THE EFFECTS OF A 10-WEEK COMBINED MAXIMAL AND EXPLOSIVE STRENGTH AND HIGH-INTENSITY ENDURANCE TRAINING PERIOD ON NEUROMUSCULAR PERFORMANCE AND 3K TIME-TRIAL IN MALES AND FEMALES

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ABSTRACT

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Combined strength and endurance training has been noted to produce significant improvements in strength and endurance performances in both men and women. However, there seems to be moderate inhibitory effect regarding strength adaptations, especially considering power production. This study was conducted to investigate the effects of a 10-week combined maximal and explosive strength and high-intensity endurance training period on neuromuscular performance and 3K time-trial in males and females.

A total of 19 healthy recreationally trained subjects (Males: M= 10, Females: F= 9) completed a 10-week combined strength and endurance training period. All subjects trained twice a week strength and twice a week endurance. Strength training consisted of maximal resistance training (~85%1RM) and plyometric exercises for the lower extremities. Endurance training sessions were 4x4min and 3x3x100m running, which both were performed once a week. Neuromuscular measurements and 3K time-trial were conducted before (PRE) and after (POST) the 10-week training period. Neuromuscular measurements consisted of a countermovement jump (CMJ), a maximal isometric force in bilateral leg press, a maximal isometric force in unilateral knee extension and flexion, and 1RM in dynamic leg press. Muscle activation (iEMG) from vastus lateralis (VL) was collected from isometric knee extension.

Both males and females improved significantly CMJ from PRE to POST (M: 10.0±8.0%, $p<0.01$; F: 11.3±5.4%, $p<0.001$). Both groups also improved significantly isometric leg press (M: 11.9±11.3%, $p<0.05$; F: 5.8±6.0%, $p<0.05$). Only males improved significantly isometric knee extension force (11.2±6.0%, $p<0.001$), and males improved their iEMG in VL during knee extension as well (29.1±25.6%, $p<0.05$). Males improved significantly isometric knee flexion force (9.0±8.6%, $p<0.01$). Both groups improved significantly dynamic 1RM leg press (M: 8.7±4.7%, $p<0.001$; F: 6.6±3.9%, $p<0.01$). Both groups improved significantly 3K time-trial performance (M: -2.2±3.1%, $p<0.05$; F: -2.0±1.9%, $p<0.05$). There were no significant differences in improvements between males and females in any measurements at any time point.

In conclusion, both males and females improved their strength and power and endurance performances. However, neuromuscular adaptations seemed to be more systematic in males. These findings suggest that combined maximal and explosive strength and high-intensity endurance training seems to be efficient training modality even for a recreationally active people.

Keywords: Combined training, maximal strength, explosive strength, high-intensity endurance, sex differences

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LIST OF ABBREVIATIONS

1RM – One repetition maximum

CET/ CAT – Continuous endurance training/ Continuous aerobic training

CI – Agonist-antagonist Co-activation

CMJ – Countermovement jump

E – Endurance training

E+S – Combined training, endurance performed before strength

HIIT/ HIAT – High intensity interval training/ High intensity aerobic training

HR – Heart rate

MVC – Maximal voluntary contraction

RFD – Rate of Force Development

S – Strength training

S+E – Combined training, strength performed before endurance

SIT – Sprint interval training

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1 INTRODUCTION

It has been stated in numerous studies that strength training can be beneficial to improve endurance performance (Hoff et al. 2002; Chtara et al. 2004; Barrett-O´Keefe et al. 2012). Especially, explosive strength training seems to play a significant role in improving efficiency of endurance performance (Osteras et al. 1999; Hoff et al. 2002). Actually, in few studies it has been stated that strength training has no negative effect on endurance performance, when both training methods have been used during the same training period (Hickson et al. 1988; Laursen et al. 2005). It is still unknown whether maximal or explosive strength training is more important factor when combining these two training modalities. Even in Taipale et al. (2013) there were no statistically significant differences between maximal, explosive and combined maximal and explosive strength training groups.

Some studies have shown that endurance training could have a negative effect on the adaptations that strength training produces (Hunter et al. 1987; Leveritt et al. 1999). Combining these two training methods, however, still seems to be quite efficient, since most of the studies regarding combined training have led to positive results in both strength and endurance performances (McCarthy et al. 1995; Paavolainen et al. 1999; Hoff et al. 2002; Häkkinen et al. 2003; Loveless et al. 2005; Mikkola et al. 2012).

It also seems that concurrent training can be effective for both sexes. In the case of combined maximal and explosive strength and high intensity endurance training, males could have a slight advantage over females, based on higher proportion of fast-twitch fibers (Miller et al. 1993) and higher initial testosterone levels (McArdle et al. 2015, 425 – 426). On the other hand, Taipale et al. (2014) presented that males may induce greater acute neuromuscular fatigue than women after a combined strength and endurance training session, which would suggest that females are more fatigue resistant compared to males.

Studies regarding combined strength and endurance training have been conducted with various strength training modalities. This study aims to determine neuromuscular adaptations and changes in 3K running performance during a 10-week combined high intensity endurance and mixed maximal and explosive strength training period in males and females.

2 CHRONIC ADAPTATIONS TO STRENGTH AND ENDURANCE TRAINING

2.1 Chronic adaptations to strength training

2.1.1 General aspects of strength training

Strength training includes basically all types of training that have added external loads, and that aim for improving or maintaining the function of the neuromuscular system. Improving neuromuscular performance and gaining the adaptations from strength training requires that loading exceeds the level of physical activity in everyday life. The physiological adaptations of strength training are always specific, and individuals are capable to improve physical performance in different ways by varying loads and training methods. Adaptations from strength training can be noticed in the muscles that have been used in training during a training period, and more importantly in those muscle fibers that have been recruited during training sessions. It is quite clear that high intensity training is required to activate type II muscle fibers. Strength, power and speed training have almost nonexistent effects on aerobic capacity and relatively small effects on cardiovascular fitness. Heavy strength and power training require much from anaerobic energy metabolism, and thus the adaptations are partly based on anaerobic glycolysis, buffering capacity and the size of ATP and PCr storages. The adaptations of strength and power training can be noticed as increased maximal power output, increased work rate in time frame, and in prolonged duration of performance when working with high intensities. (Maughan & Gleeson 1997, 194 – 199.)

The objectives for resistance training can be divided in several areas. One can aim to develop strength through resistance training to prepare for weightlifting or powerlifting competitions. Others might aim to maximize their muscular development for aesthetic goals, such as bodybuilding competitions. In addition, resistance training can be used to maximize any other sport performance, that has strength characteristics involved. Resistance training is also a commonly used method in physical therapy for rehabilitation from injury or disease, and can be used for improving and maintaining fitness and health. Also, resistance training periods and loadings can be used to study muscle physiology, structure, function, adaptations and other practical applications. (McArdle et al. 2015, 502.)

Agonist-antagonist activation. In untrained individuals there have been noted to be very high increases in strength during first months of strength training. For these individuals the improvements in force production can be influenced by the learning effect. This means that individuals actually just learn the right techniques to perform specific movements optimally and are able to coordinate and recruit the needed muscles. Daneshmandi et al. (2007) showed that during eight weeks of strength training subjects improved significantly due to enhanced agonist-antagonist activation. This has been stated by other researchers as well **(**Moritani & DrVries 1979; Häkkinen & Komi 1983; Ahtiainen et al. 2003). Moritani and DeVries (1979) stated that it seems neural factors are more dominant factors in strength increases at the beginning and hypertrophy becomes more dominant after first three to five weeks of training (figure 1).

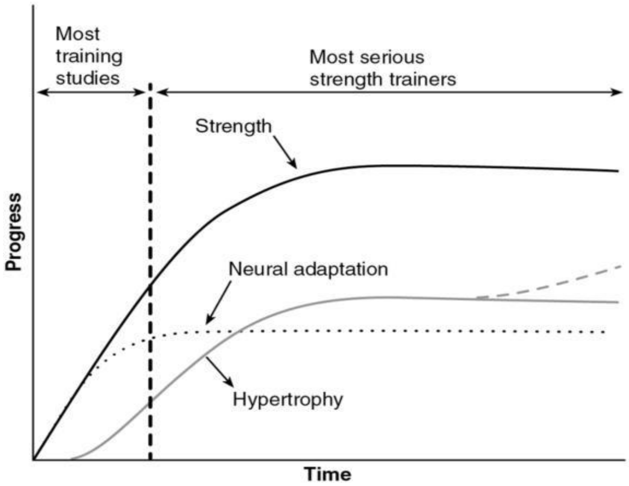


FIGURE 1. Neural and muscular adaptations to strength training over time. (Moritani & deVries 1979).

Hypertrophic training. When training for hypertrophy, muscle actions should include both concentric and eccentric phases, loads should be ~75-80% of one repetition maximum (1RM) and the number of repetitions should be in the range of 6-12, so that each set is performed near muscular failure (Wernbom et al. 2007). For hypertrophic responses, there are different variations in recovery times. In Ahtiainen et al. (2005), there were no difference between two minute and five minute rests between sets, however in Villanueva et al. (2015) it seemed that one minute of rest led to greater improvements in maximal force production and lean body mass than four minute rest intervals. It has been previously stated that at least two minutes of rest may be needed for greater total work load done during exercise, at least with multi-joint movements (Cabral Dias et al. 2014).

Hormonal responses. Depending on how strength training has been performed, there are always hormonal responses, and these hormonal responses seem to be highest for hypertrophic training (Kreaemer & Ratamess 2005; Willardson 2006; Walker et al. 2011). The major acute hormonal effects of hypertrophic strength training are increased testosterone, growth hormone, insulin-like growth factor I (IGF-I) and cortisol concentrations (Ahtiainen et al. 2003; Ahtiainen et al. 2004; Kraemer & Ratamess 2005; Frystyk 2010; Walker et al. 2013). These hormonal responses may affect the adaptations from strength training.

2.1.2 Maximal strength training

Maximal strength training can be defined as strength training with high loads and low repetitions. Different references state different percentages and number of repetitions as limits of maximal strength training, but very standard values are over 80% of one repetition maximum for loads and a maximum of six repetitions per set (McArdle et al. 2015, 513).

The aim of maximal strength training is to improve individuals' neuromuscular performance and most importantly maximal force production (Wang et al. 2010; Heggelund et al. 2013; Tillin & Folland 2014). One of the great assets of maximal strength training is the capability of improving one's force production without significant changes in body mass (Wang et al. 2010; Netreba et al. 2011), since most of the adaptations that maximal strength training produces are neural adaptations and do not require hypertrophy to occur (Netreba et al. 2011).

Both, maximal strength training and hypertrophic training are capable of improving one's force production capabilities (Ahtiainen et al. 2005; Wang et al. 2010; Heggelund et al. 2013; Tillin & Folland 2014; Villanueva et al. 2015). However, it seems that maximal strength training might be more productive than hypertrophic training when it comes to improving maximal force, even when training volume is similar (Heggelund et al. 2013).

Both maximal strength and hypertrophic strength training has been noted produce acute fatigue (figure 2), and this can be seen as decreases in both maximal voluntary contraction and in voluntary activation (figure 3), and it has also been demonstrated that both central and peripheral mechanism take part in the neuromuscular fatigue (Walker et al. 2009).

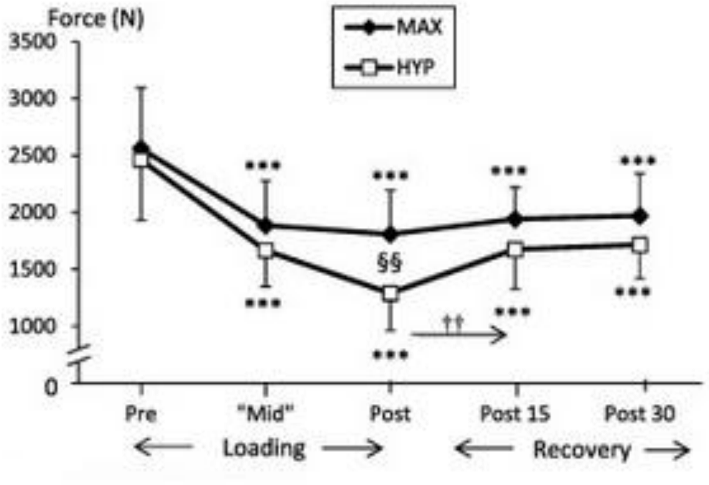


FIGURE 2. Acute responses and recovery in isometric maximal voluntary contraction during maximal strength and hypertrophic strength loading. (Walker et al. 2012).

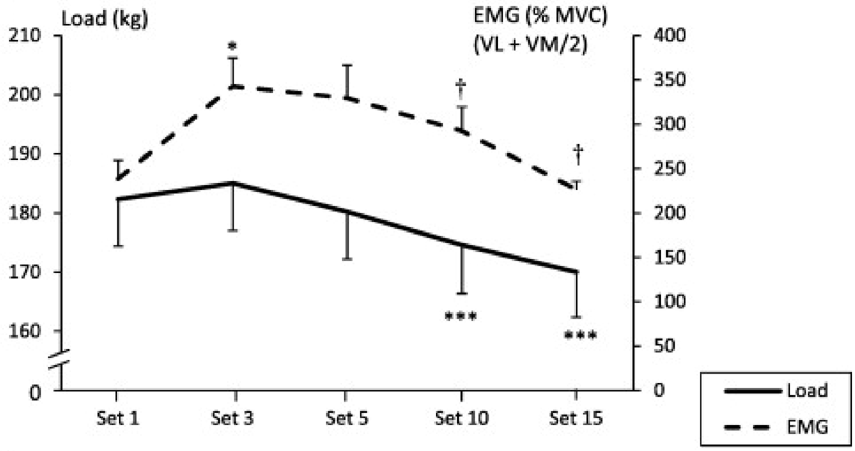


FIGURE 3. Acute responses in maximal voluntary contraction and maximal voluntary activation during 15x1x1RM loading. (Walker et al. 2012).

2.1.3 Power and speed training

The aim of power, speed, and plyometric training is to enhance individuals' rapid force production capabilities. This is very important factor in many sports, since most of the movements performed in sports allow very short time period to produce strength, for example contact time in sprint running is only around 100ms (Mero et al. 1992).

Power and speed training requires that a movement is performed with a relative high rate of force development. To gain positive adaptations from power training, loads can vary from 20% of 1RM to 80% of 1RM (de Vos et al. 2005), but the requirements for movement velocity are the same. Power training can lead to improvements in strength production over time, but also to improvements in maximal force production (Cormie et al. 2011). Also, power training seems to produce hypertrophy in type II muscle fibers (Shepherd 2013).

Plyometric training is a training modality that aims to improve power production. Häkkinen et al. (1985) reported that explosive strength training leads to great improvements in fast force production with minimal changes in maximal force, and the improvements in fast force production are accompanied by and correlated with increases in muscle activation and increases in fast twitch/slow twitch muscle fiber area ratio. Komi et al. (1982) also reported that plyometric training specificly targets fast twitch fibers and presented increased enzyme myokinase activity. The improvements in vertical jump height and increases in enzyme myokinase activity occurred simultaneously, and thus, authors hypothesized that there could be a link between these two (Komi et al. 1982). Recently, plyometric training has been reported to lead to improvements in both jumping tests (Mirtzaei et al. 2013) and in force production (Burgess et al. 2007). Nevertheless, usually plyometric training is combined with other training modalities to experience even greater adaptations, and more sport like overall physical performance.

Complex training. Studies have shown significant increases in both power and strength characteristics, when combining speed and plyometric exercises with strength training (Argus et al. 2012; Faudea et al. 2013; Kanniyan 2013). This training modality is called complex training. Fleck and Kontor (1986) suggest that complex training be done such that heavy resistant exercise is followed by a lighter exercise of a similar biomechanical movement. First movement can be either slow-speed high-load movement (i.e. 5RM back squat) or high-speed moderate-load movement (i.e. power clean) (Fleck & Kontor 1986). When using heavy sets, it has been stated that the load should be at least 85% of one repetition maximum (Carter & Greenwood 2014).

Contrast training. The main idea in contrast training is to perform some heavy load movement, which is immediately followed by biomechanically similar light-load and high-speed movement. So the difference between these two training modalities is the timing of the second set. The most relevant factor to cause enhanced performance due to this training modality is post-activation potentiation (PAP), which merely states that action’s performance is potentiated because of the previous action (Sweeney & Stull 1990). There is a theory from Sweeney and Stull (1990) that phosphorylation of the myosin light chain, in other words enhanced excitation-contraction coupling, might cause PAP. Acute adaptation can be seen as improved power production capability such as vertical jump height (Walker et al. 2010).

2.2 Chronic adaptations to endurance training

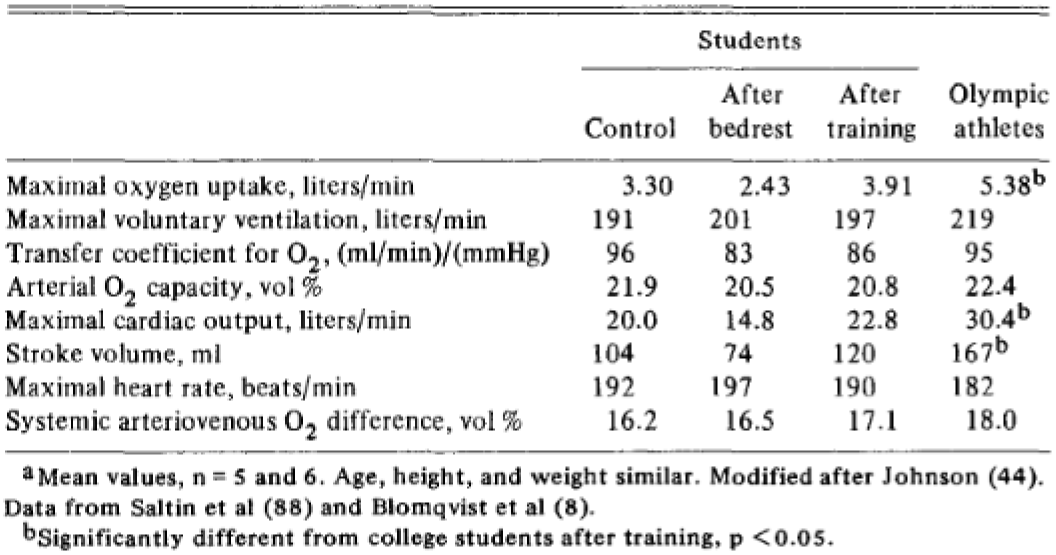
2.2.1 General aspects of endurance training

Endurance training can be described as an ability to maintain or repeat required force or power output (Stone et al. 2006). Prolonged endurance training may lead to improved maximal oxygen uptake (VO_{2max}) and enhanced performance of the cardiovascular system. When the duration of training session surpasses a few minutes, most of the used ATP is received from oxidative phosphorylation, which is produced from carbohydrates, lipids, and proteins in the mitochondria. For this to happen, there needs to be enough oxygen and nutrients available for usage. Thus, endurance training leads to increases in size and amount of mitochondria, and in their enhanced ability to produce ATP. In addition, endurance training increases the capillary density of trained muscles. The muscle fiber proportion also has its influence in endurance performance, since type I muscle fibers are in a more significant role than fast twitch fibers. It has been noted that endurance training may lead to minor hypertrophy of slow twitch fibers, and as well enhance oxidative capacity. Also, type IIb muscle fibers may transform into more oxidative type IIa muscle fibers as a result of endurance training. (Maughan et al. 1997, 177 – 180.)

More oxidative and smaller type I muscle fibers also consume less ATP, which leads to a more economic endurance performance. Conventional aerobic endurance training enhances the capability to prolong low intensity performances, but it may decrease muscular strength and anaerobic power production. To summarize, improved endurance performance capacity, increased maximal oxygen consumption, and enhanced lactate thresholds are the main physiological adaptations to endurance training. (Tanaka & Swensen 1998.)

These improvements in cardiovascular function and VO_{2max} are not limited by age, since similar results have been noted even in elderly subjects. In addition, endurance training has been stated to improve health related factors, such as blood pressure, stroke volume and heart rate, and it is concluded that endurance training will decrease resting and submaximal heart rate in both younger and older adults. (Seals et al. 1984.) Table 1 presents main cardiovascular and pulmonary differences between different level of physically active college students and Olympic level athletes.

TABLE 1. Cardiovascular and pulmonary functional capacities determined during maximal exercise in college students (control, after bedrest and after training) and in Olympic athletes. (Blomqvist & Saltin 1983)



	Students			
	Control	After bedrest	After training	Olympic athletes
Maximal oxygen uptake, liters/min	3.30	2.43	3.91	5.38[b]
Maximal voluntary ventilation, liters/min	191	201	197	219
Transfer coefficient for O_2, (ml/min)/(mmHg)	96	83	86	95
Arterial O_2 capacity, vol %	21.9	20.5	20.8	22.4
Maximal cardiac output, liters/min	20.0	14.8	22.8	30.4[b]
Stroke volume, ml	104	74	120	167[b]
Maximal heart rate, beats/min	192	197	190	182
Systemic arteriovenous O_2 difference, vol %	16.2	16.5	17.1	18.0

[a] Mean values, n = 5 and 6. Age, height, and weight similar. Modified after Johnson (44). Data from Saltin et al (88) and Blomqvist et al (8).

[b] Significantly different from college students after training, $p < 0.05$.

2.2.2 High intensity endurance training

High intensity endurance training is a training method for endurance, where repeated short high intensity bouts are combined for an endurance exercise session. There are many different variations for this training modality regarding intensity and duration of bouts, and rest intervals between. Bouts generally used have varied from 10 seconds to five minutes, and training is completed at an intensity higher than the anaerobic threshold (Laursen & Jenkins 2002). High intensity interval training has led to significant improvements in VO_{2max} in both, sedentary individuals (Perry et al. 2008) and as well in trained athletes (Støren et al. 2012). Actually, Laursen and Jenkins (2002) even state that in some instances adding high intensity training to already well trained athletes’ training programs may be the only way to gain improvements in VO_{2max}.

It seems that the greatest asset of high intensity interval training relies in its capability to improve VO_{2max} (figure 4). Hickson et al. (1977) have even reported as high as 44% increases in VO_{2max} due to high intensity interval training. However, this seems to be a rare case and improvements in the majority of studies have not reached this magnitude, since improvements have been around 5-20% (Gorostiaga et al. 1991; Tabata et al. 1996; Helgerud et al. 2007; Talanian et al. 2007). In some cases, high intensity interval training also seems to produce adaptations relatively fast. Talanian et al. (2007) observed increases in maximal oxygen uptake (13%) even after two weeks of high intensity interval training. However, this study was conducted with female subjects, which raises questions about possible sex differences regarding adaptations to high intensity training.

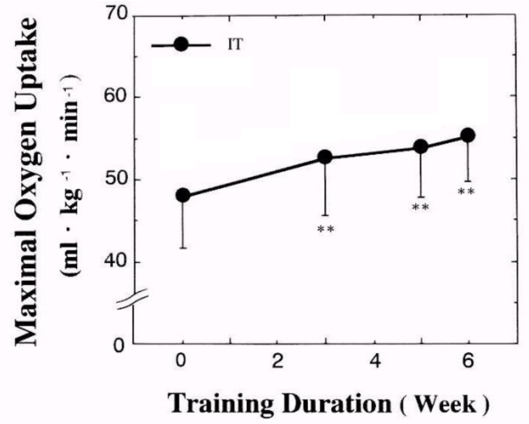


FIGURE 4. The effect of intermittent high intensity endurance training on $VO_{2max.}$ Significant increase from pretraining value at $p<0.05$ and $p<0.01$. (Modified from Tabata et al. 1996).

The duration of bouts during high intensity exercise has been discussed lately, and Helgerud et al. (2007) even presented that as short as 15-second intervals may be long enough to improve maximal oxygen uptake. In this study subjects increased their maximal oxygen uptake by 5.5% (Helgerud et al. 2007). Gist et al. (2014) presented similar findings in their meta-analysis, stating that sprint-interval training can lead to an average of 8% increase in maximal oxygen uptake.

The role of maximum strength as a component in endurance performance arises when movement velocity increases. Thus, high-intensity endurance training requires more from the neuromuscular system and force production capabilities. (Stone et al. 2006.) It has been suggested that high intensity interval training might actually produce some neural adaptations as well (Creer et al. 2004), but the lack of studies and the magnitude adaptations seem quite minimal.

2.2.3 Low intensity endurance training

Low-intensity endurance training can be described a continuous submaximal endurance training. Prolonged low intensity endurance training may increase heart size and stroke volume, increase thickness of septum and posterior walls, and thus lead to improved VO_{2max} (Maggioni et al. 2012). McArdle et al. (2015, 489) state that to gain positive adaptations from continuous or long, slow, distance training, training intensity should be at 60 to 80% of VO_{2max}, which can be estimated by heart rate.

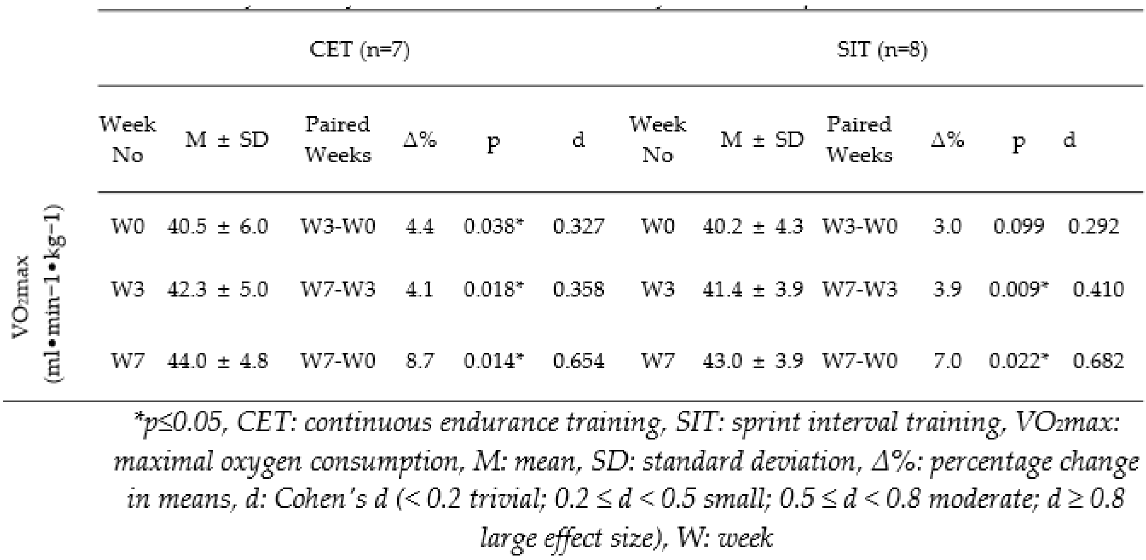
Recently, Nalcakan (2014) presented that continuous endurance training performed by cycling can produce significant improvements in maximal oxygen uptake, anaerobic power and capacity, and VO_2 utilization during submaximal workout. In addition, Nalcakan (2014) present decreases in body fat and waist circumference. Positive adaptations in VO_{2max} have been also presented by Hottenrott et al. (2012), and the authors also presented reduced visceral fat and increases in running velocity at the lactate threshold. Also, one advantage of low intensity endurance training is the fact that it can be, and usually is, done for quite a long period at a time, which leads to high energy expenditure (Tomoaki et al. 2014), and thus can be used as a part of healthy lifestyle and weight management.

The duration of low-intensity endurance training may vary depending on individuals' fitness level, training background and aims. In addition, a great variation of different endurance programs, have been reported from steady-state running to progressively increasing exercise intensity and mixed-paced exercise (Zuhl & Kravitz 2012).

2.2.4 Comparison between high intensity and low intensity endurance training

As discussed before, high intensity interval training may be a more effective way to improve individual’s maximal oxygen uptake than continuous endurance training, and thus, it has been stated by Tomoaki et al. (2014) that high intensity training can be very effective and time saving at the same time. In their study, 42 untrained male subjects were divided into three groups: the sprint interval training group (SIT), high-intensity interval aerobic training group (HIAT) and continuous aerobic training group (CAT). All groups increased their VO_{2max} during the eight-week training period. However, the high-intensity interval training group improved their VO_{2max} value the most (HIAT: 22.5±12.2%, SIT: 16.7±11.6%, CAT: 10.0±8.9%). (Tomoaki et al. 2014.) In addition, Nalcakan (2014) studied the differences between continuous endurance training (CET) and sprint-interval training (SIT). However, the author did not find any significant differences between CET and SIT in the indices of the aerobic power test, as both groups improved their maximal oxygen uptake significantly (table 2) (Nalcakan 2014).

TABLE 2. Influence of continuous endurance training (CET) and sprint-interval training (SIT) on indices of the aerobic power test (Nalcakan 2014).



	CET (n=7)						SIT (n=8)					
	Week No	M ± SD	Paired Weeks	Δ%	p	d	Week No	M ± SD	Paired Weeks	Δ%	p	d
VO_2max (ml•min−1•kg−1)	W0	40.5 ± 6.0	W3-W0	4.4	0.038*	0.327	W0	40.2 ± 4.3	W3-W0	3.0	0.099	0.292
	W3	42.3 ± 5.0	W7-W3	4.1	0.018*	0.358	W3	41.4 ± 3.9	W7-W3	3.9	0.009*	0.410
	W7	44.0 ± 4.8	W7-W0	8.7	0.014*	0.654	W7	43.0 ± 3.9	W7-W0	7.0	0.022*	0.682

**$p \leq 0.05$, CET: continuous endurance training, SIT: sprint interval training, VO_2max: maximal oxygen consumption, M: mean, SD: standard deviation, Δ%: percentage change in means, d: Cohen’s d (< 0.2 trivial; $0.2 \leq d < 0.5$ small; $0.5 \leq d < 0.8$ moderate; $d \geq 0.8$ large effect size), W: week*

It has been noted that high intensity interval training increases the excess post-exercise oxygen consumption (EPOC) for far longer than conventional low intensity endurance training (Townsend et al. 2013). Townsend et al. (2013) noticed that when subjects performed three times 30 second maximal cycling intervals with four minute rests, the energy needed for recovery was higher than it was to recover from moderate intensity 30 minute aerobic performance. Similar findings have been presented by Falcone et al. (2015).

Nevertheless, it seems that both training regimens could have their advantages. Tanisho and Hirakawa (2009) reported that high intensity interval training led to improved mean power output and fatigability in an intermittent test (10-second bouts with 40-second intervals). Consequently, the group that performed 20-25 minute continuous aerobic training reduced their lactate production and increased mean power output Tanisho & Hirakawa 2009). This indicates that both training modalities may enhance endurance capacity, but there might be different adaptations.

Stone et al. (2006) state that the association between maximum strength and endurance performance is moderately strongly related to each other, and this relationship is likely to be stronger for high-intensity endurance activities than for low intensity endurance activities. This statement receives support from the fact that lactate dehydrogenase has been reported to increase after high-intensity interval training in type IIa muscle fibers (Kohn et al. 2011), which demonstrates the different muscular requirements of high- and low-intensity endurance training (figure 5).

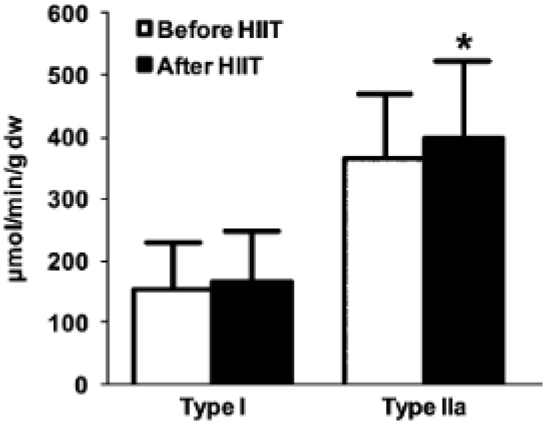


FIGURE 5. Lactate dehydrogenase activity in pools of type I and type IIa fibres before and after high-intensity interval training (HIIT). Values are means ± SD. *Significantly different from before, p<0.05. (Modified from Kohn et al. 2011).

3 CHRONIC ADAPTATIONS TO COMBINED STRENGTH AND ENDURANCE TRAINING

3.1 General aspects of combined strength and endurance training

Strength and endurance training produce very different or even opposite adaptations. For example, aerobic endurance training reduces activity of glycolytic enzymes, but increases the quantity of intracellular energy storages, the activity of oxidative enzymes, and increases the number of capillaries in muscles and the density of mitochondria. Strength training on the other hand, has almost opposite adaptations to these factors, although both training types increase the quantity of intracellular energy storages. Also common between these two training modes is the fact that they both transfer type IIb muscle fibers to more oxidative type IIa muscle fibers. Still endurance training mostly maintains or even decreases the size of muscle fibers and strength training increases them. To conclude, endurance training increases aerobic processes, and strength training increases muscle strength, anaerobic processes and power production. (Tanaka & Swensen 1998.)

Combining these two training methods, strength and endurance training, seems to be quite efficient, since most of the studies regarding combined training has leaded to positive results in both strength and endurance performances (Hickson 1980; McCarthy et al. 1995; Paavolainen et al. 1999; Hoff et al. 2002; Häkkinen et al. 2003; Loveless et al. 2005; Mikkola et al. 2012). McCarthy et al. (1995) noticed in their study that combined strength and endurance training group gained strength as much as the group that did only strength training, and also, improved their maximal oxygen uptake as much as the group that did only endurance training during a 10-week training period.

Even though there have been quite efficient results in studies made about concurrent training, it seems that it produces some level of interference effect, and may lead to compromised adaptations (Hawley 2009). Based on the literature it is safe to say that concurrent training may produce different adaptations than either of the training modalities would alone (Hickson 1980; Leveritt et al. 1999; Bell et al. 2000). Strength and endurance training can be performed on different days, so that the whole training period forms the concept of combined training, or the strength and endurance training can be performed during the same training session.

3.1.1 Different day strength and endurance training

Different day concurrent training has been shown mainly positive results regarding both, neuromuscular performance and endurance performance (Paavolainen et al. 1999; Hoff et al. 2002; Häkkinen et al. 2003; Mikkola et al. 2011; Taipale et al. 2014). Actually, results between different day training and same session training studies seem to have presented fairly similar results.

Eklund et al. (2015) recently reported that both different day combined strength and endurance training, and same session strength and endurance training lead to improved bilateral dynamic leg extension 1RM (figure 6). The authors did not find any significant between-group differences for the experimental groups at any time point, which indicates that both separate day concurrent training and same session concurrent training are efficient methods for enhancing maximal force production. There were not any significant differences between training orders for same session training, but this “order effect” will be discussed more closely later on.

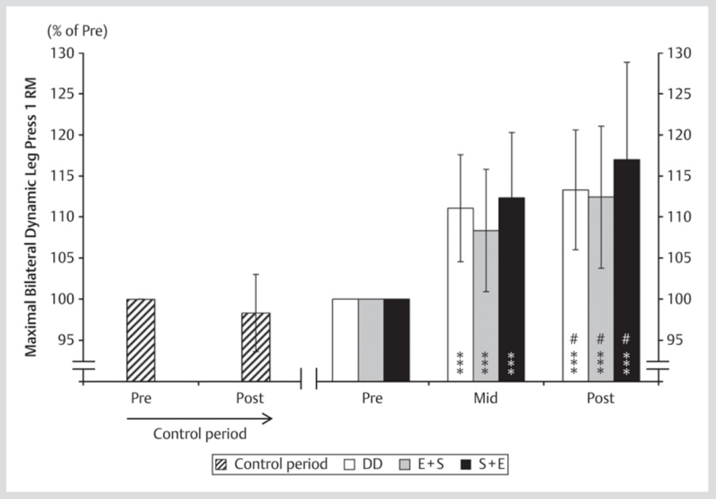


FIGURE 6. Relative Changes in maximal bilateral dynamic leg press 1RM for different day training group (DD), simultaneous E+S training group and simultaneous S+E training group during 24-week combined strength and endurance training period. (Eklund et al. 2015).

Combined strength and endurance training has been fairly well studied nowadays, however, there doesn’t seem to be studies conducted with the same precise exercise protocol only differing by the fact that the concurrent training would be performed either on same session or separate sessions. When training on different days, the individual recovery status could affect the outcome of next training session, since the neuromuscular system may not recover even in two days (Ahtiainen et al. 2004). However, it depends how the endurance training is performed, since low-intensity endurance training may not be that harmful for recovery process as high intensity endurance exercises.

3.1.2 Same session strength and endurance training

Most of the studies seem to point in the direction that it may not matter in which order the same session concurrent training is performed, at least when subjects have been sedentary individuals. Even a couple of decades ago, Collins and Snow (1993) obtained very similar results from both training orders, endurance first (E+S) and strength first (S+E), since both groups improved significantly in both endurance and strength parameters. Similarly, Chtara et al. (2008) presented no significant differences between training orders in any exercise tests performed in their study (figure 7).

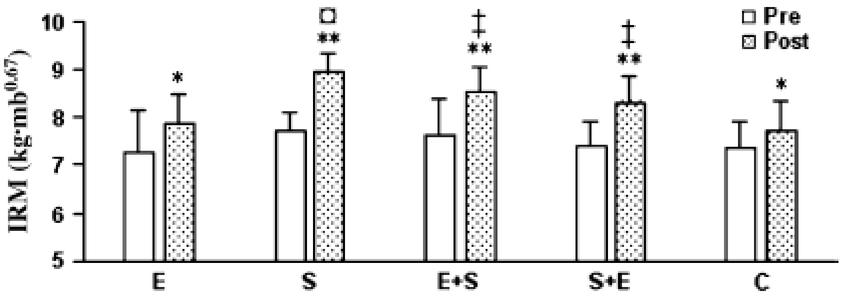


FIGURE 7. Improvements in 1RM strength values during 12 weeks of endurance (E), strength (S), or combined strength and endurance training (E+S and S+E) and in control (C) group. * and ** refer to significant within-group difference; ¤ refers to significant difference in comparison to E, E+S, S+E and C; ‡ refers to significant difference in comparison to E and C. (Chtara et al. 2008).

The order effect has also been studied in more sport specific studies. McGawley and Andersson (2013) studied the order effect of combined strength and endurance training with soccer players and soccer related measurements. The combined strength and endurance training period lead to positive results in all measurements, but there did not seem to be any difference between groups, and thus, no order effect was noticed (McGawley & Andersson 2013). However, based on Chtara et al. (2004), aerobic performance might improve more when endurance training is performed first. In their study there was noted to be difference between the combined training groups, when E+S group improved significantly more than S+E group in 4k time-trial running test, in VO_{2max} and in $_{v}VO_{2max}$.

In addition to Chtara et al. (2004), there have been other studies stating that endurance training might be more suitable to perform first. Cadore et al. (2012) concentrated on secretion of hormones during combined strength and endurance training. In their study, the secretion of hormones were independent from training order, except they found differences in the secretion of testosterone. In both groups the testosterone levels increased significantly ($p < 0.05$) from base level after the first training session, but they stayed significantly higher after the second training session when strength training was performed latter (Cadore et al. 2012). However, in Schumann et al. (2013) testosterone concentrations were significantly reduced during recovery at 24 hours (-13%) and 48 hours (11%) after E+S loading but not after S+E loading. This mainly states that the acute effects of combined strength and endurance training may have some individual variation.

There are studies stating that S+E order might produce greater adaptations in strength, and Pinto et al. (2014) presented that the S+E group improved more in legs maximal force production (1RM: S+E: 43.58±14.00%, E+S: 27.01±18.05%) and in muscle thickness (S+E: 10.24±3.11%, E+S: 5.76±1.88%). The rest of the results in this study did not significantly differ from one another when comparing the effect of training order. In this case, noteworthy is that all subjects were female and the concurrent training was performed as water-based training. (Pinto et al. 2014.)

When doing combined strength and endurance training one should note how both of these training sessions are carried out. In endurance training, one of the most important factors for performance are carbohydrates, as they work as the main energy supply (Drenowatz et al. 2012). High-intensity interval training also depletes other energy storages of human body, especially when the duration of intervals is short and intensity is high, for example, Hirvonen et al. (1992) noticed in their study that PCr storages depleted 89% during 400m maximal running performance. Thus, short maximal intervals mainly use our PCr storages, which are also in an important role during strength training. Considering this, it is possible that prior high-intensity interval training session may limit the benefits and adaptations of latter strength training session, because of the drained energy storages and fatigued energy metabolism mechanisms.

3.2 Influence of strength training on endurance performance

Improvements in strength may have positive effects on motor control attributes, which may lead to enhanced economy of movement. Basically this means that individual might be able to do same performances as before, but with less mechanical work done, or travel distances with smaller energy consumption than before. (Stone et al. 2006.) After all, endurance capacity and performance do not solely rely on aerobic factors, and concurrent training may affect performance in various different ways, as seen in figure 8.

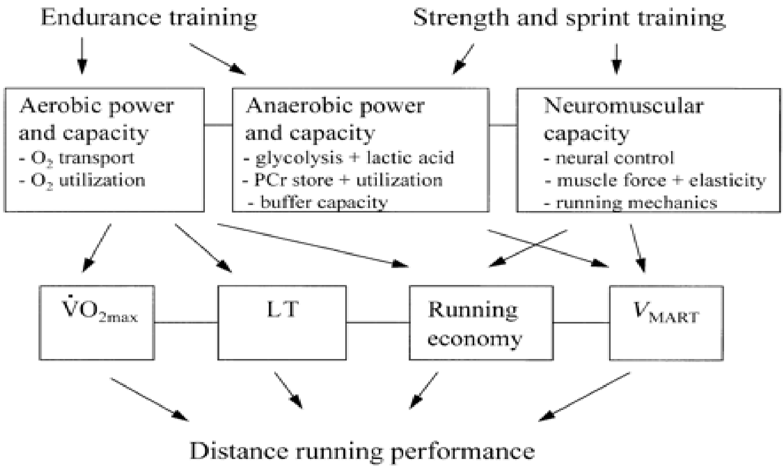


FIGURE 8. A hypothetical model of determinants of distance running performance in well-trained endurance athletes when influenced by endurance and strength training. (Paavolainen et al. 1999).

Adding strength training to endurance training can improve short- and long-lasting endurance performances in trained and untrained individuals, and it also seems to improve untrained individuals’ lactate thresholds in cycling. These might be due to improvement of muscular strength. (Tanaka & Swensen 1998.) Results received from studies regarding combined strength and endurance training has been similar between trained and untrained individuals, and Millet et al. (2002) even presented equal results with endurance athletes in their study.

Hoff et al. (2002) noticed in their study that strength training improves endurance performance and the results suggest that this improvement is gained due to enhanced economy, since there were no significant changes in individuals' VO_{2max}. Based on this, if muscular strength properties can be improved without any significant gains in muscle tissue mass, there should be an improvement in endurance performance. Also, one explaining factor for this enhanced economy might be the changes in muscle fiber conversion. Both strength and endurance training converse type IIb muscle fibers into IIa, which are more oxidative that type IIb muscle fibers, which could lead in an increase in oxidative capacity of the muscle (Laursen et al. 2005).

The study by Barrett-O´Keefe et al. (2012) also supports previous studies about the effects of strength training on endurance performance, as they noticed in their study that maximal strength training reduced oxygen consumption in trained muscles. So it seems that the improvements in endurance performance provided by strength training are not correlated with cardiovascular fitness, rather than with neuromuscular changes (Barrett-O´Keefe et al. 2012). Aagaard et al. (2010) stated similar conclusions in their study, when subjects improved their maximal strength and rate of force development values due to combined strength and endurance training without any hypertrophic response. In addition, Loveless et al. (2005) presented that economy of endurance performance can be improved by performing pure maximal strength training. Also, Hickson et al. (1988) state in their study, that strength training has no negative effect on endurance performance, when both training methods have been used during the same training period.

3.3 Influence of endurance training on the neuromuscular system

Still it seems that combined strength and endurance training could have some negative effects on physical performance, since it seems to inhibit adaptations to strength training when compared to strength training alone (Leveritt et al. 1999), and actually it seems that compromises in strength adaptations might be the biggest negative effect of concurrent training. This has been stated already in 1980 by Hickson (figure 9), whose results showed that combined training was an effective way to improve maximal oxygen uptake, but after seven weeks of training combined group experienced great interference effect on strength adaptations.

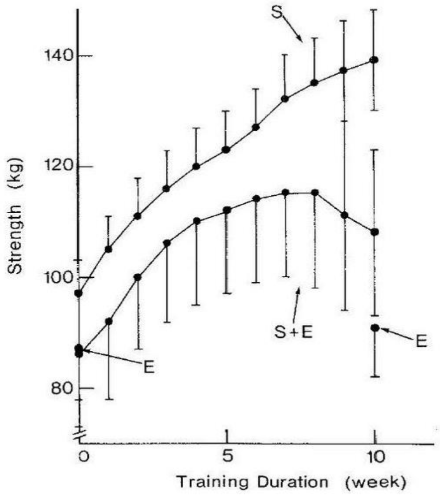


FIGURE 9. Strength development during 10 weeks of training between S+E, S and E groups. (Hickson 1980).

Hunter et al. (1987) ended up with similar results, when combined group improved their maximal oxygen uptake, but there were no significant changes in subjects' strength values by the end of training period. These findings suggest that combined strength and endurance training can lead to improvements in endurance performance, but improvements in strength production might be limited. Nader (2006) stated that different forms of exercise affect antagonistic intracellural signaling mechanisms that may have negative impacts on the muscle's adaptations to specific training modality. Activation of AMPK by an endurance loading may inhibit signaling to the protein-synthesis machinery, and may thus inhibit the activity of mTOR and its targets. This might be an explanation for the interference effect of strength development during combined strength and endurance training. (Nader 2006.)

Since there have been positive results regarding improvements in force production due to combined strength and endurance training, the main limitation seems to be the rate of force development (RFD). Even Dudley and Djamil (1985) stated already that endurance training's only negative correlation is with the force production of fast-twitch fibers. Interestingly, it has been noted by Osteras et al. (1999) that explosively performed maximal strength training can have positive adaptations to aerobic performance. Also, Hoff et al. (2002) stated in their research that improvements in RFD are more significant than improvements in maximal force production, since RFD is the factor that correlates the most with economy of endurance performance.

Still it seems that combined strength and endurance training does not support improvements in RFD, and this finding has been stated in numerous studies (Dudley & Djamil 1985; Hennessy & Watson 1994; Häkkinen ym. 2003; Mikkola ym. 2012). Figure 10 presents the changes in maximal isometric force and maximal RFD due to strength training, and combined strength and endurance training. On the other hand, there are studies that have had opposite results, and in Aagaard et al. (2010) study combined strength and endurance training led to improved endurance capacity, but RFD improved as well. They also noticed in the same study that the proportion of type IIa muscle fibers had increased and maximal force production was improved. However, due to the limitation of these studies showing positive results regarding concurrent training and RFD, it seems that some interference effect may be accompanied.

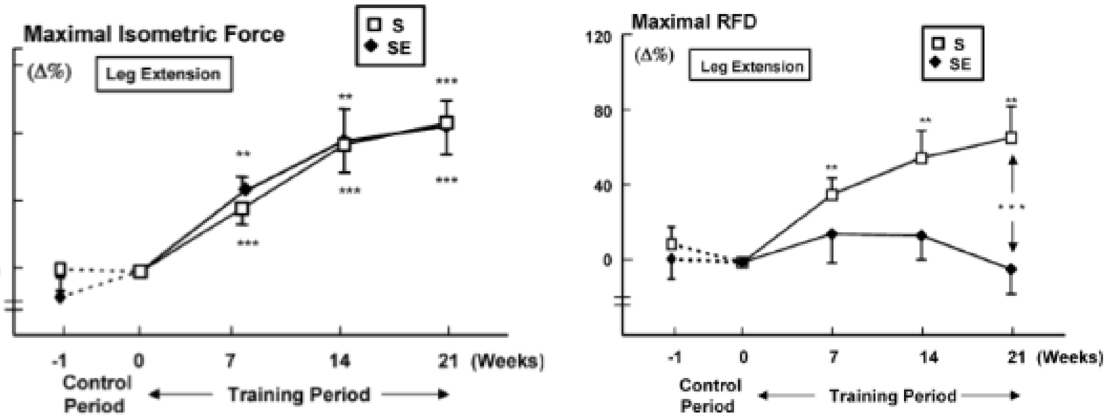


FIGURE 10. Changes in maximal isometric leg extension force and maximal RFD during one week of control and 21 weeks of training between S and SE groups. (Häkkinen et al. 2003).

3.4 Adaptations to combined maximal strength training and high intensity endurance training

Recently the positive effects of maximal and explosive strength training for endurance performance have been noted (figure 11) and studies have been conducted. There's still a limitation in the scientific field, since combined high-intensity endurance training, and maximal and explosive strength training have not been studied.

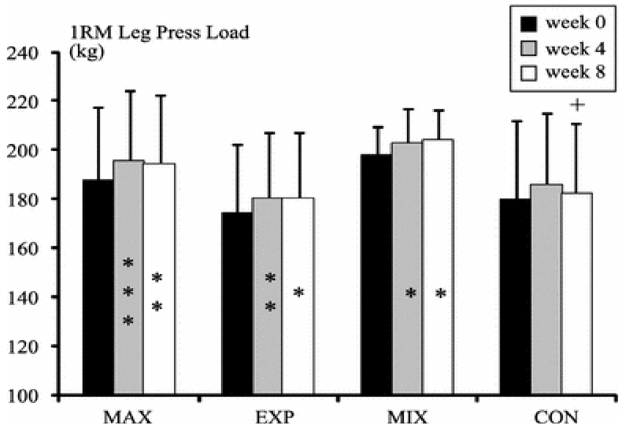


FIGURE 11. Bilateral dynamic leg press 1RM load (kg) during the 8-week combined strength and endurance training intervention (mean ± SD). MAX=Maximal strength training group; EXP= Explosive strength training group; MIX= Mixed maximal and strength training group; CON= Control group. *p ≤ 0.05, **p < 0.01 and ***p < 0.001. (Taipale et al. 2013).

Cantrell et al. (2014) also conducted a study that used similar regimens, however, their subjects performed a modified Wingate protocol as sprint interval training, which consisted of 20s bouts, and combined it with strength training, with relative high loading (85% of 1RM). As result they stated that there were no significant differences in strength measurements, between the combined training group and strength training only group. The combined group improved their maximal oxygen uptake (40.9 to 42.3 ml/kg/min), but the strength training group remained the same. (Cantrell et al. 2014.)

In addition, there are some studies that have a bit similar approach, at least on the strength training part. Mikkola et al. (2011) compared the effects of different resistance training modalities combined with endurance training. In this study they had 27 male subjects who were divided into the heavy resistance, explosive resistance and muscle endurance training groups. Subjects were recreational endurance runners and the eight-week strength training program was used as a supplement to endurance training. All groups improved their running performance on a treadmill and there were no significant differences between groups. However, the heavy resistance and explosive strength groups improved in neuromuscular measurements, and especially heavy resistance training seemed to enhance high-intensity running characteristics. (Mikkola et al. 2011.)

Taipale et al. (2014) combined heavy and explosive strength training with endurance training, which led to significant increases in explosive strength, muscle activation, maximal strength and peak running speed. However, endurance training conducted in this study was performed at below lactate threshold. The major finding in their study was that combining maximal and explosive strength training with endurance training may be more effective than more commonly used circuit training, as improvements were noted more systematic. (Taipale et al. 2014.)

Based on these studies it seems that heavy resistance and explosive strength training could be beneficial for endurance performance due to enhanced economy, and improved sprinting capabilities at the end of races (Mikkola et al. 2011). The main deficiency in this field is that endurance training is usually performed as relatively low- or moderate-intensity, and the influence of high-intensity endurance training may lead to highly different results. Docherty and Sporer (2000) presented an interference zone (figure 12) for combined training, which estimates that neural strength training might actually be more suitable combination with endurance training. However, it estimates at the same time that high-intensity endurance training might cause some level of interference effect (Docherty & Sporer 2000).

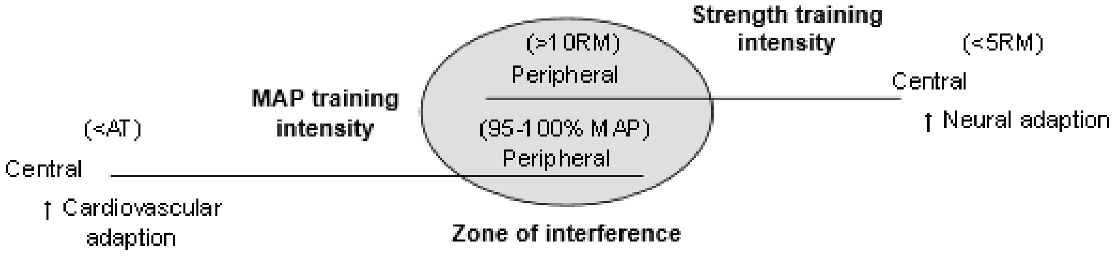
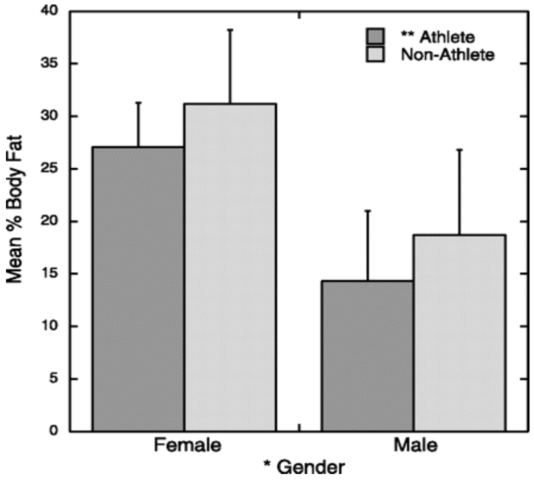


FIGURE 12. The intensity continuums and locations of adaptations for maximal aerobic power (MAP) and strength training, and possible overlapping zone of these two training modalities when performing combined training. (Docherty & Sporer 2000).

4 SEX DIFFERENCES IN ADAPTATIONS TO STRENGTH AND ENDURANCE TRAINING

4.1 Major sex differences in body composition and physical performance

Even though males and females have almost identical organisms, they have some differences regarding their body type and structure. Males have a longer period of growth, and they also tend to end up with broader shoulder than females, which allows more muscle to be packed in the skeletal frame, and thus create mechanical advantage for muscles acting on the shoulder section (Holloway & Baechle 1990). When compared to some specific body mass index, males seem to have more lean mass, and females seem to have more fat mass as seen in figure 13 (Geer & Shen 2009). Body composition also seems to differ from the fact how mass is divided in the body. Females seem to have more muscle mass and fat mass in their lower extremities, as males seem to have more muscles mass in their upper body and more fat mass in their trunk section (Holloway & Baechle 1990; Miller et al. 1993; Janssen et al. 2000; Blaak 2001). However, there is no sex difference in body weight response to exercise for similar body weight and fat mass (Holloway & Baechle 1990; Caudwell et al. 2014).



FiIGURE 13. Mean percent body fat values for college-age subjects comparing the effect of sex and athletic status. (FitzPatrick & Campisi 2009.)

This difference in body composition goes hand in hand with the fact that there’s difference in muscle cross-sectional area (CSA). Numerous studies have stated that males have greater cross-sectional area in both fiber types when compared to females, which leads to greater overall body muscle mass (Brooke and Engel 1969; Costill et al. 1976a; Simoneau and Bouchard 1989; Miller et al. 1993; Carter et al. 2001; McArdle et al. 2015, 536).

Males and females also differ from their muscle fiber composition. It has been stated in previous studies that females have greater proportion of type I muscle fibers (Brooke and Engel 1969; Simoneau and Bouchard 1989; Carter et al. 2001), and the other way around, males have greater proportion of type II fibers (Brooke and Engel 1969; Miller et al. 1993).

Difference in muscle fiber composition may partly be associated with the fact that females are capable for greater fat utilization. Tate and Holtz (1998) state in their review, women oxidize more fat during submaximal exercise, which leads to relative sparing of muscle glycogen. Similar findings have also been found in other studies (Green et al. 1984; Gauthier et al. 1992; Chenevière et al. 2011), but these studies have been discussed more closely later on.

4.2 Sex differences in adaptations to strength training

Even though males seem to have a better initial state to gain strength, females are quite suitable for strength training as well. Men experience more absolute change in muscle size in response to resistance training, because of their initial larger muscle mass. However, the muscular hypertrophy during strength training period seems to be similar when measured in relative values. (McArdle et al. 2015, 536.) Thus, it seems that males and females respond similarly in hypertrophic response to resistance training. This has been proven by previous studies, even in the upper body, where females have less muscle mass when compared to males (Cureton et al. 1988; Miller et al. 1993; Janssen et al. 2000). Even though females are capable of increasing their cross-sectional area of trained muscles, when both counterparts train for hypertrophy the sex difference stays and males have the edge (Morrow & Hosler 1981; Alway et al. 1985).

Based on the difference in muscle mass, males tend to be able to produce higher absolute force values than females (Willems & Northcott 2009; Inglis et al. 2013; Stock et al. 2013; Spiteri et al. 2014). Still, muscle mass is not the only factor that explains the differences in force production between sexes. Inglis et al. (2013) discovered in their study that neither the normalization nor covariate approach can be used to establish causal relationships, and sex differences still partly remain. The impact of neural factors is also supported by the fact that men seem to have higher motor unit discharge rates than females (Christie & Kamen 2010). However, there might still be some undiscovered neural factors involved.

However, when the absolute strength values are compared to body weight, the sex difference decreases, and when compared fat free mass the sex difference is almost completely vanished, at least in lower extremities. It has been stated that sex differences regarding force production in lower extremities could be vanished by comparing absolute values with working muscle mass. (Skinner 2005, 57.)

When investigating fatigue, Häkkinen (1993) has reported females to be more fatigue resistant, when performing 20x1x100% heavy resistance loading. In his study males experienced greater fatigue and acute recovery from fatigue was slower than in females (Häkkinen 1993). Häkkinen (1994) also found similar results after hypertrophic resistance loading. Based on these findings individual variation must always be considered, but previous literature points into direction that females might be more fatigue resistant than males. However, Willems and Northcott (2009) stated that males were capable of sustaining submaximal isometric force (50%MVC) 55% longer than females after downhill running performance. In addition, Stock et al. (2013) discovered that even though men were able to produce significantly higher force values, the decline in peak torque during fatiguing exercise tend to behave same way in both sexes.

Even though studies seem to show that the sex difference in adaptations to strength training is fairly minimal, males seem to have better initial hormonal state for strength adaptations. Males have significantly higher initial testosterone values than females (McArdle et al. 2015, 425 - 426), which has been noted to rise after strength training (da Conceição et al. 2014), and correlate highly with adaptations to strength training (Ronnestad et al. 2011). In addition, Crewther et al. (2006) presented that growth hormone seem to react more vividly to strength training in males. The same has been presented by Linnamo et al. (2005, figure 14). However, there's evidence that females can experience as great or even greater growth-hormone responses than males during sprint exercise (Esbjörnsson et al. 2009). These hormonal differences should give males a more suitable initial state for strength gains, even though actual improvements in strength seem to be similar between sexes. One factor that evens hormonal adaptations might be insulin-like growth factors, which seem to behave in the same way for both sexes (Crewther et al. 2006).

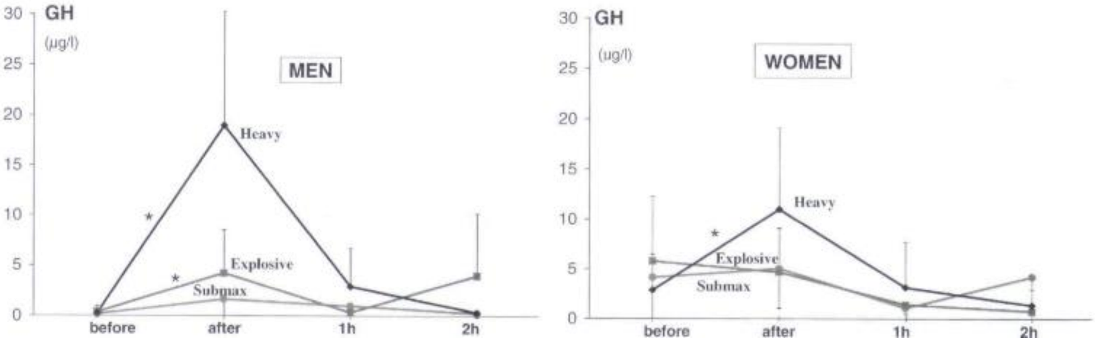


FIGURE 14. Mean (± SD) values for serum growth-hormone (GH) concentrations before and after heavy, explosive and submaximal resistance exercises. $p<0.05$. (Linnamo et al. 2005).

Females are also capable of improving their power production, and when comparing sexes improvements in percentage, females seem to have as great adaptations as males (Kreamer et al. 2001; Delmonico et al 2005). Actually, Liljedahl et al. (1999) hypothesized, that smaller areas of type II fibers and the lower activity of lactate dehydrogenase, that are usually seen in females, may be result from less frequent activation of type II fibers, and due to this females should respond to sprint training even greater extent than males. Their hypothesis actually got support from their own study when females increased their type IIb fiber area in result to sprint training more than male subjects (Liljedahl et al. 1999). Interestingly, Delmonico et al. (2005) state that improvements in neuromuscular performance due to power training results more from non-muscle mass adaptations in females.

There also seems to be a difference in recovery time from power training, as females have shown to recover faster than men from repeated high-power exercise, however males seem to have ability to generate more work (Billaut & Smith 2009). The authors explain that this might be due the fact that females tend to clear more ammonia from their muscles than males.

So it seems that both sexes are capable of improving their neuromuscular characteristics. Even older females have been observed to improve their voluntary maximal isometric bilateral leg extension force due to strength training (figure 15). Males seem to have a slight edge over women when it comes to factors that relate to muscular hypertrophy and improvements in force production, but studies have shown that relative improvements in physical performance are similar between sexes. Both sexes are also capable of increasing their power production capabilities.

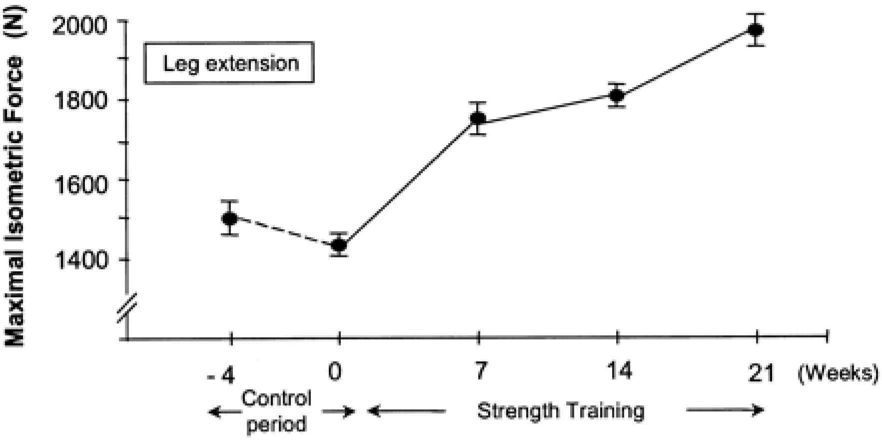


FIGURE 15. Mean ± SD maximal voluntary isometric force of the bilateral leg extension in older women during the 4-wk control period and during the course of the 21-week strength-training period. (Häkkinen et al. 2001).

4.3 Sex differences in adaptations to endurance training

There is some evidence that females might even be more suitable for endurance adaptations than males. Previous studies state that both sexes are capable of improving their endurance performance and aerobic capacity (Nalcakan 2014; Weston et al. 2014), but reasons for and size of adaptations might differ.

It has been reported that females have lower respiratory exchange ratio (RER) than males during endurance performance (Tarnopolsky et al. 1990; Phillips et al. 1993; Tarnopolsky et al. 1995; Tarnopolsky et al. 1997; Friedlander et al. 1998b; Horton et al. 1998; McKenzie et al. 2000; Edgett et al. 2013), which points into the direction that females seem to oxidize proportionately more lipids and less carbohydrates during endurance performance, at least when performed at the same relative intensity. Based on previous literature it actually seems that females might be more suitable for ultra-endurance sports when compared to males (Tarnopolsky & Saris 2001; Rust et al. 2013).

However, males seem to have higher maximal aerobic power (Hopker et al 2010), and higher maximal oxygen uptake than females, which both provide important information regarding endurance capacity (McArdle et al. 2015, 236; 242). Davis et al. (2006) also reported that males have higher maximal oxygen uptake even at the same fat-free mass. Male endurance athletes have also been generally considered to have greater values of cardiac mass and volume, and this applies even when training volume, body size and body composition are considered (Rowland & Roti 2010). Thus, body size does not seem to be the only difference making factor regarding cardiovascular function.

Mechanical economy of endurance performance between sexes has also been studied by Davies (1994), who noticed that there were no significant differences between sexes, and as well Tarnopolsky and Saris (2001) state that lactate threshold for well-trained individuals is similar between sexes. Yasuda et al. (2008) also investigated the sex differences of mechanical efficiency, and realized that there were no differences between sexes in neither arm cranking nor leg cycling. In addition, Zhang's (1992) study shows that there are not any significant differences neither in resting nor peak lactate values between sexes, and furthermore this study does not show any differences in rate of blood lactate removal rate during active recovery period.

So it seems that in most of the factors accompanying endurance capacity, there are not major differences between sexes. However, differences noted in adaptations to endurance training between sexes set a complicated table for combined strength and endurance training and its evaluation between sexes.

4.4 Sex differences in adaptations to combined strength and endurance training

Even though combined strength and endurance training has been fairly studied field nowadays, there are not too many studies conducted regarding differences between sexes. However, it has been reported that combined strength and endurance training can produce increases in maximal strength in both sexes (Guadalupe-Grau et al. 2009; Taipale et al. 2014). In addition, the hypertrophic response of combined strength and endurance training has shown positive results in both males and females and both sexes have been recorded to increase their lean-body mass due to concurrent training (Guadalupe-Grau et al. 2009).

In study by Taipale et al. (2014) both sexes were capable of improving their 1RM significantly in maximal bilateral dynamic leg press during 16 weeks of concurrent training. Interestingly females seemed to improve more than males in both, during first eight weeks (M: 3%, F: 7%) of training and during the next four weeks (M: 3%, F: 7%) of training. In addition, Guadalupe-Grau et al. (2009) resulted increases in maximal voluntary contraction (MVC) in both males (+17.2%) and females (+14.0%). The size of increases were similar even when they compared the MVC to lean mass of the lower extremities (M: +8.3%, F: 7.4%).

There seems to be some sex differences in acute response to combined strength and endurance loading (figure 16). Taipale and Häkkinen (2013) noticed significant difference between sexes during combined strength and endurance loading, since males seemed to experience greater fatigue than females. This supports previous studies stating that females are more fatigue resistant than males (Häkkinen 1993; Häkkinen 1994).

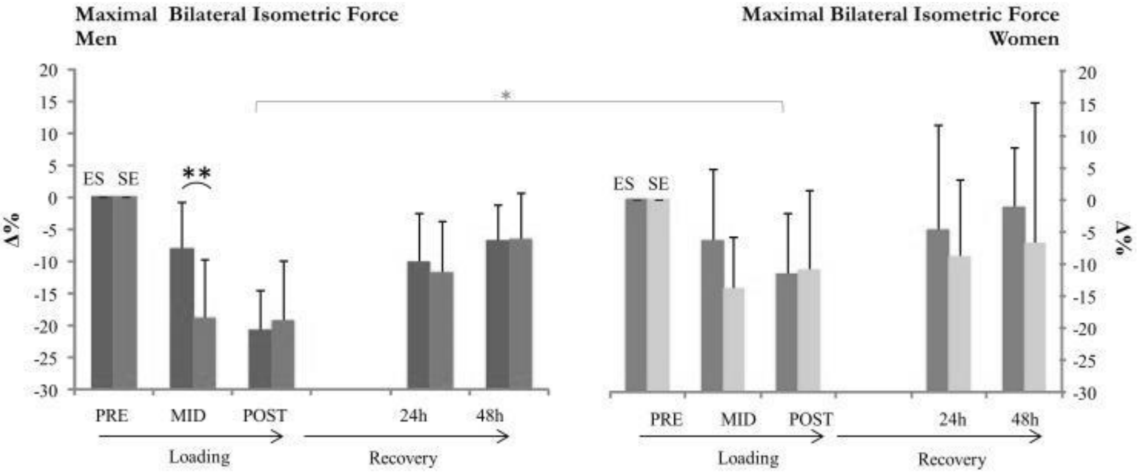


FIGURE 16. Maximal bilateral isometric force during combined strength and endurance loading in both sexes. (Taipale & Häkkinen 2013).

Taipale et al. (2014) noticed in their study that both males and females were capable of improving their countermovement jump (CMJ) performance during 16 weeks of concurrent training. However, male subjects were able to continue their improvement during the whole 16 weeks as females reached their top in 12 weeks (Taipale et al. 2014). Ramírez-Campillo et al. (2014) also noticed that there were no significant differences between sexes, and both sexes improved their CMJ height due to combined explosive strength and endurance training. In Taipale et al. (2014), despite this difference only females were able to improve their peak running speed the whole 16 week intervention, as males peaked already after eight weeks of training.

Hormonal adaptations to combined strength and endurance training seem to behave the same way as these training modalities would separately. Males tend to record increased testosterone levels, which have not been recorded in females (Taipale et al. 2014).

Results regarding endurance capacity due to combined strength and endurance training have demonstrated increases in maximal oxygen uptake in both sexes (Bell et al. 1997; Marta et al. 2013). There doesn’t seem to be any specific reason why males and females would have any major differences in this parameter. However, further study is needed.

Some combined strength and endurance training studies are missing separate training groups for strength and endurance, which means it is impossible to say if concurrent training has inhibited some adaptations or as well enhanced some adaptations. This also means that there could be some sex differences between concurrent and separate training modalities. Bell et al. (1997) took this into consideration as they separated both males and females into strength training groups and combined strength training groups. Both sexes improved their bilateral incline leg press and bench press one repetition maximums in both training groups. However, these gains were similar for males in both training groups, but females gained less with concurrent training than what the strength training alone produced. This suggests there might be sex differences involved when performing concurrent training. (Bell et al. 1997.)

Even though there are not too many studies conducted regarding sex differences during combined strength and endurance training, it seems that concurrent training is capable of improving individual’s strength and endurance performances in both sexes. There are not any major differences in adaptations to this training modality, and different results in different studies vary.

5 PURPOSE OF THE STUDY

The purpose of the present study was to examine the effects of a 10-week combined maximal and explosive strength training and high intensity endurance training period on the neuromuscular system and 3K time-trial performance in males and females.

5.1 Research problems

1. Is combined maximal and explosive strength and high-intensity endurance training capable of improving neuromuscular performance in trained individuals?

Hypothesis: Combined maximal strength training and high intensity endurance training is capable of improving neuromuscular performance or at least maximal strength.

In previous studies it has been noted that combined strength and endurance training is capable of improving both strength and endurance performance (Barrett-O'Keefe et al. 2012; Chtara et al. 2004; Hoff et al. 2002), even with athletes (Millet et al. 2002). However, it seems that endurance training might inhibit development of rapid force production (Hunter et al. 1987; Leveritt et al. 1999). Combined maximal and plyometric strength training could give some positive adaptations regarding the problem with fast force production.

2. Is combined maximal strength training and high intensity endurance training capable of improving endurance performance in trained individuals?

Hypothesis: Combined maximal strength training and high intensity endurance training is capable of improving endurance performance in trained individuals, mostly due to improved running economy provided by improved neuromuscular performance.

It has been shown that combined strength and endurance training is capable of improving both strength and endurance performance, and most of the studies show that strength training does not inhibit adaptations to endurance training (Hickson et al. 1988; Laursen et al. 2005). Recent studies even show that strength training is one of the key factors of improving endurance performance due to improved running economy (Rønnestad & Mujika 2014).

3. Are there major differences in neuromuscular changes during the 10-week combined strength and endurance training period between males and females?

Hypothesis: Both sexes will improve their neuromuscular performance. Males might have slight advantage over women in power characteristics due to higher proportion of fast twitch muscle fibers.

It has been presented by Taipale et al. (2014) that both sexes are capable of improving their countermovement jump height due to combined strength and endurance training, however, only males continued improving throughout the study (Taipale et al. 2014). Ramírez-Campillo et al. (2014) also reported that there were no significant differences between sexes, and both sexes improved their countermovement jump height due to combined explosive strength and endurance training. Both studies also reported that combined strength and endurance training can produce increases in maximal strength in both sexes (Guadalupe-Grau et al. 2009; Taipale et al. 2014). Furthermore, Bell et al. (1997) presented that when comparing pure strength and combined strength and endurance training groups, females did not improve as much in force production. However, males improved as much with combined training as they did with pure strength training. (Bell et al. 1997.)

4. Are there major differences in endurance running performance during the 10-week combined strength and endurance training period between males and females?

Hypothesis: Both groups will improve their 3K time-trial performance without any significant differences between sexes.

Results regarding endurance capacity due to combined strength and endurance training have demonstrated increases in maximal oxygen uptake in both sexes (Bell et al. 1997; Marta et al. 2013). Also, the neuromuscular adaptations may enhance running economy, and thus improve endurance performance.

6 METHODS

6.1 Subjects

Forty-eight healthy subjects aged 18-40 from the Jyväskylä region were recruited by advertisements in newspapers and social media to participate in this study (VoKe project). Half of the recruited subjects were males (n=24) and half were females (n=24). Recruited subjects were healthy non-smoking recreationally physically active men and women. Inclusion criteria were BMI <30 kg/m^2 and a cooper running test results minimum of 2300m. Exclusion criteria included any diseases, musculoskeletal or cardiac problems, or medications that would preclude a subject’s ability to perform resistance and endurance training and testing. Prior to participating in this study subject resting ECG and health questionnaires were screened by a medical doctor. Ethical approval was granted by the University Ethical Committee.

Participants were informed about the upcoming measurements and training, and about their option to drop out of the study at any time. During this meeting participant agreed to participate in the study and signed an informed consent. Subjects acted as their own controls over a 2-3 month period prior to the 10 week high-intensity combined strength and endurance training intervention. This thesis concentrates only on the 10 week intervention period and in the pre- and post-measurements, excluding the prior control period.

This thesis is part of a broader study (VoKe project). There were thirty-nine subjects in the beginning of the intervention, twenty male subjects and nineteen female subjects, from which thirty-eight (one male drop-out) finished the study. Ten of the subjects had to drop out during summer’s control period, because of minor injuries unrelated to the project or personal reasons. Nine of the male subjects belonged in a cold water immersion group and ten of the female subjects were using oral contraceptives. Results used in this thesis are only the results from male subjects who did not participate in cold water immersion (n=10) and female subjects who did not use oral contraceptives (n=9). The one male drop-out belonged in the group this thesis concentrates on, so there were eleven male subjects in the beginning of the intervention.

Anthropometrical data of the subjects used in this thesis are presented in table 3. Heights of the subject were not measured and thus presented values are based on self-reported information collected from subjects. Weight was measured from dual-energy x-ray absorptiometry (DXA) measurements with a 0.1kg accuracy, with the subjects being in a fasted (12h) state and in underwear. Body mass, muscle, and fat tissue were measured using bioimpedance (InBody 3.0, Biospace Co.), and total body estimates of muscle and fat tissues as well as bone mineral density with DXA (Gallagher et al. 2000). Body fat percentage presented in table 3 is measured with DXA, subjects being in a fasted (12h) state.

TABLE 3. Anthropometric data for male and female subjects measured at pre-tests.

Group	**n**	**Age (years)**	**Height (cm)**	**Weight (kg)**	**BMI (kg/m^2)**	**Body fat (%)**
Male	10	31.5 (±4.9)	181.8 (±4.6)	79.3 (±8.5)	23.6 (±1.4)	17.5 (±5.2)
Female	9	31.3 (±5.4)	168.3 (±5.1)	60.6 (±5.8)	21.4 (±1.7)	23.9 (±6.7)

6.2 Study design

The study was conducted between June and December 2014. The control measurements were conducted during summer (June & July), pre-measurements in the beginning of September and post-measurements in beginning of December. The 10-week training period was conducted during fall between pre- and post-measurements. Subjects also participated in mid-measurements conducted during training week five. The present thesis' intervention is presented in figure 17. A separate familiarization meeting was not arranged, but subjects were familiar with the testing equipment and protocol in the pre-measurements, because they already had control measurements in summer prior to the intervention.

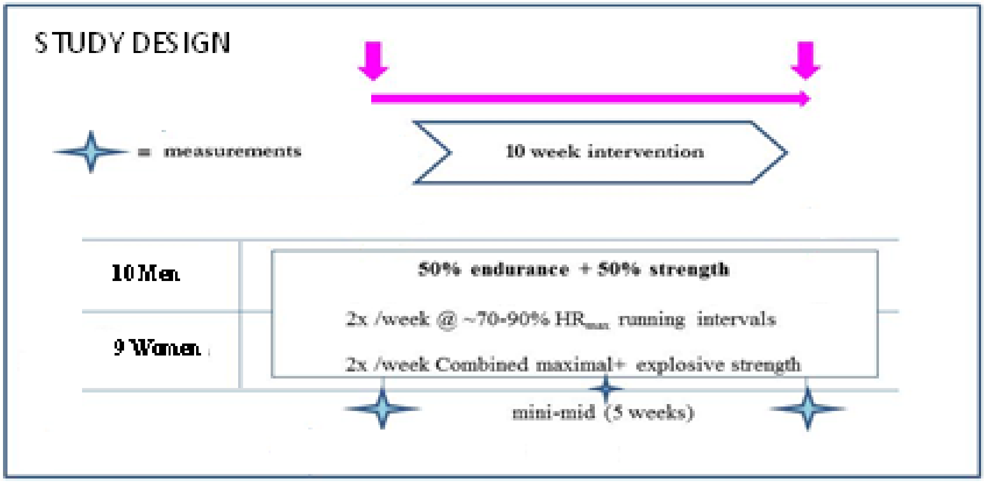


FIGURE 17. Study design: Modified to present the part of the study this thesis concentrates on.

Pre- and post-measurements consisted of collection of blood and saliva samples, anthropometrical measurements, neuromuscular measurements, treadmill running test performed until volitional exhaustion and field tests.

The neuromuscular measurements and treadmill running test were performed during same measurement session, so that neuromuscular measurements were conducted prior and treadmill running test immediately after. The duration of these laboratory performance measurements were an hour each, two hours combined. Field test consisted of 3-k time trial running test and dynamic muscle endurance tests. All measurements were performed during same time of the day (+/- 1 hour), with few exceptions.

The training consisted of maximal and explosive strength training and high intensity endurance training. Both training modalities were performed separately twice a week. The overall duration of each training session varied from 45 to 90 minutes. The contents of measurements and training sessions concentrated in this thesis are explained in more detail later on.

6.3 Training

Subjects completed the 10-week combined maximal and explosive strength and high-intensity endurance training period. Both strength and endurance training were performed twice a week separately. Subjects were informed not to complete four training sessions in a row, recommendation being two training days in a row continued with a rest day. Subjects were allowed to train in which ever order they preferred, but two same training modalities were not allowed subsequent days. During the 10-week intervention subjects executed 99.1% of the training sessions.

Training weeks one and two can be classified as preparatory training weeks, as training intensity was kept slightly lower. Training weeks five and ten were reduced on volume due to testing. During training week five subjects trained once strength (workout A, Tables 4, 5 & 7) and once endurance (workout A, Table 8), since they performed the mid-measurements during same week. Mid-measurements were fused with training so that subjects performed the plyometric exercises of strength workout B (Table 6) immediately after the mid-measurements. During training week ten, volume was decreased and subjects performed one strength (workout A) and one endurance (workout A) training session. Training period was designed progressive, and training intensity in both strength and endurance training was increased throughout the intervention.

Subjects were allowed to continue other physical activities during the study. However, training sessions involved in this study were commanded to be performed with high quality, and other physical activity was not to inhibit these training sessions. Subjects were recommended to perform one low-intensity aerobic exercise per week as a recovering exercise.

6.3.1 Strength training

Strength training sessions consisted of a mixture of maximal and explosive strength training for the lower extremities. Traditional core exercises were also included as they are a typical part of training programs for all athletes (Willardson 2007). Strength training sessions involved some complex training characteristics. Subjects performed multi-joint movements for lower extremities with relative high loads, and continued with biomechanically similar power movement, for example heavy squats were followed by countermovement jumps (table 4). Subjects performed similar pattern with leg press and calf raise as well. Knee flexion exercise was performed a bit differently, since movement was only performed with knee flexion machine and training intensity was kept on hypertrophic zone throughout the study. The program presented in table 4 was performed during every strength training session. There were no exercise order, because of the size of the gym and amount of subjects training at the same time. However contrast movements (countermovement jumps, explosive leg press, and calf jumps) were always performed after the biomechanically similar heavier movement.

Strength training sessions were mostly supervised by members of research staff (one supervisor). Due to personal reasons (for example, travelling) some training sessions had to be performed individually without supervision. The supervised strength training sessions were performed in a gym that was built for research purposes. All performed sets, reps and loads were recorded in individual training sheets.

TABLE 4. Overview of strength training sessions. The dispersion in loads means that at the beginning of study the exercise intensity was lower and was increased throughout the study.

Exercise	**Sets**	**Reps**	**Load (%1RM)**	**Rests**
Squat (~100° knee angle)	1-2 warm-ups	8-10	50-70	1
	2	4-6	70-85+	2
Countermovement jumps	2	10	BW	2
Leg press	1-2 warm-ups	8-10	50-70	1
	2	4-6	70-85+	2
Explosive leg press	2	10	30-60	2
Knee flexion	1-2 warm-ups	8-10	50-60	1
	2	8-10	70-85	2
Calf raise	1 warm up	8-10	50-70	1
	2	5-6	70-85+	2
Calf jumps	2	6	BW	2

In addition, subjects also performed some plyometric exercises. After the exercises listed in table 4, subjects performed either bounding and hurdle jump exercises (A), or broad jump and step-up exercises (B). Subjects performed additional plyometric exercises A (table 5) during the first strength training session of the week, and additional plyometric exercises B (table 6) during the second strength training session of the week. Bounding and step-up exercises are unilateral, thus the repetitions were performed with each leg.

TABLE 5. Additional plyometric exercises (A). All exercises were performed with body weight. Rest intervals were two minutes at the beginning of the study, but were reduced to one minute during the training period.

Exercise	**Sets**	**Reps**	**Load (%1RM)**	**Rests**
Bounding	2	6+6	BW	1-2
Hurdle jumps	2	6	BW	1-2

TABLE 6. Additional plyometric exercises (B). All exercises were performed with body weight. Rest intervals were two minutes at the beginning of the study, but were reduced to one minute during the training period.

Exercise	**Sets**	**Reps**	**Load (%1RM)**	**Rests**
Standing 6-jump	2	6	BW	1-2
Step-ups	2	6+6	BW	1-2

After these plyometric exercises, subjects performed upper-body and core exercises. For upper-body subjects performed hypertrophic bench press training, and as core exercises subjects performed plank, back extension, and torso rotation (table 7). The core exercises were performed mainly as muscular endurance training. After these exercises subjects were ready, but were allowed to continue their strength training session individually if they wanted.

TABLE 7. Upper-body and core exercises. *=HUR is an exercise unit that stabilizes ankles, leaving lower extremities to rest on an upward diagonal position allowing upper body to bend from hip joint, and thus is used for strengthening back extensor muscles, **=FRAPP is an exercise unit that stabilizes hips and legs, but allows proper torso movement, and thus is used for strengthening rotating muscles of the core section, ***=Loads in core exercises varied individually.

Exercise	Sets	Reps	Load (%1RM)	Rests (min)
Bench press	2-4	8-10	70-80	1-2
Plank	2	60 seconds	***	1
Back extension (HUR*)	2	10-15	***	1
Torso rotation (FRAPP)**	2	10-15	***	1

6.3.2 Endurance training

Endurance training sessions included 4x4 min running intervals at approximately 90% of heart rate max, which was measured on the treadmill, as well as 3x3x100m sprints (table 8). The 4x4 min running intervals were chosen based on the article by Helgerud et al. (2007) in which these intervals were considered the equally as effective as multiple high-intensity sprints in increasing aerobic capacity. The 3x3x100m sprints were mainly selected to improve subjects' running velocity.

For both endurance training sessions, subjects warmed up for 10 minutes, approximately 60-70%HRmax, and cooled down after the exercise for 15 minutes with same intensity that warm-up was performed. Warm-up and cool down included some dynamic stretching performed individually.

The members of research staff organized supervised endurance training sessions around Jyväskylä region. However, subjects were also allowed to perform endurance training on their own without supervision. From endurance training sessions the HR values were recorded and collected before and after every interval, and thus used as a way to monitor training intensity. Even if subjects trained individually, they collected the HR values and delivered them to the staff of the project.

TABLE 8. Overview of endurance training sessions. The dispersion in intensity means that at the beginning of study the running intensity was lower and was increased throughout the study. *=Subjects rested 2 minutes between every sprint and 5 minutes between every set. During rest period subjects were informed to do active recovery so that their HR stayed around 60-70% of their individual HRmax.

Exercise	**Intensity (%HRmax)**	**Rests**
4x4 min	75-90%	4 min (60-70%Hrmax)
3x3x100m	80-100%	2min/5min* (60-70%HRmax)

6.4 Measurements

All subjects participated in pre-, mid- and post-measurements. Pre- and post-measurements were identical and consisted of neuromuscular measurements, treadmill running test until voluntary exhaustion, field tests, anthropometric measurements and collection of blood samples. Mid-measurements only consisted of a lower number of neuromuscular measurements (countermovement jump, isometric leg press, isometric knee extension and isometric knee flexion) and blood samples.

6.4.1 Neuromuscular measurements

Before starting the actual neuromuscular measurements, subjects warmed up for five minutes with a cycle-ergometer. Subjects were allowed to adjust the ergometer themselves and intensity of warm-up was individually decided.

Countermovement jump (CMJ). The CMJ test was performed to measure the power characteristics of lower extremities. Subjects were instructed to jump as high as possible on a force plate with an explosive countermovement action before the concentric phase of the movement. The depth of the squat at the beginning of countermovement jump was not standardized, and subjects were allowed to jump as they felt the most natural with. Nevertheless, subjects had to keep their hands on their hips during the whole performance, and were not allowed to bend their legs during the flight time. When ground contact was achieved subjects were allowed to bend their knees to ease off the landing. Subjects performed three jumps with one minute rests between. An additional trial was performed if the flight time from the third trial was greater than 5% compared to the previous trial. However, the maximum amount of trials was five. From CMJ's force production and flight time were measured (Signal 4.10, CED, UK), and jump height was calculated manually from the force-time curve based on impulse, since it has been stated to be more valid measure than flight-time based evaluation (Kirby et al. 2011).

Maximal bilateral isometric leg press. Isometric strength of leg extensor muscles was measured by using an isometric horizontal bilateral leg press (figure 18, designed and manufactured by the Department of Biology of Physical Activity, University of Jyväskylä, Finland). Leg press was adjusted so that subjects' knee angle was 107 degrees, measured using the greater trochanter, lateral tibiofemoral joint space and lateral malleolus as reference points. Subjects were instructed to produce force as fast as possible as much as possible. Regarding duration subjects were instructed to produce force until the test leader told them to stop, and the duration of isometric performances were approximately 3 seconds. Force data was collected at a sampling frequency of 2000 Hz, and then filtered (20 Hz low pass filter). Force data was analyzed using customized scripts (Signal 4.10, CED, UK). Subjects performed the minimum of three maximum voluntary contractions (Häkkinen et al., 1998). If the maximum force during the last trial was greater than 5% compared to the previous trial, and additional trial was performed. However, no more than five maximal trials were performed. The best performance trial, in terms of maximal force measured in Newtons (N), was used for statistical analysis. The reliability of these measurement techniques has been previously reported (Viitasalo et al. 1980).

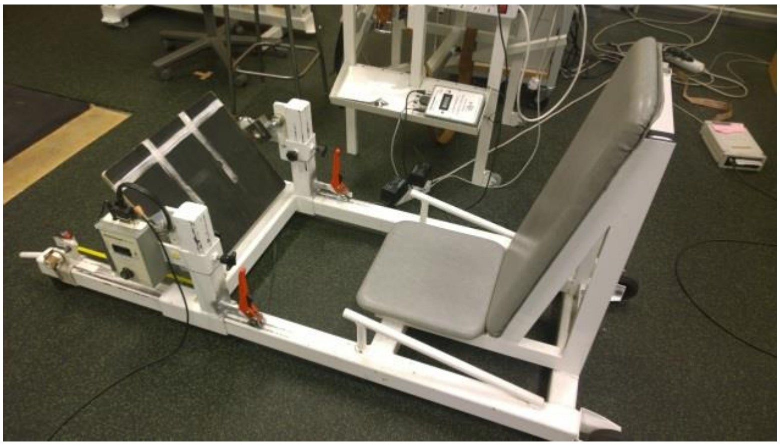


FIGURE 18. Isometric horizontal bilateral leg press, designed and manufactured by the Department of Biology of Physical Activity, University of Jyväskylä, Finland.

Maximal unilateral isometric knee extension and flexion. The isometric knee extension and flexion force were measured in modified David 200 gym equipment (Figure 19). Both extension and flexion force were measured unilaterally. Knee angle was also measured to be 107 degrees by using the same reference points that were used before, and subjects were tied to the seat with seat belt. In addition, in isometric knee extension subjects' ankle was tied to inhibit "kicking" during the trials. For knee flexion this was not necessary. Otherwise the measurement protocol, force collection and computer program were the same as in isometric leg press.

FIGURE 19. Modified David 200. Used for isometric knee extension and isometric knee flexion.

Maximal bilateral dynamic leg press. The maximal concentric strength (1RM) of leg extensor muscles were measured with leg press (Figure 20, David Sports Ltd., Helsinki, Finland). Prior to attempting 1RM, subjects warmed up with following sets; 5x ~70%1RM, 3x ~80%1RM and 2x ~90%1RM, with one minute rests between sets. Following warm-up, subjects performed one repetition at the time, and load was increased till the individual maximum was found. However, no more than 5 attempts to reach 1RM were performed. At the beginning of the movement the leg press was adjusted so that subjects' knee angle was approximately 60 degrees, measured from the same reference points as was in isometric leg press. Subjects were instructed to grasp handles located under the seat of the leg press and to keep constant contact with the seat and backrest during leg extension to a full range of motion (180 degrees), however subjects were instructed not to lock their knee joints at full extension. Verbal encouragement was given to promote maximal effort. The greatest weight that subject could successfully lift was recorded with the accuracy of 1.25 kilograms.

FIGURE 20. Maximal bilateral dynamic leg press (David Sports Ltd., Helsinki, Finland).

Neuromuscular activation (iEMG). Neuromuscular activation was measured (Signal 4.04, Cambridge Electronic Design Ltd. and Noraxon, Telemyo 2400R, USA, Inc.) from vastus lateralis (VL) by using surface electrodes (Häkkinen et al., 1998). Muscle activation from VL during isometric knee extension was selected for further analysis, and over 50% changes in iEMG were excluded from the data. Electrode placement positions were marked with small ink tattoos on the skin during the first measurement session to ensure consistency over the entire experimental period. The guidelines published by SENIAM were followed for skin preparation, electrode placement and orientation (www.seniam.org). Neuromuscular activation was only measured in the pre- and post-measurements.

6.4.2 Field tests

Field tests were performed in indoor athletics track (Hippos-hall), which had 200m meters track and a sand box for standing long jump measurements. Subjects had 10 minutes to warm-up before the measurements were started. After warm-up subjects ran a 3K time-trial, as fast as possible, and the split times for each kilometer were recorded. After the time-trial subjects had approximately 5 minutes to rest before dynamic muscle endurance tests. Dynamic muscle endurance was evaluated by performing sit-ups, pushups and standing long jump according to the guidelines of the Finnish Defense Forces (Pihlainen et al. 2011, 41 - 43). From the field tests performed in this project, this thesis will only concentrate on 3K time-trial.

6.5 Statistical analysis

Means and standard-deviations (SD) were calculated with conventional statistical methods. Independent-samples T-test and one-way analysis of variance (Oneway ANOVA) were applied for analyzing between group differences. Repeated levels ANOVA with three levels (PRE, MID, POST) and dependent-samples T-tests were applied for analyzing within group differences at different time points. Pearson – product- moment correlation was used for 3K time-trial and strength variables. The significance for all tests were set at *$p \leq 0.05$, **$p \leq 0.01$ and $p \leq 0.001$. Also, #$p \leq 0.075$ presents a statistical trend. All data was analyzed and graphed by using Microsoft Excel 2010 and IBM SPSS Statistics v.20 computer software.

7 RESULTS

7.1 Neuromuscular measurements

Countermovement jump. The mean countermovement jump height of men was significantly higher than females at pre (M: 35.4±5.4cm; F: 26.2±4.9cm, p≤0.001), and post-measurements (M: 38.8±5.3cm; F: 29.0±4.5cm, p≤0.001).

From pre- to mid-measurements both sexes improved their countermovement jump height by 7.2% (M SD: ±9.9; F SD: ±6.5), however results were only statistically significant for females (p≤0.05), while the improvement in males presented a statistical trend (p=0.064) (figure 21). During the whole training period (pre- to post-measurements) males improved their countermovement jump height by 10.0% (±8.0, p≤0.01), and females 11.3% (±5.4, p≤0.001). There were no significant differences between groups when comparing the relative improvements between any measurement time points.

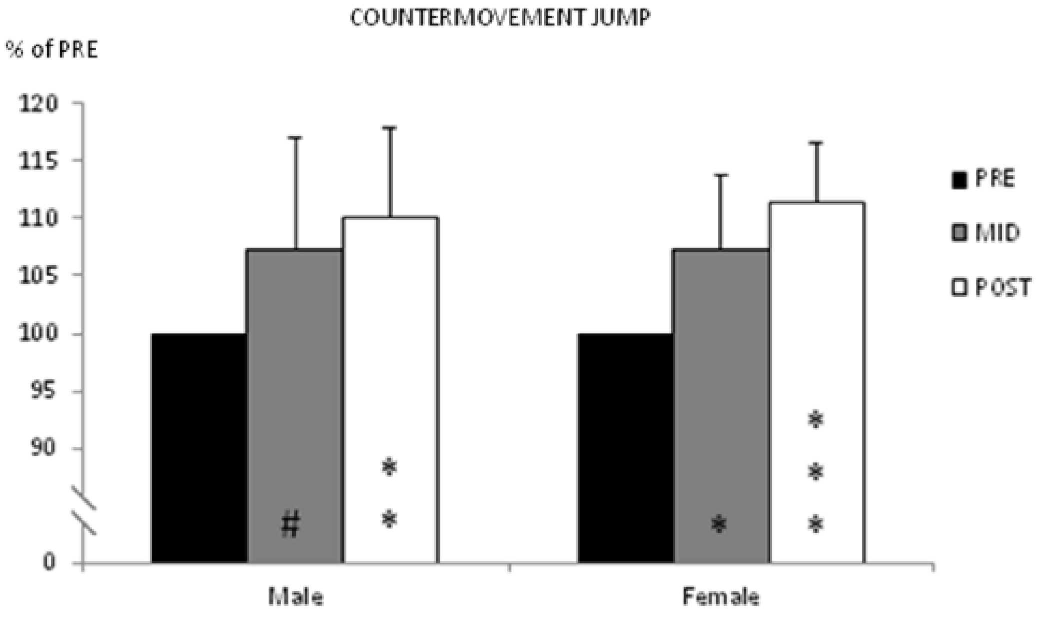


FIGURE 21. Changes in countermovement jump height expressed relatively to PRE values in both sexes. *p≤0.05, **p≤0.01, ***p≤0.001, refers to significant differences, and #p=0.064 refers to a statistical trend compared to PRE values. (M: n=9, F: n=8).

Isometric bilateral leg press. The mean isometric maximal leg press force in men was significantly higher than females at pre (M: 4114±934N; F: 2681±632N, p≤0.001), and post-measurements (M: 4606±1201N; F: 2812±577N, p≤0.001).

Both sexes improved significantly from pre- to post-measurements (M: 11.9±11.3%, p≤0.05; F: 5.8±6.0%, p≤0.05) (figure 22). Males also improved significantly from mid- to post-measurements (7.9±9.1%, p≤0.05). There were no significant differences between groups when comparing the relative improvements between any measurement time points.

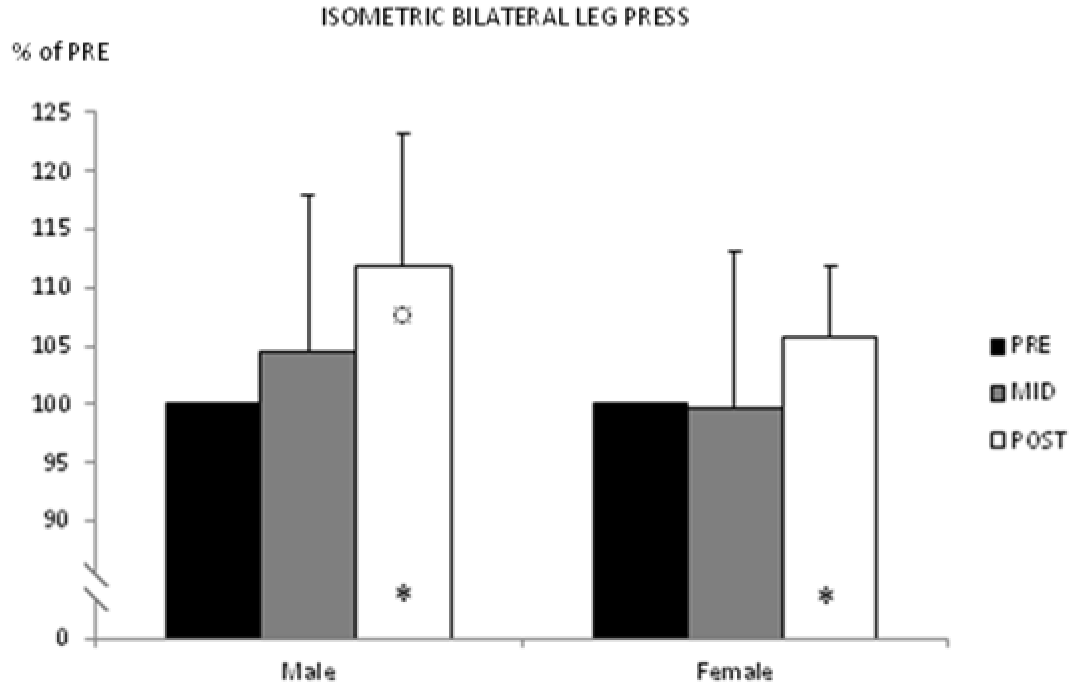


FIGURE 22. Changes in bilateral isometric maximal force expressed relatively to PRE values in both sexes. *p≤0.05 refers to significant differences compared to PRE values, and ¤p≤0.05 refers to significant difference compared to MID values.

Isometric unilateral knee extension. Males had significantly greater force values in pre- (M: 938±169N; F: 729±125N, p≤0.01), and post-measurements (M: 1039±172N; F: 796±206N, p≤0.05) than females.

Males improved significantly from pre- to mid-measurements (7.9±6.8%, p≤0.01) (figure 23). The overall improvements from pre- to post-measurements were statistically significant for males (11.2±6.0%, p≤0.001), as improvements in females presented a statistical trend (7.9±10.9%, p=0.058). Females also improved significantly from mid- to post-measurements (6.2±8.3%, p≤0.05). There were no significant differences between groups when comparing the relative improvements between any measurement time points. Males also improved significantly neuromuscular activation (22.7±19.5%) in vastus lateralis muscle (VL) during isometric knee extension from pre- (0.55±0.24µVs) to post- (0.66±0.28µVs) measurements (*p≤0.05, n=7).

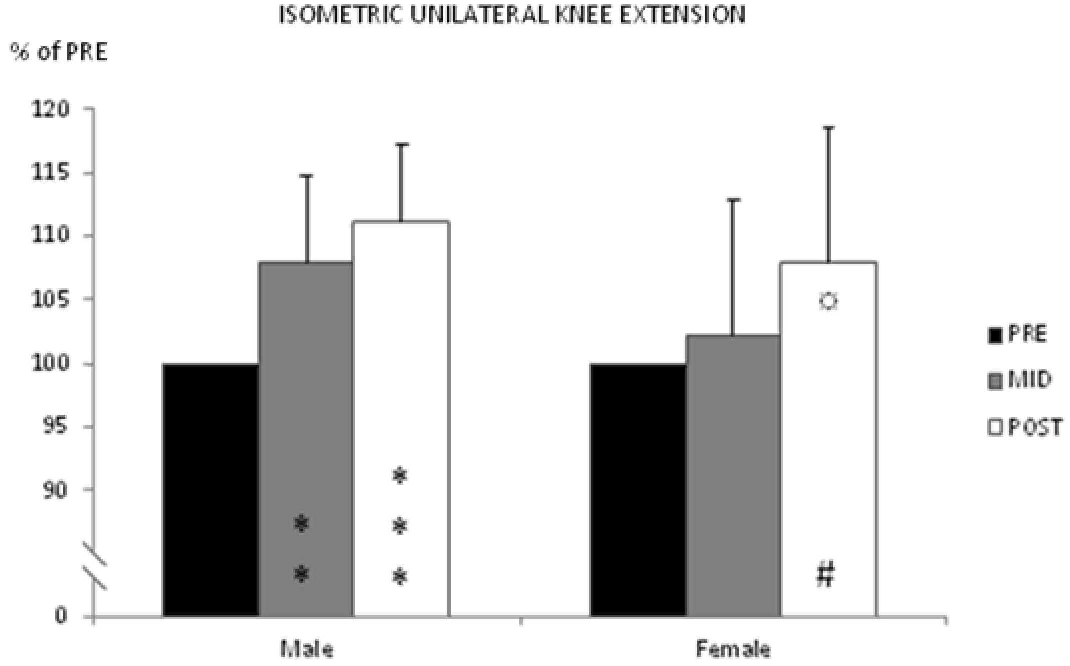


FIGURE 23. Changes in unilateral isometric maximal knee extension force expressed relatively to PRE values in both sexes. **p≤0.01, ***p≤0.001 refers to significant differences, and #p=0.058 refers to a statistical trend compared to PRE values. ¤p≤0.05 refers to significant difference compared to MID values.

Isometric knee flexion. In isometric unilateral knee flexion males had significantly greater force production at pre- (M: 413±64N; F: 315±45N, p≤0.001), and post-measurements (M: 449±68N; F: 345±36N, p≤0.001).

Males showed a statistical trend by improving from pre- to mid-measurements 7.0% (±10.9, p=0.055) (figure 24). The overall improvements from pre- to post-measurements were found to be significant for males (9.0±8.6%, p≤0.01) but not for females (10.9±15.8%, p=0.087). There were no statistically significant differences between groups' relative improvements at any time point.

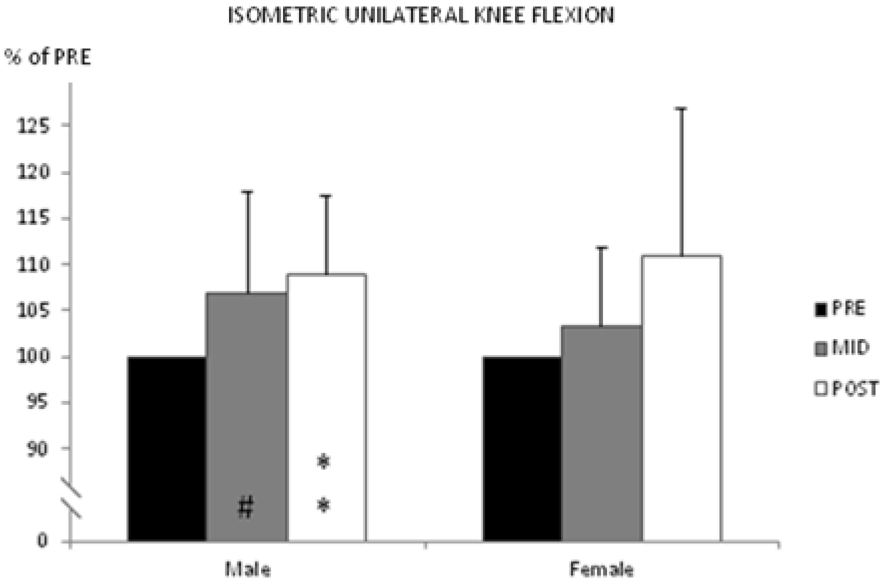


FIGURE 24. Changes in unilateral isometric maximal knee flexion expressed relatively to PRE values in both sexes. **p≤0.01 refers to a significant difference, and #p=0.055 refers to a statistical trend compared to PRE values.

Concentric bilateral leg press. Mean maximal concentric bilateral leg press values were significantly greater in men than in women at pre- (M: 166.0±25.6kg; F: 119.4±17.7kg, p≤0.001) and post-measurements (M: 179.8±24.1kg; F: 127.5±21.0kg, p≤0.001).

Both groups improved statistically significantly from pre- to post-measurements (Male: 8.7±4.7%, p≤0.001; Female: 6.6±3.9%, p≤0.01) (figure 25). There were no significant differences between relative improvements of the groups. In males there were significant correlation between changes in CMJ and changes in dynamic leg press 1RM (r=0.752, p=0.012) (figure 26).

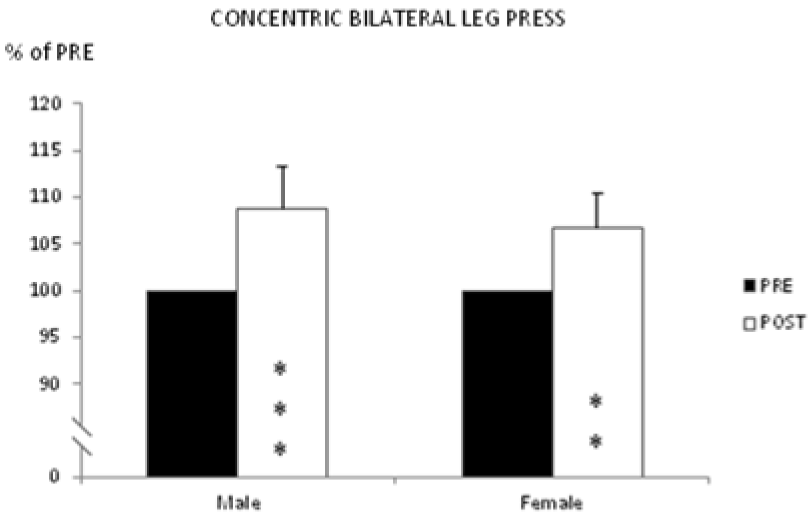


FIGURE 25. Changes in bilateral concentric 1RM expressed relatively to PRE values in both sexes. **p≤0.01, ***p≤0.001 refers to significant differences compared to PRE values.

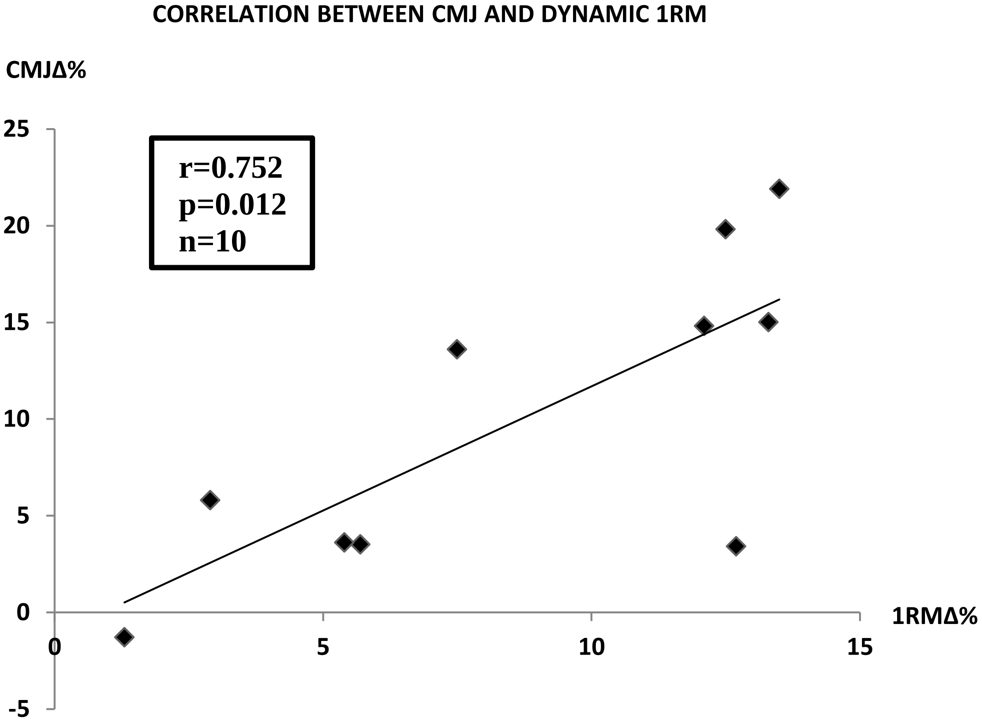


FIGURE 26. Correlation between changes in CMJ and changes in dynamic leg press 1RM in males (r=0.752, p=0.012).

7.2 3K time-trial

There were no significant differences between groups in 3K running time neither in the pre- nor post-measurements (table 9). From pre- to post-measurements, males decreased their 3K running time by an average of -2.2%±3.1 (-19.3s±26.4), whereas females decreased their running time by an average of -2.0%±1.9 (-16.9s±16.0). Both of these were found to be statistically significant ($p \leq 0.05$), but no significant differences were found between groups.

TABLE 9. 3K time-trial (TT) results and changes (presented in seconds and percentage) in PRE and POST-measurements. P-values present the statistical significance (*$p \leq 0.05$). (Males: n=10, Females: n=7)

Group	TT PRE (s)	TT POST (s)	Δ (s)	Δ (%)	p-value
Male	786.6 (±78.8)	767.3 (±61.6)	-19.3 (±26.4)	-2.2 (±3.1)	0.046*
Female	803.5 (±85.4)	789.1 (±81.7)	-16.9 (±16.0)	-2.0 (±1.9)	0.032*

8 DISCUSSION

The present study investigated the effects of the 10-week maximal and explosive strength and high-intensity endurance training period on neuromuscular performance and 3K time-trial running performance in males and females. The main findings in this study were:

1) Both sexes improved their neuromuscular performance due to combined maximal and explosive strength and high-intensity endurance training.

2) Both sexes improved significantly their 3K time-trial running performance.

3) There were no significant differences between sexes in the improvements or changes during the 10-week training period. However, neuromuscular adaptations seemed to be more systematic in males.

8.1 Neuromuscular performance

8.1.1 Force production

As expected, males presented greater absolute force values in all variables measured at pre, mid and post in all executed neuromuscular measurements. Males showed greater body weight and lower fat percentage, which would suggest that they also had more muscle mass, and similar statements have been made before in scientific studies (Brooke & Engel 1969). Both sexes demonstrated significant improvements, however, these improvements were found to be more systematic in males. Also, males seemed to improve their neuromuscular performance more during the first five weeks of training, whereas improvements in females seemed to occur mostly after the mid-measurements.

Isometric bilateral leg press. Due to combined training both sexes have been reported to improve their isometric leg extensor force (Guadalupe-Grau et al. 2009), and this study supports these findings. The magnitude of improvements is supported by previous studies as well (Häkkinen et al. 2003; Taipale et al. 2013; Eklund et al. 2015), when comparing results obtained from similar periods of training in weeks, at least in males. Males improved through the whole 10-week training period, whereas females showed increases in force production only from the mid- to post-measurements. Males may have experienced some level of interference from the endurance training after five weeks of training, however, since there were no strength and endurance only groups, too direct conclusions cannot be made. This was not noticed in females. Since females did not improve during the first five weeks, it is possible that the training was not stressful enough during the first five weeks to create positive adaptations. Females have been reported to be more fatigue resistant (Häkkinen 1993), which could be the explaining factor why the training would not have been stressful enough. As the training period continued, loads were increased, which then led to improvements in females as well. It is also possible that the endurance training may have interfered the adaptations from strength training in females during the first five weeks of training. This seems unlikely since females were capable of improving their neuromuscular performance later on when training intensity was increased. Another reason could be that females may have needed more time to familiarize themselves with this type of strength training modality.

Isometric unilateral knee extension. The results obtained from isometric unilateral knee extension measurements seem to be similar to results obtained from the isometric leg press. This seems realistic, since these actions both rely at least partly on strength of quadriceps muscles. In addition, there is a similar pattern between these tasks, since females’ improvement is noticed in the latter five week period. Interestingly, this specific task was not trained during training period. However, most of the movements performed during the training period required action from quadriceps muscles, and thus improvements in this measurement were expected for both sexes. Also, the improvements in isometric knee extension force are at similar magnitude compared to previous studies (McCarthy et al. 1995; Aagaard et al. 2010; Eklund et al. 2015). Males improved significantly their muscle activation from pre- to post-measurements during isometric knee extension, which suggests that the improved force production was at least partly due to improved neural drive.

Isometric unilateral knee flexion. The training for knee flexor muscles differed from other actions applied for lower extremities strength training, since it was performed as hypertrophic training. However, the action performed during training and the measurement applied, were fairly similar. They both were performed in a seated position, and thus the correlation between these two should be fairly high, based on previous studies conducted regarding the correlation between dynamic and isometric knee flexor measurements (Lord et al. 1992). Nevertheless, maximal strength training has been stated to lead to even greater increases in force production than hypertrophic training (Heggelund et al. 2013). The fact that the trained action was performed in a similar position as the measurement for knee flexor force is probably one of the main reasons for this magnitude of improvements. Even knee flexion showed the same pattern that males improved from the beginning, but increases in females appeared mostly during the latter five week period. Loads were increased throughout the study, so the training should have been stressful enough to create some neuromuscular adaptations. In addition, it seems that males experienced some level of inhibition after five weeks of training. This could be due to the interference of endurance training, or due the fact that the greatest neural adaptations usually occur during the beginning of training period, and the magnitude of improvements in force may not be as great after first month (Moritani & DeVries 1979). Even though the results for females were not found to be statistically significant, the pattern looks similar to isometric leg press and knee extension, which supports the previous discussion that the training may not have been stressful enough for females to gain positive neuromuscular adaptations. After all, females have been reported to be more fatigue resistant than males (Häkkinen 1993).

Concentric dynamic bilateral leg press. The dynamic leg press one repetition maximum (1RM) was the only dynamic maximal strength measurement in the study, and the used leg presses in training and measurements were fairly similar. Even the starting knee angle was measured for training and, thus, improvements were expected. The improvements seem realistic, and similar improvements have been stated in previous studies (Collins & Snow 1993; Taipale et al. 2014; Eklund et al. 2015). However, even greater improvements have been presented (Bell et al. 2000), but in untrained individuals. In addition, even minor improvements have been presented in endurance trained individuals (Mikkola et al. 2011), and the subject group of this study might be more similar to endurance trained than untrained individuals. Since dynamic 1RM was not measured during the mid-measurements, it is impossible to say if the improvements in this measurement behaved the same way the improvements in isometric measurements did. There was a significant correlation between changes in dynamic leg press 1RM and changes in CMJ in males. This was expected, since both of these are dynamic movements. Interestingly, there was no correlation in females, even though they improved significantly in the CMJ and 1RM as well. This means that the females who improved jumping height the most, may have improved only minimally in dynamic maximum strength. However, Newton et al. (2006) presented that female volleyball players were capable of improving their vertical jump performance due to ballistic resistance training, and the changes in overall jump performance were reflective of changes in power output and peak velocity during loaded squat jumps, countermovement jumps, and drop jumps. Thus, dynamic maximum strength and power related movements, such as countermovement jump, require different type of force production and might not correlate with each other.

8.1.2 Countermovement jump

Countermovement jump. Based on literature the most common problem with combined strength and endurance training is the interference in fast force production (Dudley & Djamil 1985). The current study presented positive adaptations regarding this parameter, as both sexes improved their CMJ performance. The hypothesis was that males might experience greater improvements in power related movements, such as CMJ, due the higher proportion of fast-twitch fibers (Miller et al. 1993). However, males had higher absolute values in CMJ height at all measurement time points, but there does not seem to be any differences in improvements when evaluated as relative values. From subjects who participated in this study, females seemed to be relatively more endurance trained than their male counterparts. Thus, it is surprising that both sexes improved similarly in this specific task. However, Newton et al. (2006) have reported that females can improve their vertical jump significantly in as short time frame as four weeks, and in addition, Häkkinen (1993) presented similar improvements in females vertical jump performance due to explosive strength training. It is noteworthy that both of these studies (Häkkinen 1993; Newton et al. 2006) were conducted with female volleyball players and there were no endurance training involved. It is also possible that males experienced some level of interference due the endurance training, which could explain these results. However, without endurance and strength only groups this is impossible to prove. After all, the results from CMJ differ from other neuromuscular measurements applied, since it was the only measurement where females improved significantly between the pre- and mid-measurements. Based on this it seems that the intensity and volume of plyometric training applied in this current study were high enough to produce positive adaptations in both sexes. Even previous studies have stated similar improvements in power production in relative values (Kraemer et al. 2001; Delmonico et al. 2005; Newton et al. 2006).

It actually seems that the greatest increases were already obtained during the first five weeks of training in both groups. Since strength and plyometric training were fairly new training modalities for these individuals, there might be some learning effect accompanied along with improved motor unit firing rate and synchronization. This learning effect includes the learning of correct motor control during the CMJ performance. The improvements seem to be similar in magnitude what other studies have presented due to combined strength and endurance training (McCarthy et al. 1995; Mikkola et al. 2011; Taipale et al. 2014), and as stated before there was a significant correlation between changes in CMJ and changes in dynamic leg press 1RM in males. The measured dynamic leg press was performed as concentric maximum, but CMJ allows individual to apply stretch-shortening cycle (SSC) and elastic energy to enhance force production. However, since there was a correlation between these two, it seems that the improved CMJ performance in males was not only due to improved SSC and enhanced ability to use elastic components of the muscle. So it seems that the improved dynamic force production was at least partly the reason for improvements in CMJ performance in males. Since this was not the case in females, they may have actually improved their ability to use the SSC and elastic components in the CMJ performance.

Furthermore, Liljedahl et al. (1999) hypothesized, that smaller areas of type II fibers and the lower activity of lactate dehydrogenase, that are usually noticed in females, may be result from less frequent activation of type II fibers, and due to this females could respond to sprint training to an even greater extent than males. This might apply to the results in this study, however these parameters were not investigated. Since both sexes improved their CMJ throughout the study, it seems that there was no interference effect from endurance training accompanied in this performance.

8.2 Endurance performance

Both sexes improved their 3K time-trial performance significantly. Considering that these individuals had already some training background, and much of it was even endurance based, it seems that the intervention was successful in this regard.

Based on the neuromuscular measurements the improved running performance could be due to enhanced running economy, but there might be some cardiorespiratory improvements as well. Running economy, however, was not investigated in this study. Many previous combined strength and endurance studies have presented improvement in VO_{2max} (McCarthy et al. 1995; Paavolainen et al. 1999; Mikkola et al. 2012; Cantrell et al. 2014), and even in both sexes (Bell et al. 1997; Marta et al. 2013). Nevertheless, this training program did not primarily concentrate on improving maximal oxygen uptake, since subjects completed 4x4min endurance training sessions for improving VO_2max (Helgerud et al. 2007) only once a week, and the other endurance training session was more or less speed endurance training session.

There were no significant differences between sexes regarding 3K time-trial performance. Females have been stated to have some advantages regarding ultra-long endurance performances (Tarnopolsky & Saris 2001; Rust et al. 2013), though this distance is not comparable to ultra-long distances. However, the running times of male subjects were not noted to be significantly faster than females, even though males have been reported to have higher maximal aerobic power (Hopker et al. 2010), even relative to fat free mass (Davis et al. 2006). So it seems that the female subjects in this study might have actually had a relatively stronger endurance background than their male counterparts. However, this was expected since the exclusion criteria for recruitment were the same for both males and females.

It has been stated in previous studies that rate of force development (RFD) could be the factor that correlates the most with economy of endurance performance (Hoff et al. 2002). This could be one explaining factor to the improvements in endurance performance in this study, since both sexes improved significantly their CMJ performance, which demonstrates power production capabilities. The rest of the neuromuscular measurements actually support this, since females did no present as systematic improvements as males.

However, the results obtained from this study suggest that combined maximal and explosive strength and high-intensity endurance training is an efficient training modality for improving endurance performances.

8.3 Strengths and limitations of the study

Strengths of the study. The present study was fairly well established and showed positive results regarding neuromuscular and running performance. The training program was proven to be productive and there was only one drop-out during the 10-week intervention. In addition, the research staff was experienced and measurement protocols were standardized and valid. The training sessions were mostly supervised and data was collected from each training session.

Limitations of the study. Some of the subjects had never done proper strength training, and thus part of the training period was basically used for familiarization with strength training itself. The amount of subjects included was enough for a scientific study, however more subjects would have given a more reliable sample. There is also a need of the control, endurance only and strength only groups.

The subjects were allowed to perform endurance training by themselves, and just deliver the heart rate values of the each endurance training session, so it is uncertain how individual training sessions were actually performed. The knee angle during back squat was not measured, and thus not standardized during training. It seemed that while training season progressed, and weights were increasing, so did the knee angle during squats. Thus the knee angle during squat may not have been the planned 100 degrees, which could have affected the results obtained from neuromuscular measurements. Both sexes improved their countermovement jump significantly, so it seems that the depth of squats performed during training period might have been as deep as during countermovement jump. It has been actually reported that between isometric leg extension force and countermovement jump height may correlate better with each other when knee angle is closer to 120 degrees (Marcora & Miller 2000), and this knee angle could have actually been closer to the knee angle during training in this study.

Practical applications. The present study indicates that combined maximal and explosive strength and high-intensity endurance training can be effective training modality to improve neuromuscular and running performance, even in recreationally trained population. The magnitude of the adaptations still leaves a question whether the strength training should be maximal, explosive or even hypertrophic to improve the most from combined training. In addition, there is a similar dilemma between high- and low-intensity endurance training. The improvements in the CMJ performance suggest that this type of endurance training does not inhibit the adaptations of power production neither in males or females. Based on the present study strength training should be a part of training program, even if the focus is on endurance performance. It is possible that there are some differences between sexes, and males may experience some level of interference when training intensity is high, but, females may need to train with higher intensity to even gain neuromuscular adaptations from this type of combined training. However, since there were no endurance and strength only groups, further study is needed and too direct conclusions regarding interference of endurance training should not be made.

9 CONCLUSIONS

In conclusion, both sexes improved their neuromuscular and 3K time-trial performance. There were no statistically significant differences between sexes in neuromuscular adaptations, however, males seemed to present more systematic improvements. In addition, improvements in males seemed to appear mostly during first five weeks of the training period, while improvements in females seemed to appear mostly during the latter five weeks of the training period. It is possible that males experienced some level of interference during the latter five weeks due to endurance training, whereas the training may not have been stressful enough for females during the first five weeks to create positive neuromuscular adaptations. However, since there were no endurance and strength only groups, it is impossible to say if these results are due to interference effect, and too direct conclusion should not be made. These findings present that combined maximal and explosive strength and high-intensity endurance training seems to be efficient training modality even for recreationally trained population regardless of the sex.

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