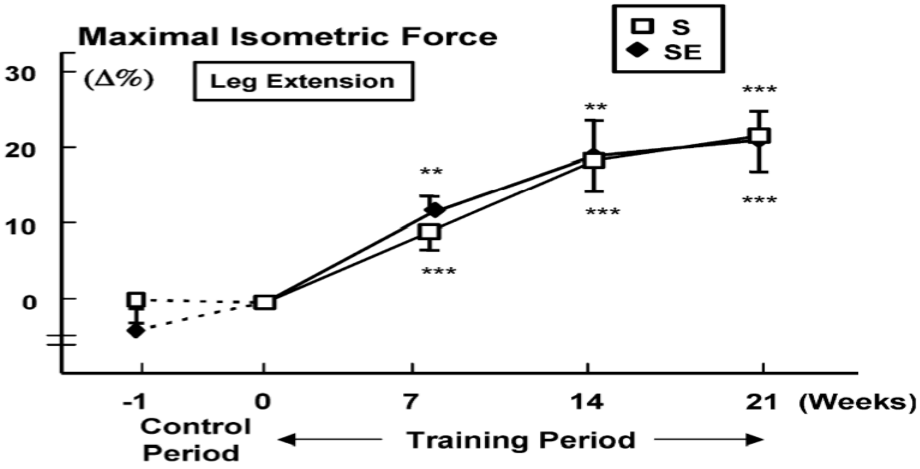

FIGURE 5. Average changes in maximal voluntary bilateral isometric leg extension force in a strength training only group (S) and a concurrently strength and endurance trained group (SE) during the control (1 week) and training (21 week) periods (**p <0.01; ***p<0.001; Häkkinen et al. 2003).

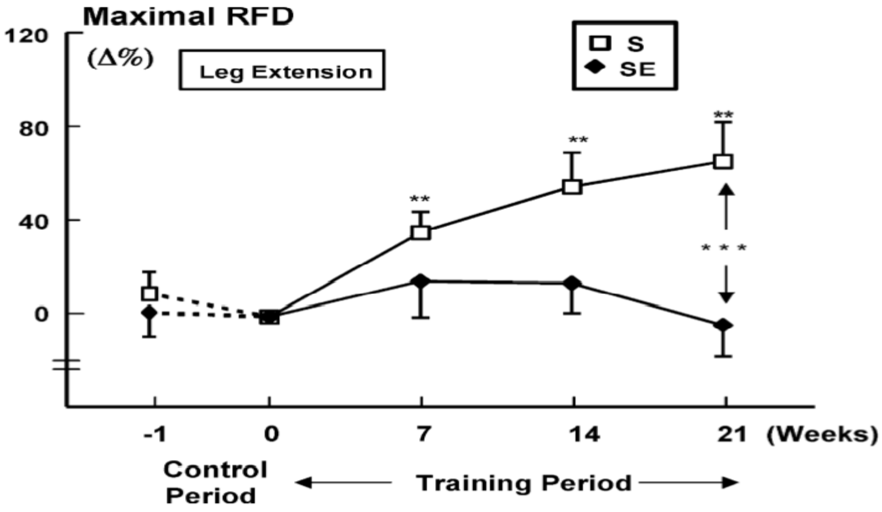

FIGURE 6. Average change in maximal rate of force development during a rapidly performed voluntary bilateral isometric leg extension in strength-only (S) and combined strength and endurance (SE) training groups during the control (1 week) and training (21 weeks) periods (**p<0.01; ***p<0.001; Häkkinen et al. 2003).

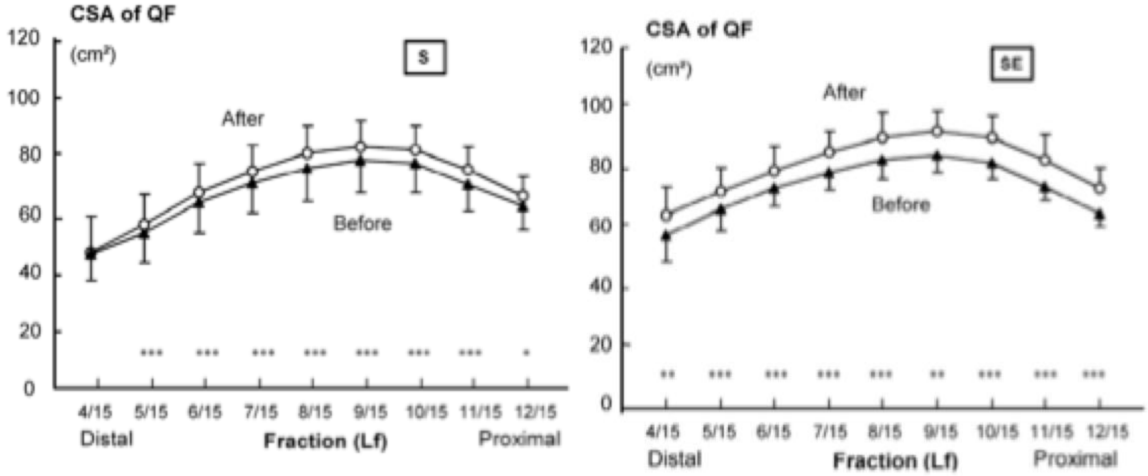

FIGURE 7. Mean quadriceps femoris (QF) muscle group cross-sectional areas (CSA) measured at 4/15 and 12/15 the length of the femur in the strength-only (S; *left*) and combined strength and endurance (SE; *right*) training groups before and after 21 weeks of training (*p<0.05; **p<0.01; ***p<0.001; Häkkinen et al. 2003).

When examining the results of different studies based on the initial training status of the subjects, Sale et al. (1990a) describes various results. In studies with previously untrained subjects, strength development was impeded, while maximal aerobic power or short-term endurance increased when the endurance and strength training involved were moderate to high intensity in volume. However, strength development was enhanced in previously endurance-trained subjects who continued their endurance training but added strength training to their regimen in comparison to a group that performed strength training alone. Endurance performance over 4 to 6 minutes and 60 to 90 minutes improved without an increase in aerobic power or oxidative enzyme activity in previously endurance trained subjects that added strength training and continued their endurance training.

During the initial seven weeks of one study, subjects performing high volume and high frequency strength (S) only and combined strength and endurance (S+E) protocols improved average strength at approximately the same rate. However, as can be seen in figure 8, between the seventh and tenth weeks the average strength in the S+E group plateaued and then decreased, while it continued to increase in the S group (Hickson 1980).

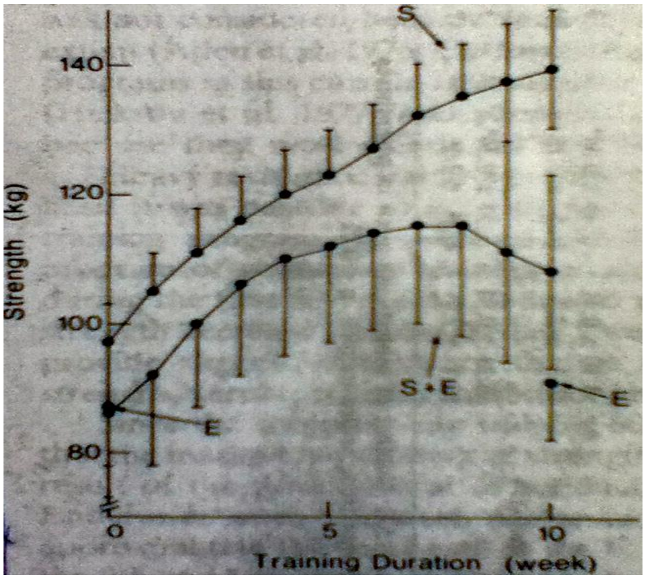

FIGURE 8. Average change in strength over 10 weeks of training in strength only (S), endurance only (E) and concurrently strength and endurance trained (S+E) groups (Hickson 1980).

Results found by Mikkola et al. (2012) were in agreement with Häkkinen et al. (2003) in that both strength trained and concurrently strength and endurance trained subjects were found to significantly increase their maximal strength, which indicates a lack of interference effect. No interference in neural adaptations was a confirmed result when Mikkola et al. (2012) found their strength only and concurrently trained subjects both had significant increases in activation (EMG signal) of the VM without a significant difference between groups. Rate of force development was found to be inhibited in multijoint bilateral and isolated unilateral isometric contractions in the combined trained group from the study by Mikkola et al. (2012) even though it performed high-velocity resistance training.

All ages of untrained and trained men and women can improve neuromuscular characteristics when strength training is performed concurrently with endurance training (Taipale et al. 2013). Maximal dynamic strength, power and maximal muscle activation increased in concurrently trained groups (Taipale et al. 2013).

In the test by Häkkinen et al. (2003), aerobic performance was measured by a VO_2max test performed on a cycle ergometer. They recorded a significant increase in VO_{2max} in the concurrently trained group (figure 9). The combined training group also significantly improved its maximal power at maximal performance along with an increase in the intensity required to reach the aerobic and anaerobic thresholds (Häkkinen et al. 2003). Concurrently strength and endurance trained subjects have also been found to have significantly improved their absolute and relative VO_2max significantly more than subjects who underwent endurance training alone (Mikkola et al. 2012). Hickson (1980) found no significant difference in the rate of increase in VO_2max between endurance only trained and combined strength and endurance trained subjects. Also, Taipale et al. (2013) found combined strength and endurance training to increase subjects' running speed at respiratory compensation threshold and maximal running speed.

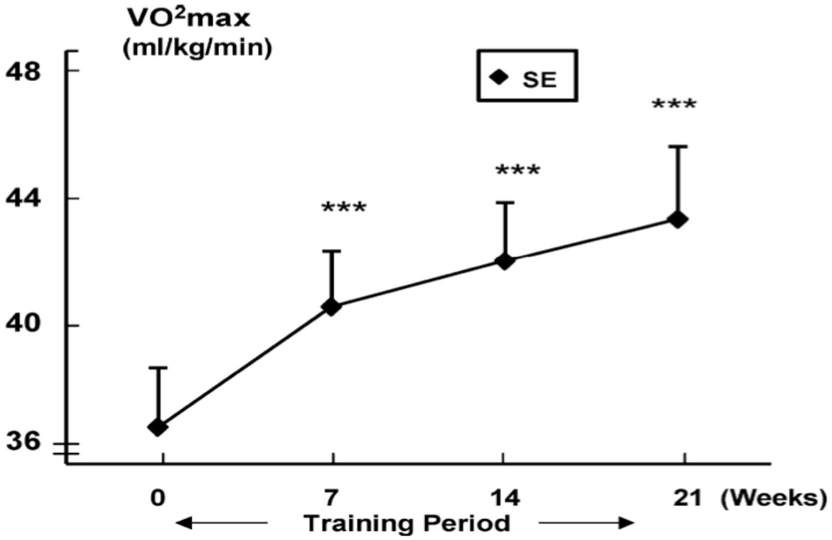

FIGURE 9. Change in maximal oxygen uptake (VO_2max) measured via cycle ergometer testing in a combined strength and endurance (SE) training group during 21 weeks of training (***$p<0.001$; Häkkinen et al. 2003).

4.2 Mechanisms to the adaptations

When performing combined training only 3 days per week, negative effects were absent, meaning the intensity and frequency of exercise may influence whether interference is seen (McCarthy et al. 1995). The theory is that an elevated catabolic hormonal state could lead to a reduced change in the cross-sectional area of skeletal muscle (Kraemer et al. 1995; Bell et al. 2000). This is in agreement with Taipale et al (2013) and other authors who discuss the possibility of testosterone and cortisol interfering with each other. Also, the endurance training may impede strength development by decreasing muscle fiber size, while capillary density and mitochondrial volume may actually decrease due to strength training, which could have a negative effect on endurance performance (Sale et al. 1990a). Interference to strength development may also be an effect of overtraining symptoms induced by chronic muscle glycogen depletion (caused by the overtraining) and an increase in catabolic hormones (Mikkola et al. 2012).

However based on many recent results, it is fair to concur that whether adaptations or interference between strength and endurance variables occurs depends heavily on the combination of the resistance training variables (i.e., mode, frequency, duration, intensity) (Häkkinen et al. 2003; Hickson 1980; Mikkola et al. 2012; Taipale et al. 2013).

5 SINGLE-SESSION VS. SEPARATE DAY COMBINED TRAINING

There is another variable that can affect the degree that which neuromuscular adaptations occur while performing combined strength and endurance training. This variable is the time relation that strength and endurance training occur at in respect to one another. Combined strength and endurance training can be performed on the separate days or on the same day in a single-session or separate sessions. This section focuses on comparing concurrent strength and endurance training performed during the same session to that performed in separate sessions on separate days.

5.1 Single-session and separate-day training adaptations

Sale et al. (1990a) examined the effects that combined strength and endurance training, equal in mode and volume, performed on separate days and during single sessions had on untrained subjects. Both training groups significantly increased maximal strength, muscle fiber area, body mass and VO_2max (Sale et al. 1990a; Cadore et al. 2012). However, the separate day training group increased maximal strength significantly more than the single-session training group, while the single-session training group significantly increased citrate synthase activity, and the separate day training group did not (figure 10) (Sale et al. 1990a). Also, single-session combined training caused significant increases in the QF muscle thickness and force per unit of muscle mass (Cadore et al. 2012).

This difference could be caused by multiple factors, one being the quality of the strength training. Strength training quality may be lessened when performing endurance training during the same session due to fatigue or anticipation from the endurance training. Also, strength training volume was averaged over the whole training period for both groups and the volume of weight lifted multiplied by the number of repetitions done per training session was significantly greater in the separate day training group (Sale et al. 1990a).

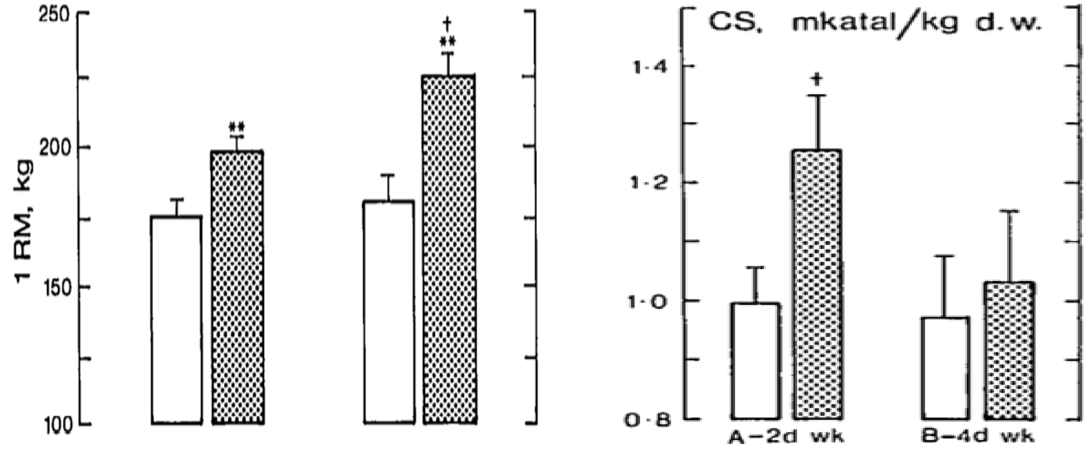

FIGURE 10. Changes in 1RM leg press (*left*) and citrate synthase (*right*) during 20 weeks of single session (*left* columns of each graph) and separate day (*right* columns of each graph) combined strength and endurance training (unfilled columns = pre measurements; filled columns = post measurements; Sale et al. 1990a).

5.2 Aerobic adaptations

Absolute and relative VO_2max, along with work output was significantly improved similarly in both same session and separate day combined training groups when they performed the maximal aerobic power test. Also, both groups were found to have a significant decrease in capillaries per unit muscle area and per fiber. Maximal heart rate during the VO_2max test decreased in both groups, but the oxidative enzyme citrate synthase was found to significantly increase in the same session training group (Sale et al. 1990a). Single-session training also caused significant increases in work at ventilator threshold and maximal work (Cadore et al. 2012).

Chtara et al. (2005) found that combined training caused significant improvements for; 4km time trial; velocity of VO_2max; and for VO_2max. Between groups for the three previous endurance parameters, the group of subjects that trained same session with endurance before strength had significantly higher improvements than the endurance only, than the strength before endurance trained, and the strength only trained groups. Some of these changes are suggested to be caused by increases in strength and power of the lower limbs.

Chtara et al. (2005) explains that interference between endurance and strength training adaptations can be explained by; the muscles inability to optimally adapt to two differing stimuli due to the need to use different energy pathways throughout the same session; residual muscle fatigue; the nature, type, and specific mode of each type of training; the physical fitness and age of the subjects; the degree of incompatibility may be affected by the training frequency, volume and intensity; and the order that the exercises are performed.

6 PURPOSE OF THE STUDY

The purpose of this study was to examine the chronic neuromuscular adaptations in 18 to 40 year-old, previously untrained men following 24 weeks of combined strength and endurance training performed either in a single-session (S+E) (with strength before endurance) or on separate days (SD).

6.1 Research questions

1) Do maximal dynamic and isometric strength gains differ over a 24-week training period between S+E and SD training protocols?

2) Do changes in maximal voluntary activation differ between S+E and SD training groups over a 24-week training period?

3) Will changes in maximal surface electromyographic signals differ between S+E and SD training groups over a 24-week training period?

4) Are there differences in the change in maximal oxygen uptake between S+E and SD groups over 24 weeks of training?

6.2 Research hypotheses

The following are hypotheses to the research questions:

1) Concurrent training with an SD protocol will have greater gains in maximal dynamic strength (Sale et al. 1990a) and isometric strength than training with an S+E protocol.

2) The SD training group will have greater gains in maximal voluntary activation than the S+E group, similarly to Sale et al. (1990a) having found gains in muscle cross sectional

area and fiber area to not be significantly different, suggesting that significantly higher gains by their SD group came from neural adaptations.

3) There will be no significant differences in the gains in maximal surface electromyographic signals in the SD and S+E groups.

4) Maximal oxygen consumption will not significantly differ between SD and S+E groups over the 24-week training period (Sale et al. 1990a).

10 REFERENCES

Ahtiainen, JP, Pakarinen, A, Alen, M, Kraemer, WJ, Häkkinen, K. 2005. Short vs. long rest period between the sets in hypertrophic resistance training: influence on muscle strength, size, and hormonal adaptations in trained men. *Journal of Strength and Conditioning Research* 19(3): 572-582.

Astrand, PO. 1967. Measurement of Maximal Aerobic Capacity. *Canadian Medical Association* 96(12): 732-735.

Astrand, PO, Saltin, B. 1961. Maximal oxygen uptake and heart rate in various types of muscular activity. *Journal of Applied Physiology* 16(6): 977-981.

Baquet, G, van Praagh, E, Berthoin, S. 2003. Endurance training and aerobic fitness in young people. *Sports Medicine* 33(15): 1127-1143.

Bell, GJ, Syrotuik, D, Martin, TP, Burnham, R, Quinney, HA. 2000. Effect of concurrent strength and endurance training on skeletal muscle properties and hormone concentrations in humans. *European Journal of Applied Physiology* 81: 418-427.

Bell, GJ, Petersen, SR, Wessel, J, Bagnall, K, Quinney, HA. 1991. Physiological adaptations to concurrent endurance training and low velocity resistance training. *International Journal of Sports Medicine* 12: 384-390.

Cadore, EL, Izquierdo, M, Alberton, CL, Pinto, RS, Conceicao, M, Cunha, G, Radaelli, R, Bottaro, M, Trindade, T, Kruel, LFM. 2012. Strength prior to endurance intra-session exercise sequence optimizes neuromuscular and cardiovascular gains in elderly men. *Experimental Gerontology* 47: 164-169.

Calder, KM, Hall, LA, Lester, SM, Inglis, JG, Gabriel, DA. 2005. Reliability of the biceps brachii M-wave. *Journal of Neuroengineering and Rehabilitation* 2(1): 33.

Campos, GER, Luecke, TJ, Wendeln, HK, Toma, K, Hagerman, FC, Murray, TF, Ragg, KE, Ratamess, NA, Kraemer, WJ, Staron, RS. 2002. Muscular adaptations in response to three different resistance-training regimens: specificity of repetition maximum training zones. *European Journal of Applied Physiology* 88: 50-60.

Caputo, F, Mello, MT, Denadai, BS. 2003. Oxygen uptake kinetics and time to exhaustion in cycling and running: a comparison between trained and untrained subjects. *Archives of Physiology and Biochemistry* 111(5): 461-466.

Chtara, M, Chamari, K, Chaouaachi, M, Chaouachi, A, Koubaa, D, Feki, Y, Millet, GP, Amri, M. 2005. Effects of intra-session concurrent endurance and strength training sequence on aerobic performance and capacity. *British Journal of Sports Medicine* 39: 555-560.

Coyle, EF. 2005. Very intense exercise-training is extremely potent and time efficient: a reminder. *Journal of Applied Physiology* 98(6): 1983-1984.

Collins, M.A. & Snow, T.K. 1993. Are Adaptations to combined endurance and strength train- ing affected by the sequence of training? *Journal of Sport Sciences*, 11(6): 485-491.

Cureton, KJ, Collins, MA, Hill, DW, Mcelhannon, FM. 1988. Muscle hypertrophy in men and women. *Medicine and Science in Sports and Exercise* 20(4): 338-344.

De Luca, CJ. 1997. The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics* 13(2): 135-163.

Enoka, RM. 2002. Neuromechanics of Human Movement 3rd ed. Human Kinetics

Publishers, 289-291.

Eston RG, Lemmey, AB, McHugh, P, Byrne, C, Walsh, SE. 2000. Effect of stride length on symptoms of exercise-induced muscle damage during a repeated bout of downhill running. *Scandinavian Journal of Medicine and Science in Sports* 10(4): 199-204.

Gandevia, SC. 2001. Spinal and Supraspinal factors in human muscle fatigue. *Physiological Reviews* 81(4): 1725-1789.

Gibala, MJ, Little, JP, van Essen, M, Wilkin, GP, Burgonmaster, KA, Safdar, A, Raha, S, Tarnopolsky, MA. 2006. Short-term sprint interval versus traditional endurance training: similar initial adaptations in human skeletal muscle and exercise performance. *Journal of Physiology* 575(3): 901-911.

Harridge, S, Kryger, A, Stensgaard, A. 1999. Knee extensor strength, activation, and size in very elderly people following strength training. *Muscle and Nerve* 22: 831-839.

Häkkinen, K, Alen, M, Kraemer, WJ, Gorostiaga, E, Izquierdo, M, Rusko, H, Mikkola, J, Häkkinen, 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, Komi, PV. 1983. Electromyographic changes during strength training and detraining. *Medicine and Science in Sports and Exercise* 15(6): 455-460.

Häkkinen, K, Newton, RU, Gordon, SE, McCormick, M, Volek, JS, Nindl, BC, Gotshalk, LA, Campbell, WM, Evans, WJ, Häkkinen, A, Humphries, BJ, Kraemer, WJ. 1998a. Changes in muscle morphology, electromyography activity, and force production characteristics during progressive strength training in young and older men. *The Journal of Gerontology: Biological Sciences* 53(6): B415-423.

Häkkinen, K, Kallinen, M, Izquierdo, M, Jokelainen, K, Lassila, H, Mälkiä, E, Kraemer, WJ, Newton, RU, Alen, M. 1998b. Changes in agonist-antagonist EMG, muscle CSA, and force during strength training in middle-aged and older people. *Journal of Applied Physiology* 84(4): 1341-1349.

Harridge, SDR, Kryger, A, Stensgaard, A. 1999. Knee extensor strength, activation, and size in very elderly people following strength training. *Muscle & Nerve* 22: 831-839.

Helgerud, J, Hoydal, K, Wang, E, Karlsen, T, Berg, P, Bjerkaas, M, Simonsen, T, Helgesen, C, Hjorth, N, Bach, R, Hoff, J. 2007. Aerobic high-intensity intervals improve VO_{2max} more than moderate training. *Medicine & Science in Sports & Exercise* 39(4): 665-671.

Hermens, HJ, Freriks, B, Merletti, R, Stegeman, D, Blok, J, Rau, G, Disselhort-Klug, C. 1999. European recommendations for surface electromyography: result of the SENIAM project. Roessingh Research and Development. Enschede, The Netherlands.

Hickson, RC. 1980. Interference of strength development by simultaneously training for strength and endurance. *European Journal of Applied Physiology* 45: 255-263.

Holloszy, JO, Coyle, EF. 1984. Adaptations of skeletal muscle to endurance exercise and their metabolic consequences. *Journal of Applied Physiology* 56: 831-838.

Izquierdo, M, Ibañez, J, Häkkinen, K, Kraemer, WJ, Larrión, JL, Gorostiaga, EM. 2004. Once weekly combined resistance and cardiovascular training in healthy older men. *Medicine & Science in Sport & Exercise* 36: 435-443.

Karavirta, L, Häkkinen, A, Sillanpää, E, García-López, D, Kauhanen, A, Haapasaari, A, Alen, M, Pakarinen, A, Kraemer, WJ, Izquierdo, M, Gorostiaga, E, Häkkinen, K. 2009. Effects of combined endurance and strength raining on muscle strength, power and hypertrophy in 40-67-year-old men. *Scandinavian Journal of Medcine & Science in Sports* 21: 402-411.

Karlsson, J, Astrand, PO, Ekblom, B. 1967. Training of the oxygen transport system in man. *Journal of Applied Physiology* 22(6): 1061-1065.

Kosek, DJ, Kim, J-S, Petrella, JK, Cross, JM, Bamman, MM. 2006. Efficacy of 3 days/wk resistance training on myofiber hypertrophy and myogenic mechanisms in young vs. older adults. *Journal of Applied Physiology* 101: 531-544.

Kraemer, WJ, Fleck, SJ, Evans, WJ. 1996. Strength and power training: physiological mechanisms of adaptations. *Exercise and Sport Sciences Review*s 24: 363-397.

Kraemer, WJ, Häkkinen, K. 2002. Strength Training for Sport 1st ed. Wiley-Blackwell, 20.

Kraemer, WJ, Patton, JF, Gordon, SE, Harman, EA, Deschenes, MR, Reynolds, K, Newton, RU, Tripplet, NT, Dziados, JE. 1995. Compatability of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. *Journal of Applied Physiology* 78: 976-989.

Kyröläinen, H, Avela, J, McBride, JM, Koskinen, S, Andersen, JL, Sipilä, S, Takala, TES, Komi, PV. 2005. Effects of power training on muscle structure and neuromuscular performance. *Scandinavian Journal of Medicine & Science in Sports* 15: 58-64.

Kubukeli, ZN, Noakes, TD, Dennis, SC. 2002. Training techniques to improve endurance exercise performance. *Sports Medicine* 32(8): 489-509.

Lepers, R, Millet, G, Maffiuletti, N. 2001. Effect of cycling cadence on contractile and neural properties of knee extensors. *Medicine and Science in Sports & Exercise* 33(11): 1882-1888.

Lepers, R, Hausswirth, C, Maffiuletti, N, Brisswalter, J, Van Hoecke, J. 2000. Evidence of Neuromuscular fatigue after prolonged cycling exercise. *Medicine and Science in Sports & Exercise* 32(11): 1880-1886.

McCarthy, JP, Agre, JC, Graf, BK, Pazniak, MA, Vailas, AC. 1995. Compatibility of adaptive responses with combining strength and endurance training. *Medicine and Science in Sports & Exercise* 27: 429-436.

McKenzie, DC. 2012. Respiratory physiology: adaptations to high-level exercise. *British Journal of Sports Medicine* 46: 381-384.

McPhee, JS, Williams, AG, Stewart, C, Baar, K, Schindler, JP, Aldred, S, Maffulli, N, Sargeant, AJ, Jones, DA. 2009. The training stimulus experienced by the leg muscles during cycling in humans. *Experimental Physiology* 94(6): 684-694.

Merton, PA. 1954. Voluntary strength and fatigue. *Journal of Physiology* 123(3): 553-564.

Mikkola, J, Rusko, H, Izquierdo, M, Gorostiaga, EM, Häkkinen, K. 2012. Neuromuscular and cardiovascular adaptations during concurrent strength and endurance training in untrained men. *International Journal of Sports Medicine* 33(9): 702-710.

Moritani, T, deVries, HA. 1978. Reexamination of the relationship between surface integrated electromyogram (IEMG) and force of isometric contraction. *American Journal of Physical Medicine* 57(6): 263-277.

Moritani, T, deVries, HA. 1979. Neural factors versus hypertrophy in the time course of muscle strength gain. *American Journal of Physical Medicine* 58(3): 115-130.

Palmieri, RM, Ingersoll, CD, Hoffman, MA. 2004. The Hoffman Reflex: methodologic considerations and applications for us in sports medicine and athletic training research. *Journal of Athletic Training* 39(3): 268-277.

Sale, DG. 1988. Neural adaptation to resistance training. M*edicine and Science in Sports & Exercise* 20(5): 135-145.

Sale, DG, Jacobs, I, MacDougall, JD, Garner, S. 1990a. Comparison of two regimens of concurrent strength and endurance training. *Medicine & Science in Sports & Exercise* 22(3): 348-356.

Sale, D.G., MacDougall, J.D., Jacobs, I. & Garner, S. 1990b. Interaction between concurrent strength and endurance training. *Journal of Applied Physiology*, 68(1): 260-270.

Taipale, RS, Mikkola, J, Vesterinen, V, Nummela, A, Häkkinen, K. 2013. Neuromuscular adaptations during combined strength and endurance training in endurance runners: maximal versus explosive strength training or a mix of both. *European Journal of Applied Physiology* 113(2): 325-335.

Theurel, J, Lepers, R. 2008. Neuromuscular fatigue is greater following highly variable versus constant intensity endurance cycling. *European Journal of Applied Physiology* 103: 461-468.

Westcott, WL. 2012. Resistance training is medicine: effects of strength training on health. *Current Sports Medicine Reports* 11(4): 209-216.