ACUTE HORMONAL AND MUSCULAR RESPONSES AND RECOVERY: CHRONIC ADAPTATIONS TO SINGLE-SESSION COMBINED STRENGTH AND ENDURANCE TRAINING WITH REGARD TO ORDER EFFECT

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ABSTRACT

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Combining both strength (S) and endurance (E) exercise loadings into a single training session can be considered to be of interest e.g. for time management purposes. However, the first loading in a combined session tends to produce notable acute fatigue responses, which can lead to the second loading being performed in a compromised state. Research on fatigue and recovery from a combined session with different loading orders is currently scarce, with even less attention given to the acute responses. Thus, this study investigated the long-term adaptations in the acute responses of a combined strength and endurance loading and whether or not there is an order effect.

A total of 29 male subjects completed the study which consisted of 24 weeks of combined strength and endurance training. All subjects participated first in the basal measurements of strength and endurance and were then assigned to one of the two groups: performing endurance before strength (E+S) or vice versa (S+E). Measurements of acute responses and recovery took place in the first week of training (*0 weeks*) and at the end of the study (*24 weeks*). The acute loadings were completed in an assigned order. The endurance loading consisted of 30 minutes of continuous endurance exercise on a bicycle ergometer at 65% of W_{max}. The strength loading consisted of 3x40% 1RM, 4x75-90% 1RM and 4x75-80% 1RM. Maximal voluntary isometric contractions (MVC) and force production in 500ms (MVC 0-500ms) as well as serum testosterone and cortisol concentrations from a venous blood sample were measured before the loading (Pre), after the first part (E or S) of the loading (Mid), after completion of the loading (Post) as well as during recovery (at 24h and 48h).

Both groups experienced a significant ($p<0.001$) decline in MVC at 0 and 24 weeks at Post. A significant-between group ($p<0.05$) difference was observed at Mid-loading at 0 and 24 weeks. At 24 weeks S+E was significantly ($p<0.05$) more fatigued in terms of force production at Mid and Post compared to 0 weeks. In MVC 0-500ms a significant ($p<0.05$) between-group difference was found at Mid at 24 weeks. E+S was slightly more fatigued at 0 weeks Post than S+E ($p<0.001$ vs. $p< 0.05$). Both were equally fatigued at Post at 24 weeks ($p<0.001$). S+E was significantly ($p<0.05$) more fatigued at Post at 24 in comparison to 0 weeks. A significant ($p<0.05$) response in testosterone was observed at Mid for E+S (0 and 24 weeks). At 48h at 0 weeks E+S showed significantly ($p<0.05$) lowered testosterone levels. At Mid at both 0 and 24 weeks a significant ($p<0.05$) cortisol response in E+S and a significant ($p<0.05$) between-group difference was noted. Both groups experienced significant ($p<0.001$) increases in training induced changes in maximal dynamic 1RM.

The findings provide some evidence for an order effect in terms of adaptations to the acute responses of a combined strength and endurance loading. However, no order effect was found for training induced adaptations in maximal dynamic 1RM.

Keywords: fatigue, recovery, order effect, interference effect, combined training, strength, hormones

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I would like to express appreciation towards all the people who were involved in the research project at any phase, and who thus made the current thesis possible. I also wish to express my biggest gratitude to the supervisor of my thesis, Professor Keijo Häkkinen, who allowed for me to participate in the conduction of the broader study and who continuously encouraged me towards self-improvement and development in the field of sport sciences.

LIST OF ABBREVIATIONS

1 RM – One repetition maximum

C - Cortisol

E – Endurance training

E+S – Combined training, endurance before strength

hGH – Human growth hormone

HR – Heart rate

La^- – Lactate (ions)

MVC – Maximal voluntary isometric contractions

RFD – Rate of force development

S – Strength training

S+E – Combined training, strength before endurance

T - Testosterone

T/C – Testosterone-cortisol ratio

VO_{2max} – Maximal oxygen uptake

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1 INTRODUCTION

Both strength and endurance are to be considered to be of importance both in terms of athletic performance as well as from a health perspective and combining the two training modalities into the same training session can be a reasonable solution from the time-management and convenience point-of-views. However, the first loading in a combined strength and endurance session tends to produce notable acute fatigue responses independent of the loading sequence (Cadore et al. 2012), which can possibly lead to the second loading being performed in a compromised state. This raises questions about the relative adaptations to strength and endurance performances in a long-term perspective, if the latter loading is constantly impaired.

Research concerning single-session combined strength and endurance training and the effect of intra-session loading sequence on the differences in both acute responses and long-term adaptations is currently scarce. However, as it appears that the main maladaptation from combined training is directed towards the development of strength (Hunter et al., 1987; Häkkinen & Pakarinen 1995; Kraemer et al. 1995) it is likely that the interference stems from an endurance loading induced response causing inhibition in the force-generating properties of the neuromuscular system (de Souza et al. 2007; Häkkinen et al. 2003).

It appears that the type of endurance exercise is of key importance with regard to the magnitude of impairments on subsequent strength exercise, whereas the effect of a strength loading on subsequent endurance performance appears to be less specific (de Souza et al. 2011). Low intensity and moderate duration endurance exercises do not seem to interfere with subsequent strength performance regardless of the type of strength loading. Conversely, aerobic exercise at intensities close to VO_{2max} is likely to produce peripheral fatigue impairing strength performance (de Souza et al. 2007). Endocrine responses with regard to endurance exercise does not negatively affect the acute testosterone response to resistance exercise, as far as moderate-intensity, continuous endurance exercise is concerned (Cadore et al. 2012).

Less attention has been given to the long-term adaptations of the acute responses of a combined strength and endurance loading, and how these adaptations are affected by the intra-session loading sequence. Thus, this study addressed the acute hormonal and muscular responses and recovery following a combined strength and endurance loading. Attention was paid to the chronic adaptations of the acute responses as well as to the order effect of the intra-session loading sequence.

2 ENERGY SYSTEMS AND ACUTE FATIGUE RESPONSES TO EXERCISE

The human body relies on a combination of different systems to provide energy (adenosine triphosphate, ATP) for muscle contractions (ie. physical activity), depending on the type and duration of the activity in question (figure 1, table 1) (Gastin, 2001). The combined amounts of cell ATP and cell phosphocreatine (PCr) are used for maximal and short (8-10 seconds) bursts of muscle work, whereas prolonged activities rely on the aerobic system to oxidize ingested foodstuffs into ATP. This system provides energy as long as nutrients last. (Guyton &Hall 2000, pp. 969-971; Gastin 2001.)

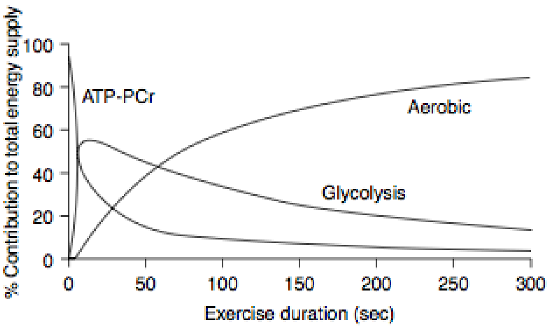

Fig. 1 Relative energy system contribution to the total energy supply for a given duration of maximal exercise (Gastin 2001).

The glycolytic system generates energy by degradation of glycogen or glucose to ATP, which at light and moderate intensities functions with the aid of oxygen (*aerobic glycolysis*) providing energy for 1.3-1.6 minutes (Guyton &Hall 2000, pp. 970; Gastin 2001). Strenuous exercise raises the energy needs to exceed the supply of oxygen (*anaerobic glycolysis*) and results in byproduct-accumulation of lactate and hydrogen ions. The extent of the usage of glycolysis is thus reflected in blood lactate concentrations (Gastin 2001), but absolute values do not correspond to the same exercise intensities between individuals (Tesch et al. 1982; Held & Marti, 1999).

Whereas lactate serves as an important source for further energy turnover, the acidity caused by hydrogen accumulation is one of the mechanisms that initiates the onset of exercise-induced fatigue in the human body (Gladden 2000; McArdle et al. 2001, pp. 141-144; van Hall 2010). Referred to as an exercise-induced acute decline in performance, fatigue can be detected in test measures such as compromised muscle force and power (eg. Häkkinen & Pakarinen 1993; Knicker et al. 2011).

Depending on the type of exercise performed, fatigue can also be of neural origin rather than metabolic. Either the central (CNS) or peripheral (PNS) nervous system can serve as a site of fatigue. Central fatigue is a result of loss of motoneuronal output (Gandevia, 2001), whereas factors contributing to peripheral fatigue include impairments in muscle contractility and changes in intramuscular pH and amounts of PCr (Miller, 2006).

2.1 Acute responses to strength loading

Strength loadings of different types (Häkkinen et al. 1988), volumes (Häkkinen & Pakarinen 1993) and intensities produce vastly different acute responses (eg. McCaulley et al. 2009), with the differences also being related to different training backgrounds (Häkkinen & Myllyllä 1990). Loads are commonly expressed as numbers or percentages of *repetition maximums* (RM), and the load a person can successfully lift only once is referred to as a *1 RM*. Accordingly, 50% of 1 RM refers to using a load equivalent to half of the determined 1 RM load as resistance. (Kraemer & Häkkinen 2002, pp. 50-51.)

The demands of a loading can be shifted towards either a more metabolically or neurally demanding nature by manipulating intensities as well as the number of repetitions, sets (Häkkinen 1994) and the length of rest periods (McCaulley et al. 2009). The different modes and details of resistance exercise loadings are found in table 1.

Table 1: Intensities, rest periods and number of repetitions of different resistance exercise modes. (Compiled from Kraemer & Häkkinen 2002, pp. 50-51; Kraemer & Ratamess 2004).

Type of loading	Intensity (% of 1 RM)	Repetitions per set	Length of rest (s)	Neural-metabolic continuum
Power (explosive)	30-60 %	8-10	180	Neural
Strength	70-100 %	1-6	120-180	↓
Hypertrophy	70-80 %	6-12	60-90	↓
Strength endurance	50-70 %	15+	moderate repetitions < 60 high repetitions 60-90	Metabolic

2.1.1 Force production

The acute fatigue induced by resistance loading can be detected as an impaired force production capability (eg. McCaulley et al. 2009; Linnamo et al. 1998; Ahtiainen et al. 2004). The neuromuscular response and the magnitude of the impairment depend on the type loading and thus, all the variables it is based on (table 1) (Linnamo et al. 1998; McCaulley et al. 2009).

Greater losses in maximal voluntary isometric force production are associated with metabolically demanding resistance exercise rather than with predominantly neurally stressing loadings (Linnamo et al. 1998; Ahtiainen et al. 2004; Ahtiainen et al. 2005; McCaulley et al. 2009). The constant decline in maximal force production throughout a heavy loading session is illustrated in figure 2 (Häkkinen 1994).

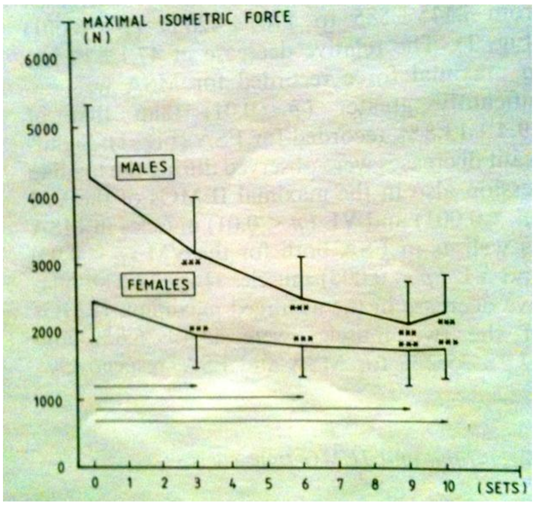

Fig. 2 The changes in bilateral maximal isometric force during the course of a heavy resistance hypertrophic training session (Häkkinen 1994).

Heavy resistance hypertrophic loading–induced fatigue is also reflected in impairments in rapid force production (fig 3) (Häkkinen 1994; Linnamo et al. 1998). The rate of force development (RFD) is significantly affected by hypertrophic and strength resistance loadings, whereas light and explosive loading results in less dramatic impairments (Linnamo et al. 1998; McCaulley et al. 2009).

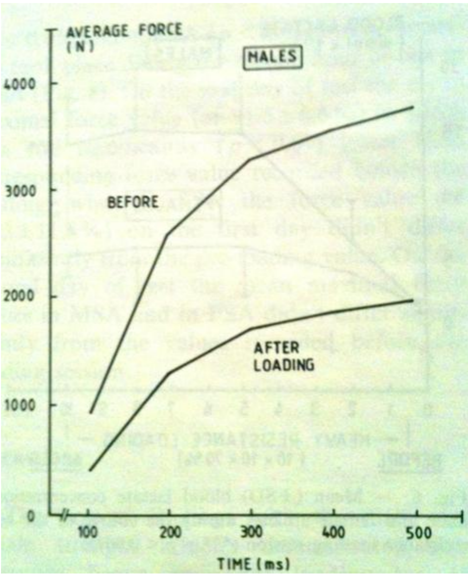

Fig. 3 Average force-time curve of the leg extensor muscles in rapidly produced maximal voluntary isometric leg extension in male athletes before and immediately after a heavy resistance loading session (Häkkinen 1994).

The fatigue-related impairments in force production in response to a given loading seem to be of similar nature in non-athletes as well as in individuals with previous strength training experience. The responses tend to be of a somewhat greater magnitude in the strength trained (eg. Ahtiainen et al. 2004), with the underlying causes composed of differences in either neural fatigue, metabolic factors or a combination of both (Häkkinen 1993).

2.1.2 Lactate responses

Elevations in blood lactate concentrations can be noted after a single exercise bout (Kraemer et al. 2009) with high loading-volumes, long working periods and short rest periods accounting for further increases (Häkkinen & Pakarinen 1993; Crewther et al. 2006). Thus, explosive loadings tend not to produce significant lactate responses, whereas hypertrophic and strength loadings typically result in remarkably elevated blood lactate concentrations (figure 4) (Linnamo et a. 1998; McCaulley et al. 2009).

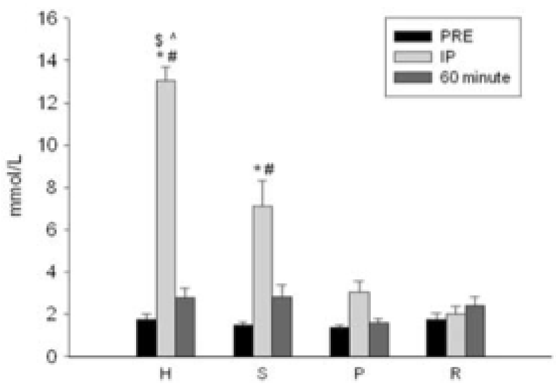

Fig. 4 Comparison of lactate responses to hypertrophic (H), strength (S) and power (P) resistance loadings and resting (R) conditions. (McCaulley et al. 2009).

In addition, the lactate responses induced by heavy resistance hypertrophic loading have been found to correlate well with individual decreases in maximal force (Linnamo et al. 1998; Ahtiainen et al. 2004). The nature of lactate responses induced by heavy strength loading seem to be independent of training status (Kraemer et al. 1999; Ahtiainen et al. 2004; Ahtiainen et al. 2005).

2.1.3 Recovery from strength loading

The absolute time needed for maximal force production to fully recover depends on the type of loading used to induce fatigue (eg. Linnamo et al. 1998). Light and explosive resistance exercise impairs the force production for two hours, whereas 48-72 hours may be required for complete recovery after very strenuous and metabolically very demanding loading (fig 5) (Häkkinen 1994; Linnamo et al. 1998; Ahtiainen et al. 2004; McCaulley et al. 2009). The recovery of force production following heavy strength loading follows similar patterns for both strength trained athletes and non-athletes (Ahtiainen et al. 2004).

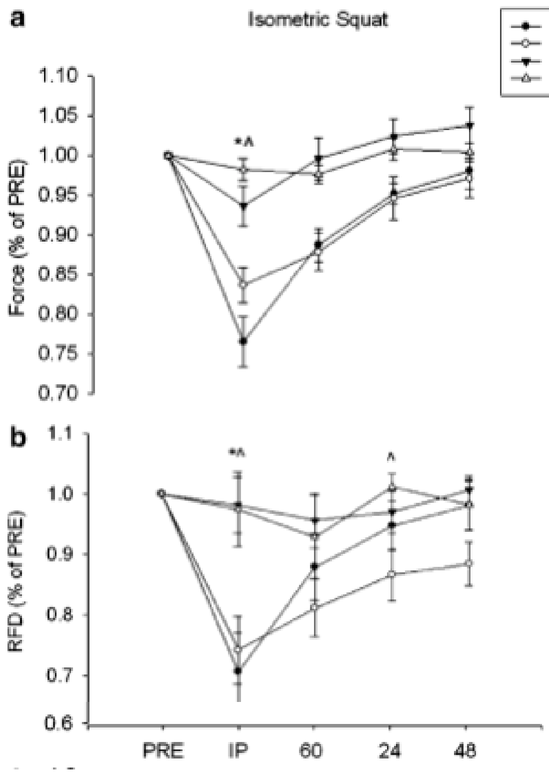

Fig. 5 Comparison of the mean percent of baseline isometric squat force (a) and RFD (b) - values before, immediately after, 60 minutes after, 24hrs after and 48hrs after different strength loading protocols (hypertrophy (H), strength (S), power (P)), and rest (R) conditions during an isometric squat test. (Modified from McCaulley et al. 2009.)

Worth noting in figure 5 are the differences between the recovery of maximal force and the recovery of RFD following different loadings. Despite the immediate fatigue being slightly smaller in response to strength loading, the recovery of RFD is slower than following hypertrophic resistance exercise. This difference has been suggested to be an indication of the strength protocol having a greater acute disruptive effect on the function of the nervous system. (McCaulley et al. 2009.)

In terms of monitoring recovery, it is important to note the time-of-day dependency that, to some extent, exists for recovery of force and power. Complete recovery time for isometric maximal voluntary contractions has been found to be greater when strength exercises are performed in the morning than in the afternoon. (Nicolas et al. 2007; Weipeng et al. 2011.)

2.2 Acute responses to endurance loading

Fatigue induced by an endurance loading is highly dependent on training type and intensity. Prescription of endurance exercise is commonly based on ranges of heart rate relative to maximum as well as blood lactate concentrations (de Souza et al. 2007; Seiler 2010). Table 2 presents the guidelines for endurance exercise based on the before mentioned parameters and their relation to oxygen consumption.

Table 2: Intensity scale for endurance training prescription and monitoring used by the Norwegian Olympic Committee based on years of testing of cross-country skiers, rowers and biathletes. (Modified from Seiler 2010).

VO_2 (% max)	Heart rate (% max)	Lactate ($mmol \cdot L^{-1}$)	Typical accumulated duration within zone
50–65	60–72	0.8–1.5	1–6 h
66–80	72–82	1.5–2.5	1–3 h
81–87	82–87	2.5–4	50–90 min
88–93	88–92	4.0–6.0	30–60 min
94–100	93–100	6.0–10.0	15–30 min

Furthermore, a relationship exists between lactate concentration to work intensity and thresholds between aerobic and anaerobic conditions, as is shown in figure 6.

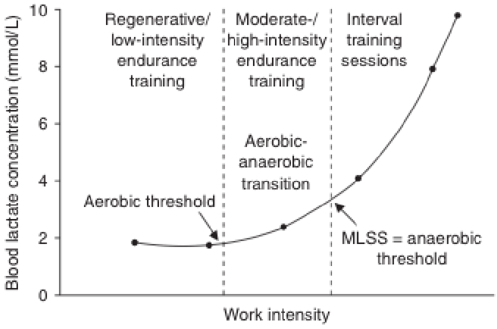

Fig. 6 A typical lactate-workload graph showing the aerobic-anaerobic transition to derive endurance training intensities for different intensity zones. (Faude et al. 2009).

2.2.1 Force production

A major factor affecting the acute responses in force production following an endurance loading, is whether the endurance loading is performed continuously or intermittently (de Souza et al. 2007). Table 3 summarizes the acute effects of different endurance loadings on both maximal strength and strength endurance performance.

Table 3: The acute effect of two different types of endurance loadings on acute strength performance. Compiled from de Souza et al. 2007.

	Intermittent endurance exercise	**Continuous endurance exercise**
Effect on maximal strength	Near significantly impaired	No changes
Effect on strength endurance	Significantly impaired	No changes

The acute fatigue effects of endurance exercise on lower body force production is evident after treadmill running as well as bicycle ergometer exercise (Leveritt & Abernethy 1999; de Souza et al. 2007; Theurel & Lepers 2008). Theurel & Lepers (2008) reported acute impairments in maximal voluntary contraction torque (MVC) following a cycling protocol, with the magnitude of decreases dependent on the type of cycling. A protocol with varying power output had a greater impact on MVC’s than a constant power-output protocol (figure 7) (Theurel & Lepers 2008), which underlines the effects of endurance exercise type and intensity on subsequent strength performance.

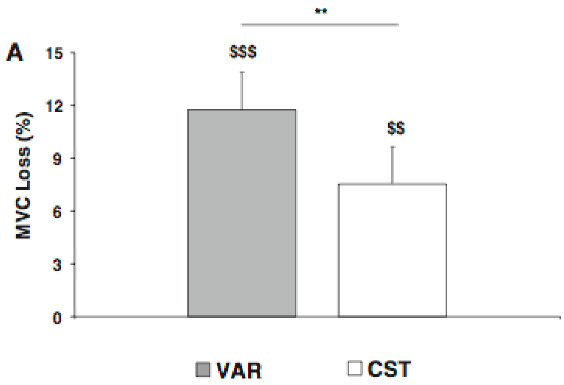

Fig. 7 Reductions in maximal voluntary contraction torque after cycling with a variable (VAR) power output protocol versus a constant power output protocol (CST) in well-trained male cyclists. (Theurel & Lepers 2008).

2.2.2 Lactate kinetics in endurance exercise

Endurance exercise conditions, intensity and duration are reflected as elevations in blood lactate concentration (Bouckaert et al. 1990; Nummela et al. 2007; Beneke et al. 2011). The greater lactate responses to high intensity and incremental, variable power output endurance exercise serve as indicators of a possibly greater anaerobic contribution to energy production in comparison low-intensity and constant output loadings (Leveritt & Abernethy 1999; Theurel & Lepers 2008). Figure 8 presents a typical lactate response to endurance exercise with incremental intensity in relation to exercise duration.

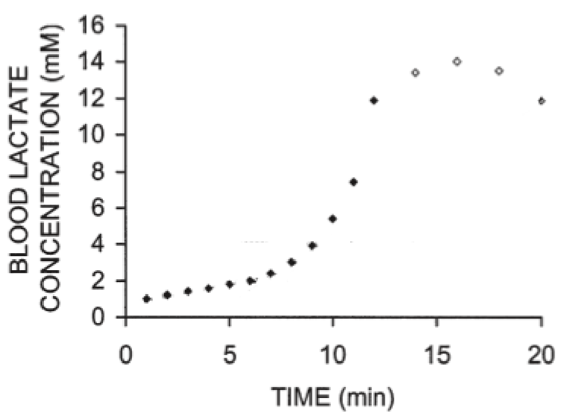

Fig. 8 A typical lactate curve in response to incremental endurance exercise in relation to performance duration. (Modified from Svedahl & McIntosh 2003).

The elimination process of accumulated blood lactate during recovery appears to be more efficient when active recovery is performed (Siegler et al. 2006; Menzies et al. 2010). The rate of clearance is related to the intensity at which the active recovery is performed, with maximum clearance occurring at intensities close to the lactate threshold (Menzies et al. 2010).

3 ACUTE ANABOLIC AND CATABOLIC HORMONAL RESPONSES TO EXERCISE

The endocrine system regulates anabolic and catabolic processes in the human body and has, thus, a major role in the physiological responses and adaptations to exercise training. Exercise poses as a stress factor that disrupts the homeostasis which the human body tries to maintain, and the function of the endocrine system as a whole helps the body in adapting to the changing conditions. (Kraemer & Rogol 2005). Different host organs (glands), chemical messengers (hormones) and targets or receptor organs make up the endocrine system and constitute as one of the internal communication systems in the human body (Guyton & Hall 2000, pp. 836; McArdle et al. 2001, pp. 410). The locations of the major endocrine glands are shown in figure 9.

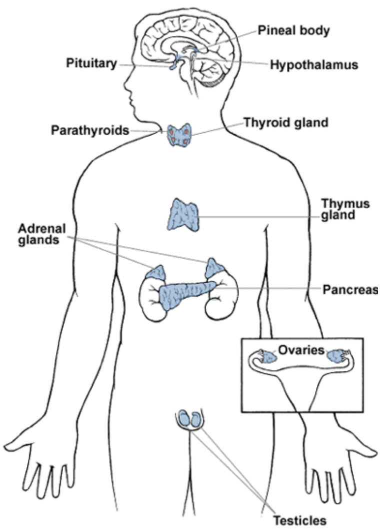

Fig. 9 The major endocrine glands in the human body (American Medical Association).

Hormones initiate reactions by binding with receptors after being secreted into the bloodstream by specific host glands (Guyton & Hall 2000, pp. 836; McArdle et al. 2001, pp. 410). Hormonal release to the blood stream can occur either through a constitutive or regulated release. In a constitutive release, the hormones are released into the bloodstream right after being synthesized, whereas in a regulated release, hormones are briefly stored in the host gland before being released. (Kelly, 1985.) After a hormone binds to a receptor to initiate a specific cellular response, the receptor is considered as occupied, and cannot provide a binding site for any other hormone at that time (Kraemer & Rogol, pp. 18).

Hormonal responses to exercise are mediated by four main determinants: exercise intensity, exercise duration, training status of the individual and the hormonal needs to maintain homeostasis (eg. Viru 1992; Häkkinen & Pakarinen 1993; Viru et al. 1996). Table 4 presents the general properties and functions of the hormones that are of interest in this study.

Table 4: Overview of the general properties of cortisol, human growth hormone, and testosterone. (Compiled from Vanhelder et al. 1985; Staron et al. 1994; Kraemer et al. 1998; Raastaad et al. 2000; McArdle 2001, pp. 415-417; Guyton & Hall 2000, pp. 838; Kraemer & Rogol 2005, pp. 2; Vingren et al., 2010).

Hormone	Effects	Releasing gland	Acute effects of exercise
Cortisol (C)	Promotes fatty acid and protein (muscle) catabolism, inhibits protein synthesis. Conserves blood sugar.	Adrenal cortex	Increases in heavy exercise only. Reflects training stress.
Human growth hormone (hGH)	Stimulates tissue growth.	Anterior pituitary gland	Increases with increasing exercise. Rises with a delay.
Testosterone (T)	Controls muscle size. Modulates muscle mass.	Testes	Increases induced by metabolically demanding resistance exercise.

3.1 Acute hormonal responses to strength loading

The acute hormonal responses associated with a single resistance exercise bout indicate stress and fluid regulation in the body (Kraemer et al. 1999). The magnitude of the responses are dependent on the amount of muscle mass activated, intensity and type of resistance loading and the number of sets and repetitions performed (Vanhelder et al.

1984; Vanhelder et al. 1985; Kraemer et al. 1999; Smilios et al. 2003; Ahtiainen et al. 2004; Linnamo et al. 2005). Thus, the largest acute elevations in testosterone, hGH and cortisol are typically elicited in response to anaerobic resistance exercise of high-volume, moderate or high intensity and short rest periods (Häkkinen & Pakarinen 1993; Smilios et al. 2003; Ahtiainen et al. 2005; Kraemer & Ratamess 2005). The acute hormonal responses seem to be of similar nature independent of subject training status (Ahtiainen et al. 2004), as is illustrated in terms of cortisol responses in figure 10.

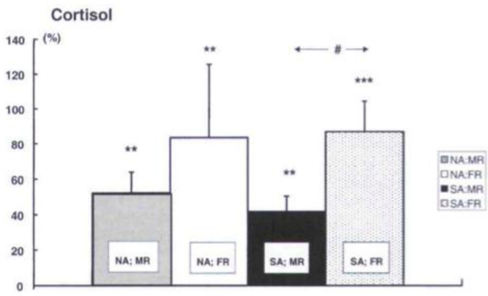

Fig. 10 Relative changes in cortisol concentrations before and after (post 15 min) a forced repetitions (FR) loading protocol and a maximal repetitions (MR) loading protocol in strength athletes (SA) and non-athletes (NA). (Ahtiainen et al. 2005.)

Metabolically demanding resistance exercise loadings that elicit the highest acute hormonal responses are also associated with elevations in blood lactate concentration. Accordingly, blood lactate is strongly suspected to stimulate the secretion of hGH and testosterone (Häkkinen & Pakarinen 1993; Raastaad et al. 2000), with a simultaneous presence of cortisol and lactate also being noted (Ratamess et al. 2005). On the contrary, sub-maximal and explosive protocols that are less taxing on the metabolic system do not seem to result in significant acute hormonal responses (fig 11) (Linnamo et al. 2005; McCaulley et al. 2009).

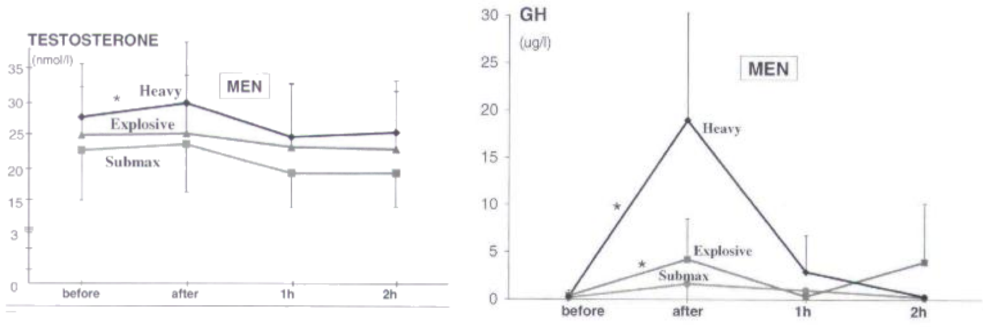

Fig. 11 Concentrations of testosterone and hGH before, during and after heavy, explosive and sub-maximal resistance exercise in men. (Modified from Linnamo et al. 2005.)

3.2 Acute hormonal responses to endurance loading

The endocrine responses to endurance exercise are affected by the intensity, type (intermittent or continuous), and to some extent the duration of exercise (Kuoppasalmi et al. 1981; Gray et al. 1993; Tremblay et al. 2005; Vuorimaa et al. 2008). Intense intermittent, anaerobic exercise results in significantly greater acute hormonal responses than a predominantly aerobic loading, even when the workloads of the loadings are equated (Vanhelder et al. 1984b; Gray et al. 1993; Van Bruggen et al. 2011).

Particularly the hGH responses appear to be sensitive to exercise, as even relatively low intensities of endurance exercise may be enough to elicit responses (Gray et al. 1993). Submaximal endurance loadings tend to produce significant increases in hGH-levels independent of loading duration and training status, with increases evident already after a warm-up (Wilkerson et al. 1980; Viru et al. 2001; Bouassida et al. 2009.) There also seems to exist a relationship between hGH and lactate, as the threshold rise in hGH seems to follow the pattern of blood lactate accumulation during incremental exercise (Chwalbinska-Moneta et al. 1996).

Additionally, hormonal responses to endurance exercise have a tendency to be related to training background (Viru et al. 2001; Vuorimaa et al. 2008). Although endurance-trained athletes respond to steady-state exercise with an increased testosterone response (Wilkerson 1980), a higher anaerobic capacity seems to enable greater acute elevations in testosterone-levels in response to intermittent endurance exercise (Vuorimaa et al. 2008). On the other hand, the increased cortisol response typically associated with a prolonged endurance exercise (Viru et al. 2001) tends to be lower in athletes who are used to continuous endurance exercise of longer durations (figure 12) (Vuorimaa et al. 2008).

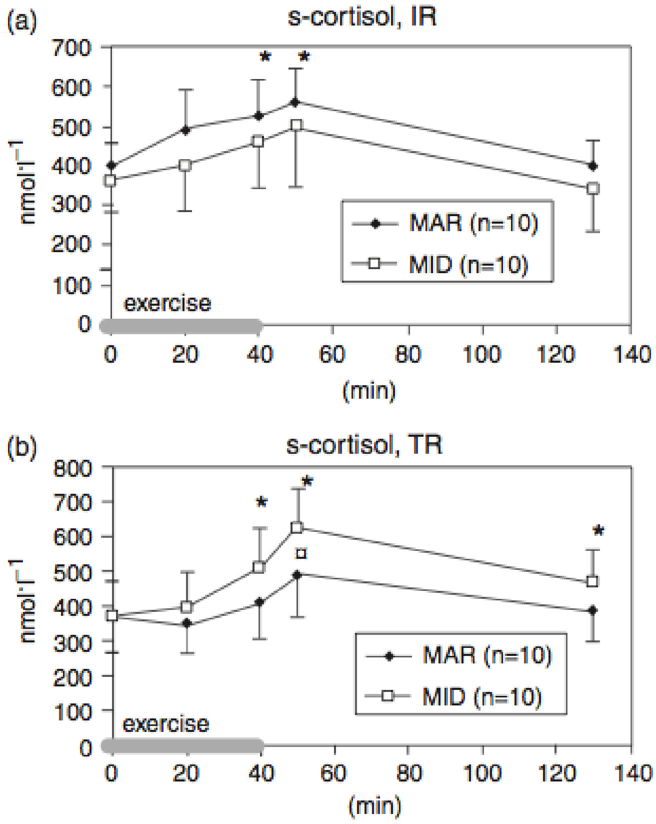

Fig. 12 Serum cortisol during and after intermittent (IR, a) and tempo (TR, b) running in marathon (MAR) and middle-distance (MID) runners. * indicates significant differences in pre-post values. ¤ indicates significant time group interactions. (Vuorimaa et al. 2008).

4 CHRONIC ADAPTATIONS TO EXERCISE

4.1 Strength training

4.1.1 Adaptations in force development

Already the early phases of resistance training results in some gains in strength (2 weeks, Staron et al. 1994), with further gains being obtained by longer-term (11-21 weeks) progressive resistance training (eg. Häkkinen et al. 2003, figure 13). Increases in both maximal strength and explosivity (RFD) can be obtained simultaneously with training programs specifically addressing these properties (Aagaard et al. 2002; Häkkinen et al. 2003; Walker et al. 2010). Strength training aimed at targeting strength-endurance may even result in some cardiorespiratory performance adaptations (Chtara et al. 2005).

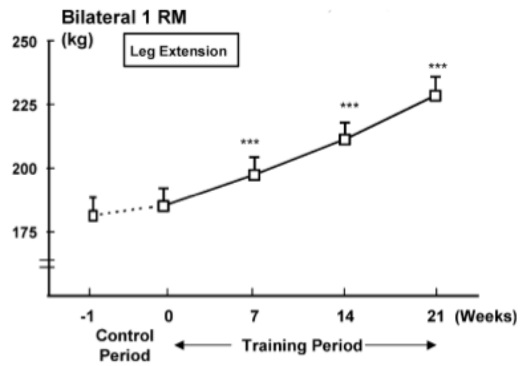

Fig. 13 Development of maximal bilateral leg extension strength during the course of 21 weeks in recreationally trained subjects. (Modified from Häkkinen et al. 2003.)

Whereas the training adaptations appear to be specific to the training performed, untrained subjects may initially increase power and maximum strength without any specific training program showing to be more advantageous over another (Juárez et al. 2009). The adaptations of the nervous system rather than increases in muscle size are mostly responsible for the initial (3-5 weeks) gains in strength (Moritani & deVries 1979; Kraemer et al. 1999b).

Manipulation of the volume and intensity of a training program influences the long-term effectiveness and is thus of importance in the development of strength (de Salles et al. 2009). Even though maximal force can to some extent be improved by different types of strength training protocols, the magnitude of gains in strength are not equal. As is evident in figure 14, a low-repetition training protocol with heavy (3-5 RM) loads appears to be superior in improvement of maximal strength. (Campos et al. 2002.) Furthermore, forced repetitions have been suggested to be beneficial in producing gains in maximal strength and muscle mass, especially for individuals already experienced in strength training (Ahtiainen et al. 2004).

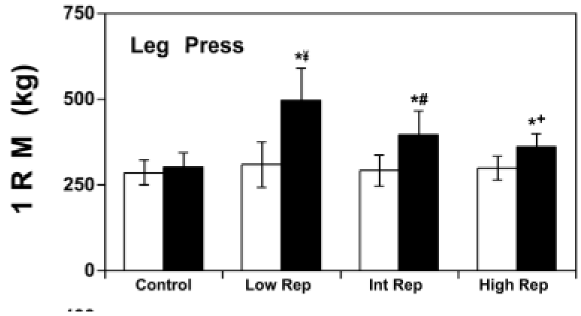

Fig. 14 Maximal strength (leg press 1RM) performance pre- (white bar) and post- an 8-week training period with different repetitions. (Campos et al. 2002.)

Adaptations to the acute responses following a strength loading have been noted in recreationally trained athletes already after short-term training periods. Raastaad et al. (2002) found that the attenuation in neuromuscular fatigue following two weeks of high volume strength training was significant in recreationally trained subjects. In addition, the time to complete recovery from a given loading was reduced. (Raastaad et al. 2002.)

4.1.2 Hormonal adaptations

Training-induced changes in resting (basal) hormone levels are a contradictory issue as different adaptations have been found in individuals with different baseline training statuses. As hormonal adaptations have in some studies not been apparent in individuals with previous strength-training experience neither short-term (2 weeks, Raastad et al. 2003) nor long-term (6 months, Ahtiainen et al. 2005), it may well be that adaptations in the already trained individuals require even longer periods of monitoring of hormone levels for any adaptations to be evident (Häkkinen et al. 1987).

Conversely, for untrained individuals embarking on a resistance training program, endocrine adaptations may be exhibited even after relatively short-term training regimens (Kraemer et al. 1998). Increases in resting levels of testosterone in previously untrained men have been reported already after four weeks of resistance training, as well as decreases in resting cortisol levels after 6-8 weeks (Staron et al. 1994; Kraemer et al. 1998). Hypertrophy-associated gains in strength performance are evident after 3-5 weeks (Moritani & deVries 1979). Even if no changes in basal testosterone levels occur, a decrease in cortisol levels leads to an elevated testosterone/cortisol-ratio (T/C-ratio), which serves as an anabolic marker in the body. A change of this nature has been linked to increased isometric force of the leg extensor muscles (Häkkinen et al. 1985; Häkkinen et al. 1988).

Whereas no changes in resting levels of hGH with training might occur, an increased exercise-induced (acute) response can be observed already after one week of resistance training (Kraemer et al. 1998). As for serum testosterone, Kraemer et al. (1999b) reported no significant adaptations in the acute responses in recreationally trained males after 10 weeks of resistance training (figure 15) (Kraemer et al. 1999b).

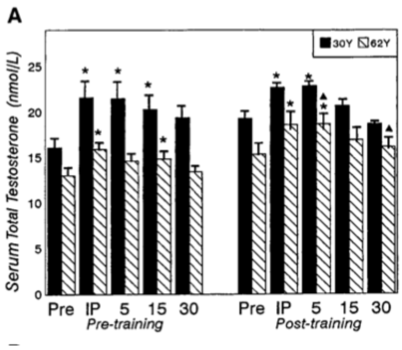

Fig. 15 Total testosterone after a heavy-resistance exercise test before and after 10 wk of strength and power training for 30Y / 62Y men. * = significantly different from corresponding pre-exercise value; Δ = statistically different from corresponding pre-training value. Pre, pre-exercise; IP, immediately after exercise; 5, 15, and 30: 5, 15, and 30 min after exercise.

4.2 Endurance training

4.2.1 Adaptations in exercise performance

In previously untrained subjects, gains in key components of endurance performance - such as VO_{2max} and maximal power output - can be observed even after short (3-5 weeks) training periods of exercising at moderate and sub-maximal intensities (Grandys et al. 2009; Murias et al. 2010). Despite this, progressive elevation of exercise intensity is of great importance in order to maximize performance gains (McNicol et al. 2009), and exercise at intensities close to VO_{2max}, has proven effective in improving aerobic power (Chtara et al. 2005). In addition, slight gains in maximal strength have been reported following high-intensity interval training (Chtara et al. 2008).

However, lactate kinetics during exercise do not seem to be sensitive to changes in endurance capacity. Studies have shown training periods of 6-12 weeks to be ineffective in affecting the onset of rise in lactate (lactate minimum speed, LMS) during identical exercise protocols before and after training. (Carter et al. 1999; Sedlock et al. 2010.)

4.2.2 Hormonal adaptations

As far as endocrine adaptations to endurance training are concerned, training background seems to heavily influence the outcome. Endurance trained individuals have been found to respond to 10 weeks of intensified training with simultaneous decreases in testosterone levels and increases in cortisol levels, resulting in a decreased T/C ratio (ie. a catabolic state) (Hoogeveen & Zonderland 1996). Even exercise at the same absolute levels of sub-maximal exercise tends to elicit smaller cortisol responses in untrained individuals (Hackney et al. 1988), and except for slight increases in testosterone levels, the adaptations in untrained counterparts are mostly insignificant, thus leaving the T/C-ratio largely unchanged (Bell et al. 2000; Grandys et al. 2009).

Despite differences in hormonal adaptations, improvements in performance variables have been observed in both trained and untrained subjects over similar time courses. Thus, it should be noted, that an increased catabolic state does not automatically exclude performance gains. (Hoogeveen & Zonderland 1996; Grandys et al. 2009.)

5 ACUTE RESPONSES AND CHRONIC ADAPTIONS TO COMBINED STRENGTH AND ENDURANCE TRAINING

The main problem with training regimens of concurrently performed strength and endurance loadings seems to be the inevitable compromises in strength adaptations (eg. Hickson et al. 1980). Concurrent strength and endurance training have been found to result in different adaptations than either training modality alone (eg. Hickson 1980; Leveritt et al. 1999; Bell et al. 2000), and previously untrained subjects who start training for aerobic fitness and strength simultaneously, experience a disadvantage in strength gains (Hunter et al. 1987). The investigation of this phenomenon has during the last decades been focusing on the patterns in adaptations even on the molecular level, uncovering complex networks of cross-talk and non-linear regulatory components that play remarkable roles in combining the two vastly different training modalities (Hawley, 2009). Much less attention has been given to the sub-phenomenon of the challenges associated with combined training, the *order effect*, which refers to whether the intra-session loading order of endurance and strength loadings is of importance regarding the physiological adaptations.

5.1 General aspects of combined training

The main difficulty with a combined training regimen seems to be the development of strength. Both the structural properties of the muscle as well as the endocrine responses seem to be affected differently by concurrent strength and endurance training than by either strength or endurance performed alone. (eg. Hickson 1980, Bell et al. 2000.)

Whereas strength development to some degree suffers due to a combined training, the addition of different modes of resistance training to endurance training has been proven to be beneficial for improving endurance performance (Millet et al. 2002; Mikkola et al. 2011). The mechanisms affecting endurance performance are numerous (figure 16), of which strength and power training play a role in improving anaerobic power and capacity, and thus, affecting the actual endurance performance (Stone et al. 2006).

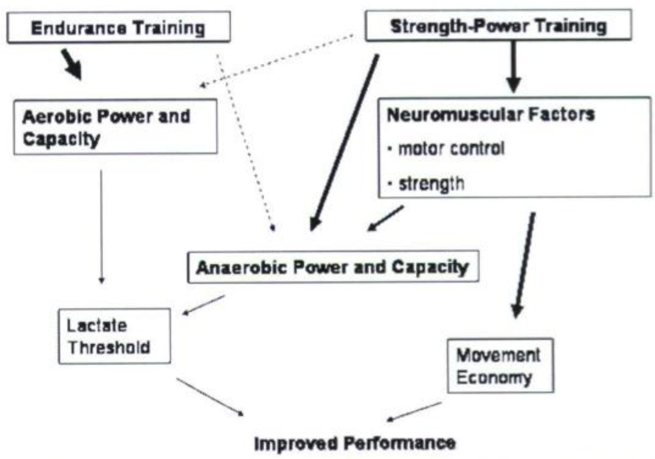

Fig. 16 Potential interrelated mechanisms that affect endurance performance (Stone et al. 2006).

As the physical demands of several sporting events - such as decathlon, swimming and football - are dependent on both strength and endurance capacities for optimal performance, a combined training regimen is a common method in numerous sports at the elite level (Nader 2006; Aspenes et al. 2009). Figure 17 shows the placement of selected sports on the hypothetical *strength-endurance-continuum* (SEC), which has its foundations in DeLorme's (1945) governing work concerning the specificity of training. According to DeLorme, low-repetition, high-resistance exercises produce power, while high-repetition, low-resistance exercises produce endurance. Furthermore, DeLorme stated that each of the types of exercise would be incapable of producing results obtained by the other. (DeLorme 1945.) Hence, training for many of the activities presented in figure 17 is likely to result in some limitations of development (Nader 2006).

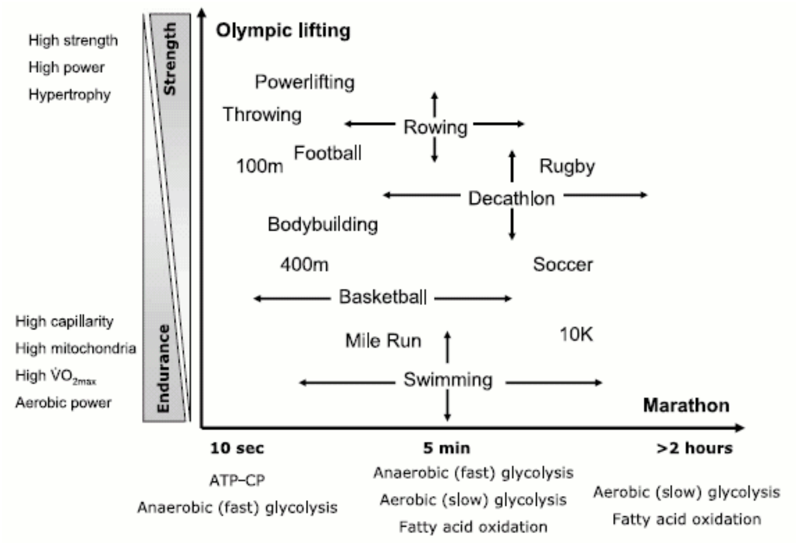

Fig. 17 Different sporting events depicted on the hypothetical Strength-Endurance-Continuum (Nader 2006).

The benefits of combined training could be considered of equal importance for non-athletes as athletes. Resistance training plays an important part in injury prevention as well as evokes beneficial effects regarding certain inflammatory and cardiovascular risk factors (Sheikoleslami et al. 2011), and adults (aged 18-64) are generally recommended to perform resistance training twice weekly for means of health promotion (UKK-institute). In order to maintain health in terms of cardiovascular function, recommendations state that endurance-type activities should be performed in a total of 2,5 hours weekly, preferably spread out to three separate days (The Finnish Heart Association). Considering the time-consuming aspects of these recommendations, a combined training regimen could be of interest even for non-athletes.

5.2 Interference in strength development related to combined training

The concept of the *interference effect* was originally introduced following research by Robert Hickson in 1980 to describe the attenuated gains in strength when training for endurance and strength concurrently, as opposed to training for either modality alone (figure 18). More than three decades after the initial investigation and further research within the field, it has been relatively solidly established that concurrent strength and endurance training with an overall high volume to some degree hinders the gains in strength and the physiological adaptations that typically occur with single-mode training (eg. Kraemer et al. 1995; Leveritt et al. 1999; Chtara et al. 2008).

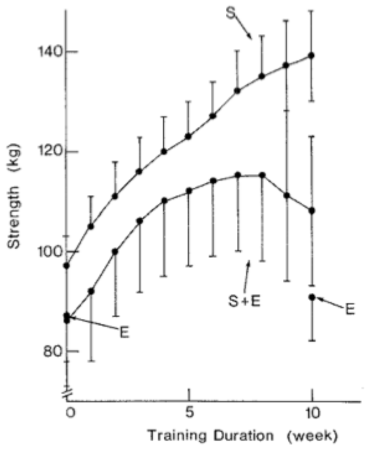

Fig. 18 The development of strength in response to strength (S), endurance (E) or combined (S+E) training over a 10-week period (Hickson, 1980).

Especially pronounced is the interference of endurance training on the improvements in muscle strength and the ability of the muscle to obtain both hypertrophic and / or mitochondrial training-induced adaptations (Hickson 1980; Dudley & Djamil 1985; Leveritt et al. 1999; Bell et al. 2000; Hawley 2009). Acute interference effects in concurrent strength and endurance exercise have been observed to occur when both the strength and endurance loadings produce local peripheral fatigue (de Souza et al. 2007). The interference has not only been suggested to be related to impairments of neural adaptations (Cadore et al. 2010) but also to be caused of an increased state of catabolism (Kraemer et al. 1995), though the specific underlying mechanisms still remain unclear (Hawley 2009).

However, even though gains in strength tend to be compromised, improvements in endurance performance variables (VO_{2max}) obtained with concurrent training suggest a lack of interference of resistance training on endurance performance (Hennessy & Watson 1994; Bell et al. 2000; Häkkinen et al. 2003; Mikkola et al. 2011).

As a means for predicting the possible interference effect of different training protocols, Docherty & Sporer (2000) developed an interference predicting model based on close examination of previous research concerning the phenomenon (figure 19). According to the model, interference is maximized with a combination of metabolically demanding resistance training and high intensity interval training, whereas strength protocols of the neural type are bound to result in less interference. Continuous endurance training below the aerobic threshold would, according to the model, have minimal interference on strength development independent of the type of resistance protocol performed in conjunction. (Docherty & Sporer 2000.)

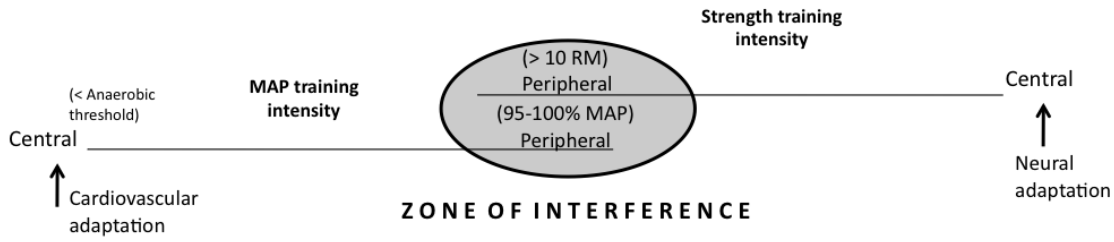

Fig. 19 Intensity continuums and primary locations of maximal aerobic power (MAP) and strength training, and the suggested overlap of the two combined training modalities. (Modified from Docherty & Sporer 2000.)

In terms of the relation of intensity to the extent of interference, the relevance of training intensity becomes well underlined by investigating the outcome of previous studies **(**table 5**)** that are in line with the model by Docherty & Sporer. However, even though an inability to obtain gains in maximal strength is repeatedly observed after training periods with high intensities (eg. Hickson 1980; Kraemer et al. 1995), attention should also be given to the current training status of the subject along with the prescribed training dosage. Shaw et al. (2009) found that sedentary subjects experienced gains in strength after 16 weeks of low-intensity combined training, with no differences in adaptations in comparison to a strength-only training group. Conversely, Hunter et al. (1987) reported hindered gains in strength for untrained subjects embarking on a combined-training regimen with a higher overall intensity than what was utilized by Shaw et al. (2009).

Less interference in performance adaptations seems to occur in well-trained individuals, likely due to a higher tolerance for long-term combined training (Hunter et al. 1987). In order for recreationally trained individuals to gain significant improvements, higher dosages of strength training have been suggested (Shaw et al. 2009). Additionally, priorities regarding the main goal of training and the desired adaptations should be taken into account by periodizing training programs accordingly (Häkkinen et al. 2003).

Table 5: Training details and strength-related outcomes of selected studies investigating the adaptations to combined strength (S) and endurance (E) training.

Reference	Duration and subject material	Training program	Adaptations
Hickson 1980	10 weeks, 6x / week, 2h between training modes, sedentary subjects	**S:** Heavy (80% 1RM) **E:** high intensity interval (near VO_{2max}) and continuous endurance (as fast as possible)	Attenuations in S-gains from the 6th week onwards
Hunter et al. 1987	12 weeks, 2 x combined session / week, endurance trained (ET) and untrained (UT) subjects	**S:** 3 sets of 7-10 repetitions **E:** 75% of HR_{max}	UT: Hindered development of strength ET: No disadvantages in strength gains
Kraemer et al. 1995	4x / week, 12 weeks, S and E on same day	**S:** Heavy and light 4-day split routine **E:** Running at 80-100% VO_{2max}	Inhibited 1RM strength
Bell et al. 2000	12 weeks, 3 x / week S and E on alternate days, recreationally trained subjects	**E:** Continuous + interval **S:** low-velocity, 2-4 sets of 4-12 repetitions, 70-80% 1 RM	No compromises in S-gains, time course of adaptation different to S-training only
Häkkinen et al. 2003	21 weeks, 2+2 sessions / week, recreationally trained subjects	**S:** 50-80% 1RM **E:** Walking/Cycling 30-90 min under and above aerobic threshold	Steady increase in strength, inhibited improvements in RFD
Shaw et al. 2009	16 weeks, 3x/week combined sessions, sedentary subjects	**S:** 60% 1RM, 15 repetitons **E:** 22min at 60% age-predicted HR_{max}, 5% increase every 4 weeks	Increases in 10 RM strength in all training exercises

The extent of eventual interference associated with combined training is dependent on the overall properties of the training regimen, with high frequency and / or volume resulting in notable limitation in strength gains (Häkkinen et al. 2003). Depending on the long-term construction of the training program, concurrent training seems to suppress improvements in explosive force production even though gains in maximal force are simultaneously observed (Hennessy & Watson 1994; Häkkinen et al. 2003).

It appears that larger gains in strength are associated with lower training frequencies, although adaptations to rapid neural activation have been found to be severely attenuated despite programs promoting a low training frequency and addressing explosive strength (figure 20). Thus, even low-frequency concurrent strength and endurance training lead to some degree of interference over longer training periods. (Häkkinen et al. 2003.) Conversely, the combination of high-intensity endurance and heavy resistance training cause compromised adaptations already in the short-term perspective (Hickson, 1980).

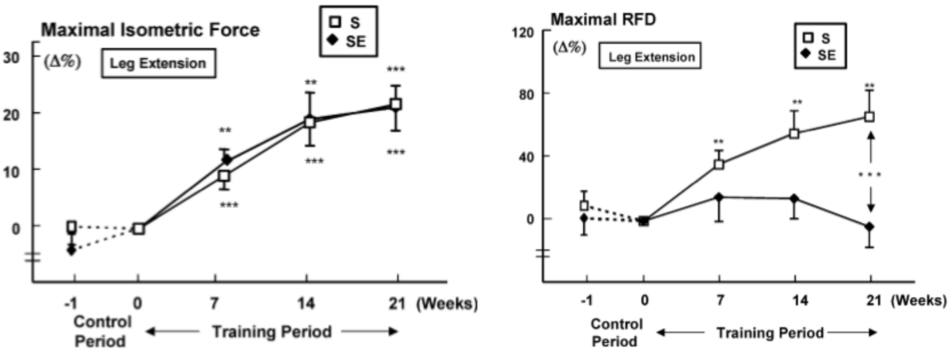

Fig. 20 Mean changes in maximal voluntary bilateral isometric leg extension force and maximal rate of force development (RFD) in the rapidly produced voluntary bilateral isometric leg extension action in the strength training group (S) and combined strength and endurance training group (SE) during the 1-week control and 21-week training periods (**p<001; ***p<0001). (Häkkinen et al. 2003).

5.3 Endocrine considerations of combined training

The questionable compatibility of concurrent strength and endurance training in terms of compromised strength development has been suggested to be a result of overtraining, which is a potent factor for inducing a catabolic endocrine environment (Kraemer & Ratamess 2005). Furthermore, too-frequent training sessions may result in alterations in adaptive protein synthesis, and thus, anabolic responses (Nader 2006). Accordingly, Kraemer et al. (1995) found significant increases in acute cortisol responses following 12 weeks of high-volume combined strength and endurance training carried out four times weekly. As inhibitions in 1RM-strength were also observed, the endocrine responses and adaptations to combined training could, in this case, possibly be a result of high-volume related overtraining induced by a combined training regimen. However, Cadore et al. (2010), did not report any change in catabolic status in elderly men following 12 weeks of three times weekly combined training sessions, and thus, no relationship between adaptations in strength and endocrine variables. The findings by Cadore et al. (2010) contradict a suggestion of systematic, overtraining-type induced impairment in adaptations, and rather suggest local, neural interference (Cadore et al. 2010). However, different experimental designs complicate the comparison of the outcomes of different studies.

5.4 Order effect of combined training

Due to the fact that the main maladaptation from combined training seems to be directed at the development of strength (eg. Hickson 1980; Hunter et al. 1987; Kraemer et al. 1995), it appears that the interference stems from an endurance training induced response, which causes inhibition in the force-generating properties of the neuromuscular system (eg. Häkkinen et al. 2003; de Souza et al. 2007). However, research concerning the possible effects of intra-session loading sequence (*the order effect)* on the differences in both acute responses and long-term adaptations is currently scarce.

5.4.1 Effect of training order on adaptations in strength

Whereas the effect of a strength loading on endurance performance does not appear to very specific, the type of endurance exercise is of key importance with regard to the magnitude of impairments on subsequent strength exercise (de Souza et al. 2011). Low intensity and moderate duration endurance exercises do not seem to interfere with subsequent strength performance regardless of the type of strength loading. Conversely aerobic exercise at intensities close to VO_{2max} is likely to produce peripheral fatigue with an impairing effect on strength performance. Hence, should strength development be the main focus of a training program, a suggestion of strength preceding the endurance loading may be suggested. (de Souza et al. 2007.)

However, equal adaptations have been observed regardless of the intra-session loading sequence in physically active individuals without previous strength-training background. A combination of high-intensity interval training and high-repetition circuit training with relatively light loads was found to result in similar gains in lower-body 1 RM strength (figure 21) and 5-jump performance. (Chtara et al. 2008.)

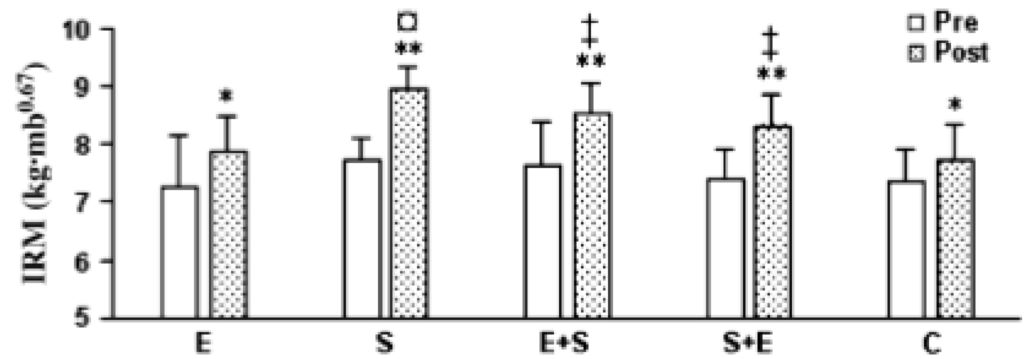

Fig. 21 Gains in 1RM strength after 12 weeks of endurance (E), strength (S), combined training with different exercise orders (S+E, E+S) or no exercise. Asterisks (*) indicate significant within-group pre-post-difference, ° indicates significant improvement in comparison to E, E+S, S+E and C. ‡ indicates significant improvement in comparison to E and C. (Chtara et al. 2008.)

In terms of improving aerobic capacity, a training program similar in nature would seem to be superior in endurance performance when aerobic exercise is performed before strength (Chtara et al. 2005). The specific study design of intermittent endurance exercise combined with periodized circuit training does not, on the other hand, seem to result in any compromised gains in either maximal or explosive strength with regard to the intra-session loading order (Chtara et al. 2008). However, having a strength-endurance loading to constitute for the strength loading (Chtara et al. 2005; Chtara et al. 2008) does not apply for strength loadings towards the other end of the neural-metabolic continuum, thus leaving the possible effects of heavier resistance loadings uncovered.

5.4.2 The effect of loading order on serum hormone responses

For recreationally strength trained individuals, the acute elevations in testosterone and cortisol during a combined loading have been suggested to be higher after the first exercise modality than after the second, independent of the loading order. Furthermore, after the initial significant elevation, concentrations return to near-baseline during the second part of the loading. Thus, no differences in the relative total change of cortisol seem to be evident in response to a combined loading, regardless of intra-session exercise orders. (Cadore et al. 2012.)

However, a prolonged acute elevation in testosterone levels has been noted as a response to a combined session with endurance exercise preceding the strength loading (figure 22). This would indicate that endurance exercise does not negatively affect the acute testosterone response to resistance exercise, as far as moderate-intensity continuous endurance exercise is concerned. (Cadore et al. 2012.) This finding supports the observations made by de Souza et al. (2007), which states a lack of interference of continuous low-intensity endurance exercise on subsequent strength performance.

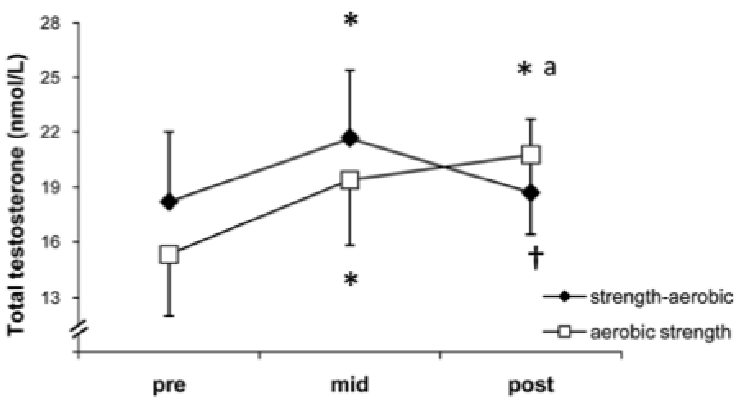

Fig. 22 Responses in total testosterone over the time course of a concurrent strength and endurance loading (Cadore et al. 2012).

6 PURPOSE OF THE STUDY

The purpose of the present study was to address the acute hormonal and muscular responses and recovery following a combined strength and endurance loading, the chronic adaptations of the acute responses as well as to the order effect of the intra-session loading sequence.

6.1 Research problems

Acute responses

1) Which training order (S+E or E+S) produces greater acute muscular fatigue responses in terms of changes in force production (MVC and MVC 0-500ms)?

2) Does the recovery for force production differ at 24 h and / or 48 h post-loading between S+E and E+S?

3) Are there any differences in acute endocrine responses between the training orders (S+E / E+S) after a combined strength and endurance loading?

4) Are there any differences in hormone concentrations at 24h and / or 48 post-loading between S+E / E+S?

Chronic adaptations (Δ 0wk-24wk, S+E vs. E+S)

1) Does the development of maximal strength differ between S+E and E+S over a 24-week training period?

2) Which order of training improves the recovery for force production more over a 24-week training period?

3) Are there any differences in acute endocrine responses (adaptations) to combined strength and endurance loading between S+E and E+S after 24 weeks of training?

5) Are there differences in recovery at 24h and / or 48h for force production between orders?

7 METHODS

7.1 Subjects

Forty-two healthy men aged 18-40 from the Jyväskylä region were recruited to participate in the study. Recruitment was conducted by posting ads in public places such as gyms, libraries, buildings at the campus area of the University of Jyväskylä as well as on the websites of the city of Jyväskylä and the Jyväskylä University and on the university staff- and student e-mail lists. Requirements for participation included the subjects to be recreationally active (ie. no systematic and / or progressive strength or endurance only -training for at least one year prior to the study) a BMI of less than 30 kg/m^2, as well as no smoking for a minimum of one year prior to the start of the study as well as free from chronic illnesses (eg. asthma, diabetes) and injuries or ailments of the locomotor system.

All subject candidates were interviewed in terms of general health aspects and attended a screening for resting ECG and resting blood pressure before being granted a place as a subject in the study. Furthermore, the ECG and blood pressure-results as well as a health questionnaire were screened and approved by a cardiologist as a part of the pre-screening process.

The chosen subjects participated in a meeting together with the head and staff of the research project and agreed to participate after receiving detailed information about the upcoming measurements and procedures and signing an informed consent. The subjects were also informed of their option drop out of the research project at any time.

Due to subjects having to quit the study because of minor injuries or medical issued and subjects opting to drop out because of motivational issues or other reasons, the first twelve weeks of the study was completed by 32 subjects and the entire 24-week training intervention was completed by 30 subjects. Table 6 contains the data from subjects who completed the entire 24-week program. Height was measured with subjects standing upright, back against a measuring tape with a 0.1 cm accuracy fastened to the wall. Subjects were instructed to keep their feet shoulder width apart, heels against the wall and to keep their chin in a neutral position when the measurement was conducted. Weight was measured with a digital scale with a 0.1 kg accuracy, with the subjects being in a fasted (12h h) state, with heavy clothing and shoes removed.

Table 6: Subject anthropometrics separated by group of training (E+S / S+E).

Group	n	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m^2)
E+S	13	29.2 (± 5.5)	178 (± 6.0)	78.1 (± 9.6)	24.6 (± 2.8)
S+E	17	30.0 (± 4.5)	179 (± 5.0)	75.31 (± 8.7)	23.5 (± 2.2)

7.2 Study design

The study spanned over a 24-week-period with its onset in October 2011. All subjects were initially familiarized with the training- and measurement protocols and equipment of the current study before proceeding to basal measurements of maximal strength and endurance. Dynamic 1 RM Strength was measured using a dynamic leg press (David 210, David Sports Ltd., Finland) with a starting knee-angle of less than 60°. After three sub-maximal warm-up sets with increasing weight and decreasing repetitions, weight was progressively increased so that the true dynamic 1RM was reached within five trials.

After the basal measurements, each subject was then assigned into one of the two training groups for the entire duration of the study: performing an endurance training session followed by a strength training session (E+S) or performing the loadings within the training session in the opposite order (S+E). Assignment was done by pairwise matching physical characteristics and performance. Thereafter, subjects proceeded to 24 weeks of combined strength and endurance training in the order they were assigned to. Acute responses to a single-session combined strength and endurance loading were measured during the first training session. The measurement protocols were repeated after the completion of the 24-week training period. The overview of the study design is presented in figure 22.

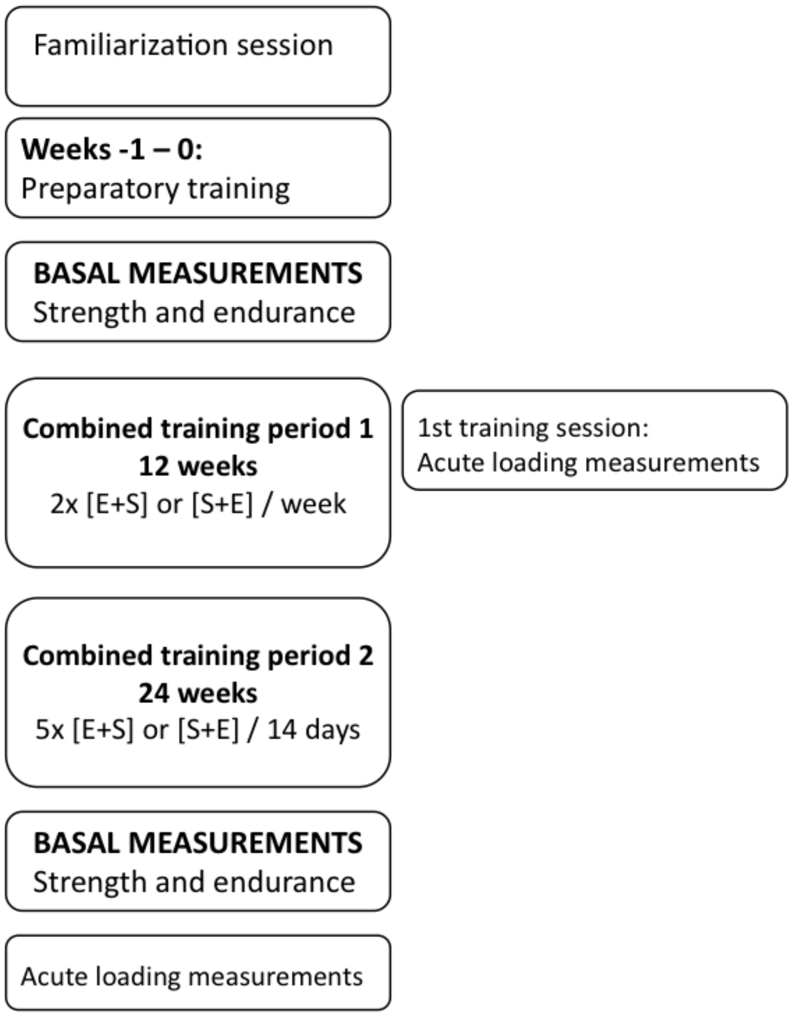

Fig. 22 Overview of the study design.

7.3 The acute loading design and measurement setup

Measurements and evaluation of acute combined training induced fatigue and recovery was performed two times during the 24-week training period: during the first single training session of the first 12-week training period ("*0 weeks"*) as well as after the completion of all training sessions and basal measurements (*"24 weeks"*). The loading protocol for measuring the acute fatigue and recovery responses to combined strength and endurance loading was conducted for each subject in the same order as they performed the training (eg. subjects training in the order S+E also completed the acute loading measurements in the same order). The acute loading was performed with regard to the time of day that the subjects trained during the 24-week training period in order to minimize the time-of-day-variation in the measured variables. The loading protocol for measuring acute responses is presented in fig 23.

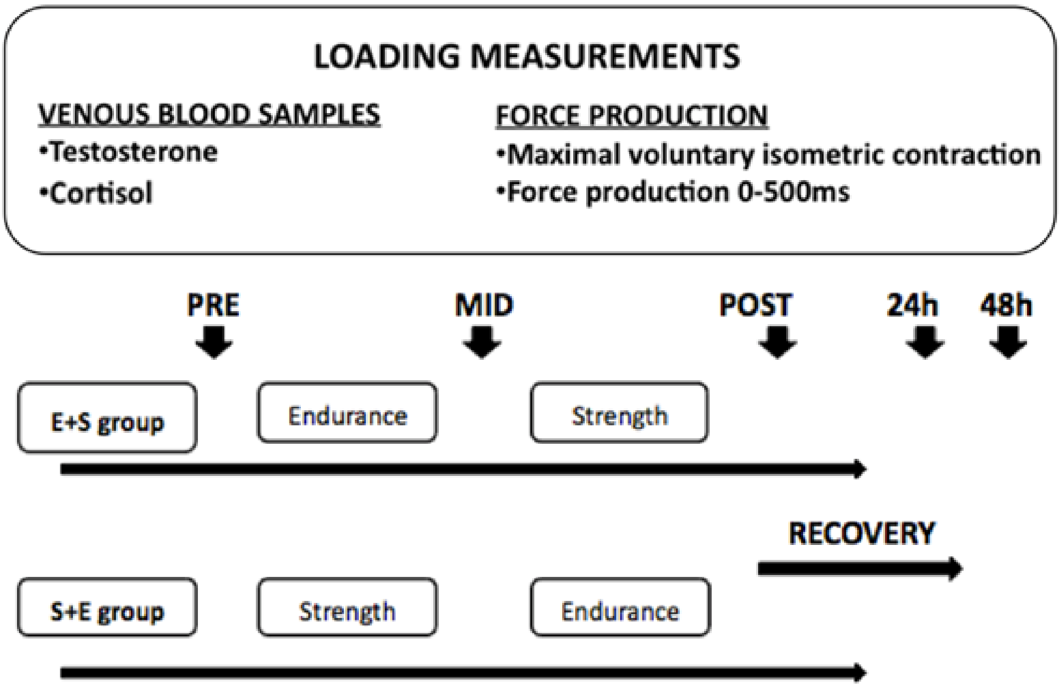

Fig. 23 Overview of the measurement protocol for evaluation of acute fatigue and recovery. PRE = Before the combined strength and endurance loading. MID = After the first part of the loading. POST = After completion of the entire combined loading. 24h and 48h = Follow-up measurements after 24 and 48 hours, respectively.

7.3.1 Strength and endurance loadings

Both the strength and the endurance loading were conducted using relative loads and intensities, respectively. After 24 weeks of training, new relative loads were calculated from the basal measurements to be utilized in the acute loadings design. Verbal encouragement was provided throughout the loadings to ensure the subject was fully motivated to give an optimal performance.

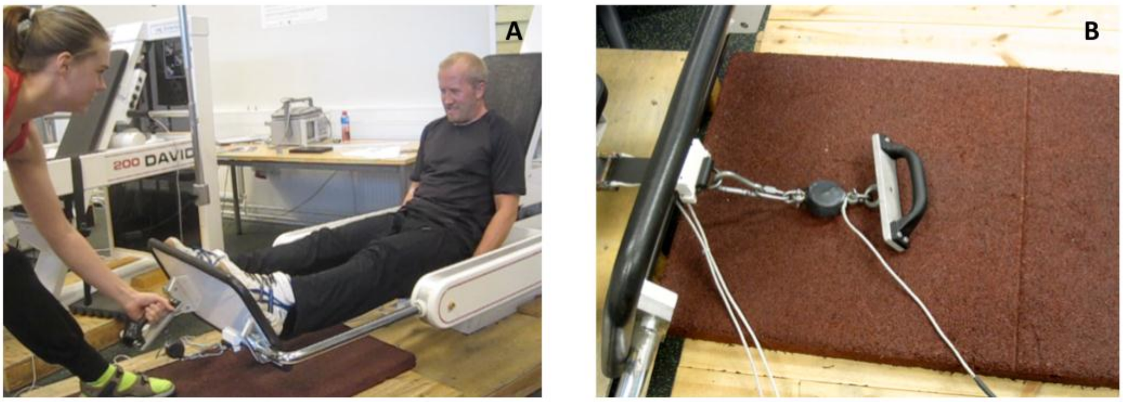

Fig. 24 A) Conduction of the strength loading. B) Detachable handle for possible assisting.

Strength loading. The strength loading was conducted using a dynamic leg press (David 210, David Sports Ltd., Finland), with a detachable handle for assisting if necessary (Fig 24). The loading was a mixed strength loading, with sets of explosive, maximal and hypertrophic strength following one another (table 7). The loads were calculated based on the 1RM-test performed during the preceding basal measurements with the same leg press machine. The starting knee angle was measured to be less than 60°, and subjects were instructed to fully extend their legs without locking their knees.

Table 7: The strength loading with intensities, number of sets and reps as well as rest periods. ** Indicates weight was added if the previous set appeared to be too light for the subject.

Explosive	10x 40% Leg press explosive
	3min rest
	10x 40% Leg press explosive
	3min rest
	10x 40% Leg press explosive
	3min rest
Maximal	3x 75% Leg press
	3min rest
	3x 90% Leg press
	3min rest
	3x 90% (RM) Leg press**
	3min rest
	3x 90% (RM) Leg press**
	2min rest
Hypertrophic	10x 75% Leg press
	2min rest
	10x 80% (RM) Leg press**
	2min rest
	10x 80% (RM) Leg press**
	2min rest
	10x 75% Leg press

During the explosive sets, subjects were instructed to be as fast and explosive as possible, and to aim for the foot plate to leave the soles of the shoes, allowing for full ankle extension. All 10 repetitions were performed explosively and rapidly, without rest between repetitions. During the maximal and hypertrophic sets subjects were instructed to keep the eccentric and concentric phases controlled and equal in duration.

Subjects were not allowed to leave a set unfinished. If the subject was unable to complete the required number of repetitions for the set in question, they were assisted by a staff member pulling a handle that was attached to the foot plate of the leg press. Subjects were assisted to the degree that they could complete the set, but with full effort from themselves still required.

Endurance loading. The endurance loading consisted of 30 minutes of continuous work on a Monark bicycle ergometer with electric resistance, with the saddle set to the height of the iliac crest. The intensity used was 65 % of maximal workload (watts) as determined during the endurance test of the basal measurements. Subjects were instructed to keep the pedaling pace at 70 revolutions per minute (rpm). In case of the subject being unable to keep up the required pace (ie. rpm dropping below 65 for longer than a minute), the workload was lowered by 15 watts. If the subject was unable to keep up the pace even after the reduction (1 minute), the workload was further reduced by 15 watts. The procedure was repeated until the subject was able to keep up the required pace.

7.3.2 Evaluation of fatigue and recovery

Pre-tests. Before the loading, three maximal voluntary isometric contractions (MVC) were performed for determining the baseline for force and explosivity. Subjects were allowed one minute of rest in between trials and the trial with the highest force value was selected as the baseline. The MVC's were performed at a knee angle of 107°, which was measured with a hand-held goniometer during the measurement familiarization in the same isometric leg press dynamometer. To ensure the knee angle being the same throughout the study period, subjects were asked to wear the same shoes in all measurement sessions throughout the study. The distance of the seat and the foot plate being the same throughout the study period was ensured by using a measuring tape fixed to the dynamometer (fig 25). The distance was marked down for future reference during the familiarization session.

The force signal was transferred to a Windows-operated desktop computer and processed with a low-pass filter of 20Hz and automated scripts with Signal 2.6 Software (Cambridge electronics Design Ltd, Cambirdge, United Kingdom).

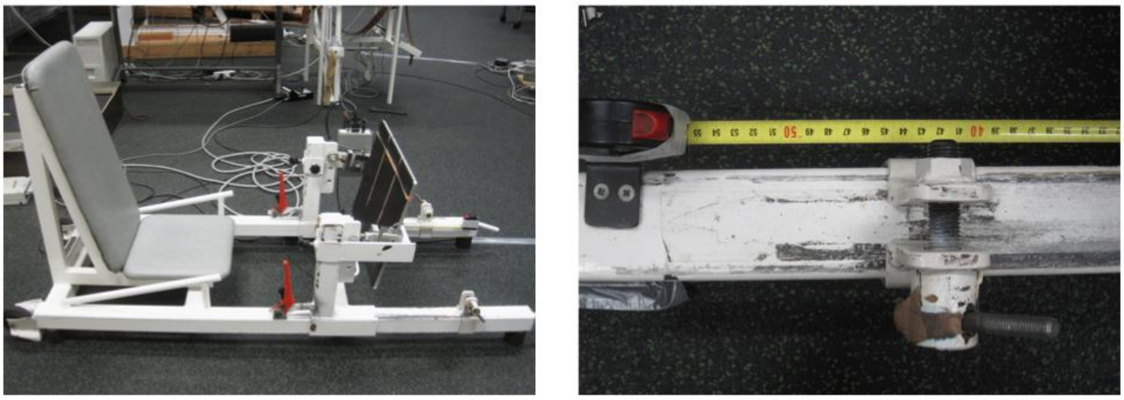

Fig. 25 The isometric leg press used in evaluation of muscular fatigue and recovery.

Mid- and post-tests. During mid- and post-tests the same isometric leg press (fig. 25) as in pre-tests was used to monitor fatigue. Mid- and post-tests were performed immediately after the loading was completed, with two trials and no rest in between. Venous blood samples were drawn by a trained laboratory technician from the antecubital vein at both time points for means of measuring hormonal concentrations of testosterone, human growth hormone and cortisol.

Follow-up measurements. Follow-up measurements were conducted at 24 and 48h after the completion of the full loading. Three trials of MVC with the same isometric leg press dynamometer as previously mentioned were performed, and a rest of one minute between trials was allowed. Venous time-of-day blood samples were drawn for means of measuring the before mentioned hormonal concentrations.

7.3.2 Order of events

Subjects proceeded to the laboratory facilities on the morning of the loading in a fasted state (12h) after sleeping a minimum of 7h, in order to give a venous blood sample. In case of the subjects having their loading in the morning (between 07.00 and 09.00), they received a standardized breakfast at the laboratory before proceeding to the loading. For the subjects who had their loading scheduled for later in the day, another venous blood sample was taken at the time of arrival for the actual loading (*time of day blood sample*). All subjects were instructed to refrain from alcohol for 24 hours and caffeine for 12 hours prior to the loading. Subjects were allowed a minimum of two full days (48h) of rest before performing the acute loading measurements.

After the initial venous blood sample, subjects had their body weight measured and received a heart-rate monitor to wear for the duration of the loading. A 5-minute warm up on a bicycle ergometer was performed at an intensity and workload (watts) of the subjects' choice. Subjects were instructed to keep the workload light and to pedal at a brisk pace that would not leave them short of breath.

Following completion of the warm-up, subjects proceeded to the isometric leg press for pre-tests in order to determine a baseline for later evaluation of loading-induced fatigue. Subjects then proceeded to start the combined loading. Subjects assigned to the E+S training group completed the loading session in the same order, ie. an endurance loading preceding the strength loading, while subjects from the S+E –group completed their loading in the opposite order. The time between the two loading types did not exceed 15 minutes.

The level of fatigue was evaluated at mid-loading (after the first loading, E or S respectively to the loading order of the group in question) as well as after the completion of the entire combined loading. Venous blood samples were drawn at the same time points. Subjects were allowed to drink 2dl of water at Mid, after the venous blood sample was taken. In order to minimize any diluting effects on bodily fluids, and thus, interference with the measured blood variables, no other ingestion was allowed during the course of the loading.

Recovery was monitored at 24 and 48 hours after the completion of loading with maximal voluntary isometric contractions as well as venous blood samples (time-of-day blood samples).

The order of events are further described in table 8.

Table 8: The order of events for the acute loadings protocol. *Time of day blood samples were only drawn for subjects who performed the loading after 09.00. **Weight was added between sets in order to make the set a true RM. ***Mid- / Post-tests.

STRENGTH + ENDURANCE	**ENDURANCE + STRENGTH**
MORNING BLOOD SAMPLE	MORNING BLOOD SAMPLE
Time of the day blood sample*	Time of the day blood sample*
Breakfast* Bodyweight (incl. shoes) 5min warm-up (cycling) Max. bilateral isom. leg press x3	Breakfast* Bodyweight (incl. shoes) 5min warm-up (cycling) Max. bilateral isom. leg press x3
10x 40% Leg press explosive 3min rest 10x 40% Leg press explosive	30 minutes endurance cycling (65% of $Watts_{max}$)
3min rest 10x 40% Leg press explosive 3min rest 3x 75% Leg press	Max. bilateral isom. leg press x2*** Blood sample Water (2 dl)
3min rest	10x 40% Leg press explosive
3x 90% Leg press	3min rest
3min rest	10x 40% Leg press explosive
3x 90% (RM) Leg press**	3min rest
3min rest	10x 40% Leg press explosive
3x 90% (RM) Leg press**	3min rest
2min rest	3x 75% Leg press
10x 75% Leg press	3min rest
2min rest	3x 90% Leg press
10x 80% (RM) Leg press**	3min rest
2min rest	3x 90% (RM) Leg press**
10x 80% (RM) Leg press**	3min rest
2min rest	3x 90% (RM) Leg press**
10x 75% Leg press	2min rest
Max. bilateral isom. leg press x2*** Blood sample Water (2 dl)	10x 75% Leg press 2min rest 10x 80% (RM) Leg press** 2min rest 10x 80% (RM) Leg press**
30 minutes endurance cycling (65% of $Watts_{max}$)	2min rest 10x 75% Leg press
Max. bilateral isom. leg press x2*** Blood sample Bodyweight	Max. bilateral isom. leg press x2*** Blood sample Bodyweight

7.4 Training

The 24-week training period was divided into two 12-week periods and was preceded by a preparatory phase with familiarization of the training procedures, equipment, loads and management of training programs and logs. The training consisted of progressive, periodized endurance and strength training combined into a single training session. In training period 1, all subjects completed either two weekly sessions of [1E+1S] or [1S+1E], depending on which group they were assigned to. During training period 2 the training frequency was increased to 5 training sessions (five weekly sessions of [1E+1S] or 5x [1S+1E]).

Preparatory training (-1 – 0 weeks). Strength training with light strength-endurance loads using intensities ranging between 30-50% 1RM, including 1 to 2 sets of heavier loads (80-95% 1RM). Endurance loadings were below the aerobic threshold for 30 minutes per session.

Combined training period 1 (0-12 weeks). Strength training was initiated with light resistances, using 40-60% 1RM loads during the first 2 weeks and thereafter progressing up to 60-80% 1RM loads during weeks 3-7. Further progression in training loads were made during weeks 8-12 when loads of 80-95% of 1RM were utilized. In addition, explosive strength exercises were included in weeks 8-12 with loads of 30 and 40% 1RM. Initial endurance training intensity was kept between the aerobic and anaerobic threshold for 30-45 minutes per session.

Combined training period 2 (13-24 weeks). Training periodization of the combined training period 1 will be repeated during the second training period with increasing training intensity and frequency.

Training programs were the same for all subjects, with the only exception being the intra-session loading order. Subjects maintained their designated training order throughout the study. All training sessions were consistently supervised by members of the research group.

Resistance exercises. Strength training was performed for all major muscle groups focusing on the knee extensors and flexors, but also including exercises for extensors and flexors of the arms as well as for core stability. Both free weights and resistance exercise machines were utilized. Exercises performed during the course of the 24-week training period are listed in table 10.

Endurance training. All endurance training sessions were carried out indoors on a bicycle ergometer with a magnetic resistance. The training intensity was controlled by heart rate zones, which were determined after the maximal bicycle ergometer endurance test during basal measurements.

Table 10: List of strength exercises performed during the course of the 24-week training period.

Upper body	Bicep curls (standing and seated) Dumbbell fly (pectoralis) Lat pulldown (Latissimus dorsi) Military press Triceps pushdown
Lower body	Knee extension (bi- and unilateral) Knee flexion (bi- and unilateral) Leg press Explosive leg press
Core	Abdominals on bench and floor Back extension on bench

7.5 Statistical analysis

All data was analyzed and graphed using Microsoft Excel 2010 and IBM SPSS Statistics v.20 computer software. Microsoft Excel was used for calculations of means standard deviations (SD), and relative values as well as for drawing graphs. SPSS was used for more complex statistical analysis. All data was analyzed as relative values from the pre-loading value.

At 0 and 24 weeks, separately, within-group differences were analyzed with a five-level repeated measures ANOVA, whereas between group differences were analyzed with an independent samples t-test. A paired samples t-test was utilized for comparing values at the acute loadings time points (pre, mid, post, 24h, 48h) with their corresponding value across 24 weeks. Significances were set at *$p<0.05$ and ***$p<0.001$.

8 RESULTS

8.1 Force production

Maximal voluntary isometric force production during loadings: 0 weeks. Both groups experienced acute reductions in maximal voluntary isometric force production at Mid (E+S -11.6 % ± 7.0, S+E 20.4 % ± 12.7, both $p<0.001$) and Post (E+S -25.1 % ± 12.5, S+E 21.9 % ± 8.9, both $p<0.001$). (Fig 26.) The difference between E+S and S+E (3.3 %) at post was not significant. Both groups were recovered already at 24h (E+S 95.1 % ± 6.4, S+E 97.2 % ± 13.4). A between-group difference was found at Mid, where the decrease in MVC was larger (8.8 %) for S+E (79.6% of Pre) than E+S (88.4% of Pre). The relative contribution of the first part of the loading to the total decrease in MVC was 46.0% for E+S and 93.2% for S+E.

Maximal voluntary isometric force production during loadings: 24 weeks. Both groups experienced a decline in maximal voluntary isometric force production at Mid (E+S -15.6% ± 9.1, S+E -25.5% ±10.3, both $p<0.001$) and Post (E+S -25.9% ±10.4 and S+E -27.1% ±10.2, both $p<0.001$). (Fig 26.) A between-group difference was seen at Mid, where S+E was significantly more fatigued (74.6% of Pre) than E+S (84.4% of Pre). For S+E a significant ($p<0.05$) difference was observed at Mid and Post compared to 0 week-loadings (Mid Δ 0 weeks and 24 weeks = -5.1%, Post Δ 0 weeks and 24 weeks = -5.2%). Both groups had recovered already by 24h. The relative contribution of the first part of the loading to the total decrease in MVC was 60.0% for E+S and 93.9% for S+E.

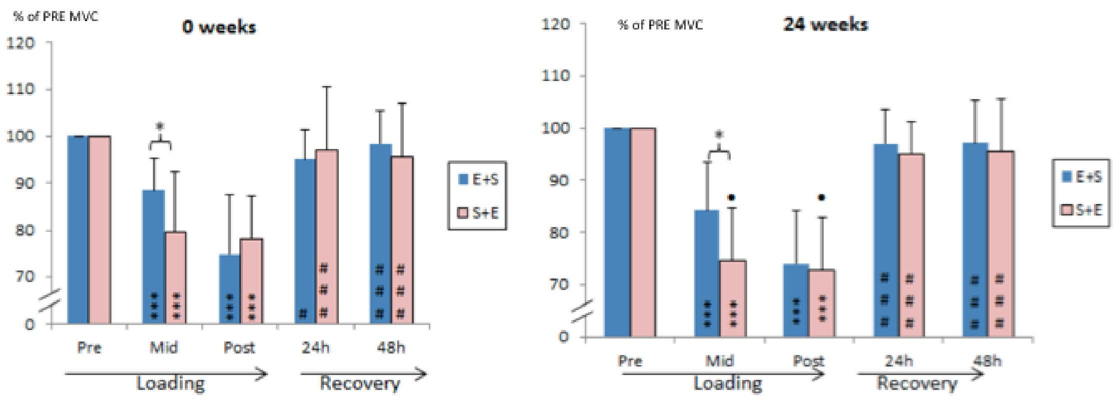

Fig 26. Maximal voluntary isometric contractions for E+S and S+E during loading and recovery at 0 and 24 weeks. * = significant from pre # = significant from post. ⌐ Indicates between-group difference. • Indicates within-group difference to corresponding timepoint at 0 weeks. *p<0.05 and ***p<0.001. #p<0.05 and ###p<0.001 and •p<0.05.

Force production in 500ms during loading: 0 weeks. Both groups experienced a significant decrease in rapid force production at 0-500ms at Mid (E+S -13.3 % ±10.1, S+E -15.8% ±18.5, both p<0.05) and at Post (E+S -24.2% ±13.4 p<0.001, S+E -16.9% ±14.5 p<0.05). (Figure 27.) The E+S group experienced a further decline from Mid to Post (-10.9%), and was more fatigued (but not significantly) at Post than S+E (E+S 75.8% p<0.001, S+E 83.1% p<0.05). Force production was still compromised for E+S at 24h (92.1% ± 5.2, p<0.05) but not for S+E (96.2% ±18.1). Both groups were recovered at 48h (E+S 97.6% ± 8.15, S+E 97.0% ±14.4). No significant between-group differences were noted at any time point.

Force production in 0-500ms during loadings, 24 weeks. Both groups experienced a decline in force production 0-500ms at Mid (E+S -15.1% *p<0.05, S+E -24.5% ***p<0.001) and Post (E+S -28.2 %, S+E -68.9% both ***p<0.001). (Figure 27.) A between-group difference (p<0.05) was seen at Mid, where S+E was had a significantly more impaired force production (75.5% of Pre) than E+S (84.9% of Pre). For S+E a significant (p<0.05) difference was seen at Post compared to 0 week-loadings (Post Δ = -10.0%) but not for E+S (PostΔ = -1.8%). Both groups had recovered already by 24h.

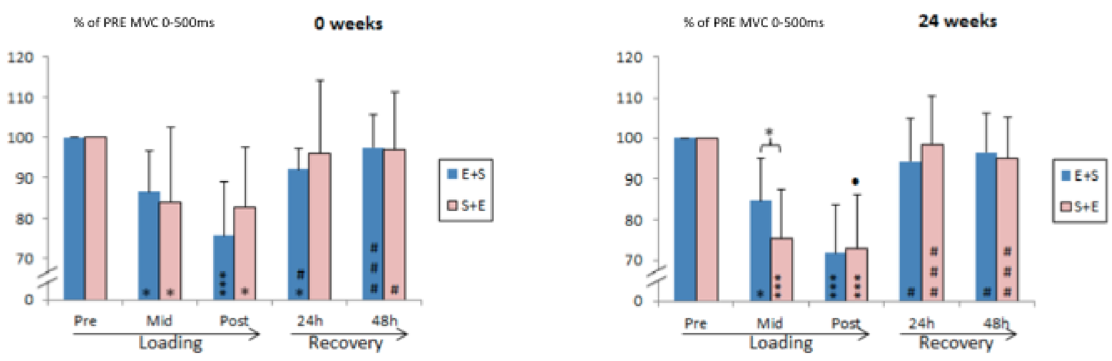

Fig 27. Force production 0-500ms for E+S and S+E during loading and recovery at 0 and 24 weeks. * = significant from pre, # = significant from post. ⌐ Indicates between-group difference. • Indicates within-group difference to corresponding time point at 0 weeks. *p<0.05 and ***p<0.001. #p<0.05 and ###p<0.001. •p<0.05.

Training induced changes in maximal dynamic 1RM. Both groups experienced significant (p<0.001) increases in dynamic 1RM (E+S +13.4% ±7.7, S+E +16.8% ±11.8). (Fig. 28.) There were no significant differences in absolute force between the groups at either 0 weeks (E+S 159.9kg ± 29.6kg, S+E 142.7kg ± 23.9kg) or 24 weeks (E+S 177.8kg ± 27.8kg, S+E 164.9kg ± 20.8kg).

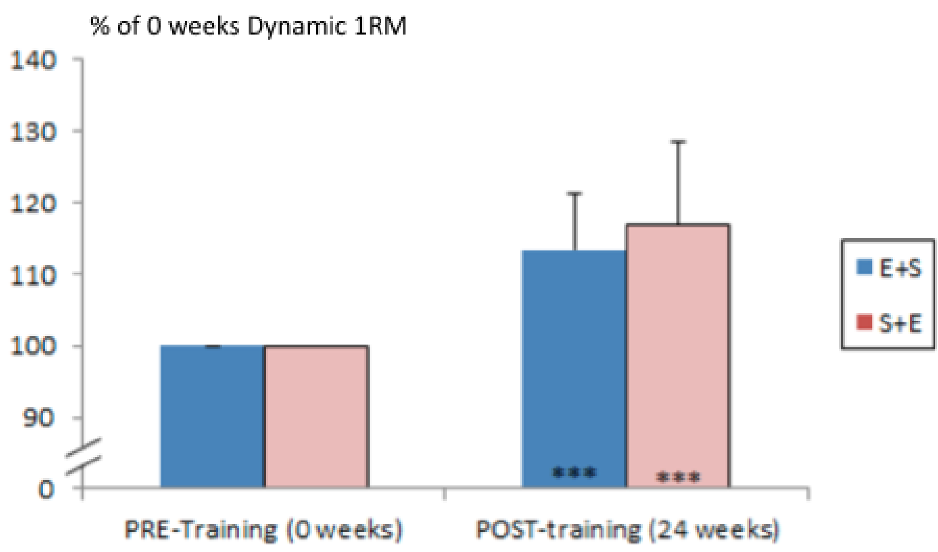

Fig. 28. Relative changes in dynamic 1RM from PRE-training to POST-training. *** = significant within-group difference from PRE-training, ***p<0.001.

8.2 Hormonal responses

Testosterone responses during loadings: 0 weeks. A significant (p<0.05) testosterone response was observed at Mid for E+S (+20.1% ±17.6 p<0.05) but not for any time point for S+E. (Fig 29.) Testosterone was significantly (p<0.05) lowered from Pre and Post at 48h for E+S (85.6% ±18.1 and 84.2% ±16.1 respectively), but not for S+E. A significant between-group difference was noted at Mid.

Testosterone responses during loadings: 24 weeks. A significant testosterone response was observed at Mid for E+S (+26.1%) but not for S+E (-0.3). (Fig 29.) This difference was also significant between the groups (p<0.05).

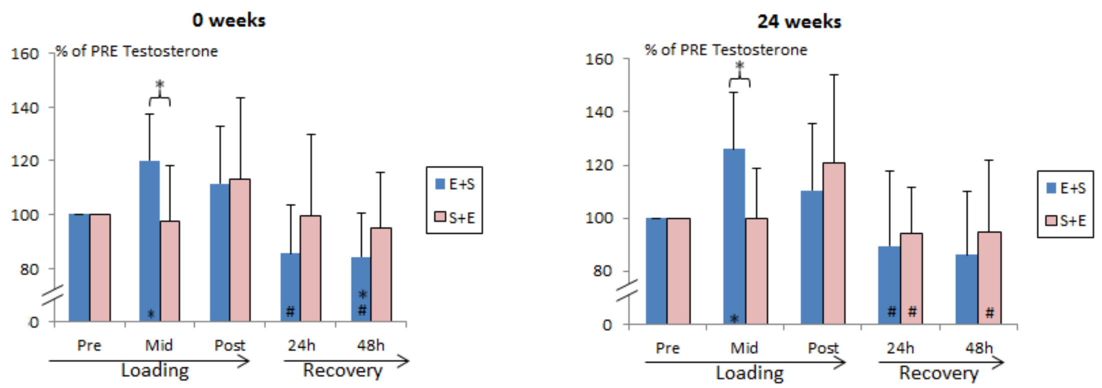

Fig. 29. Testosterone responses for E+S and S+E during loading and recovery at 0 and 24 weeks. ***** = significant from pre, # = significant from post.⌐ Indicates between-group difference. *p<0.05 and ***p<0.001. #p<0.05 and ###p<0.001.

Cortisol responses during loadings: 0 weeks. S+E showed a significantly (p<0.05) larger increase in serum cortisol levels at Post compared to E+S (42.6%). (Fig. 30.) Cortisol levels were lowered from Pre and Post for both groups at 24h (E+S -24.5% from Pre, S+E -26.9% from Pre) and 48 h (E+S -25.4% from Pre, S+E -29.0 from Pre).

Cortisol responses during loadings: 24 weeks. Neither group experienced a significant cortisol response from Pre at any time point during the loading and nor were any significant between-group differences noted. (Fig 30.) S+E demonstrated lowered cortisol levels at 24h and 48h. For E+S a significant difference to the corresponding time point at 0 weeks was noted (Δ = +20.5%).

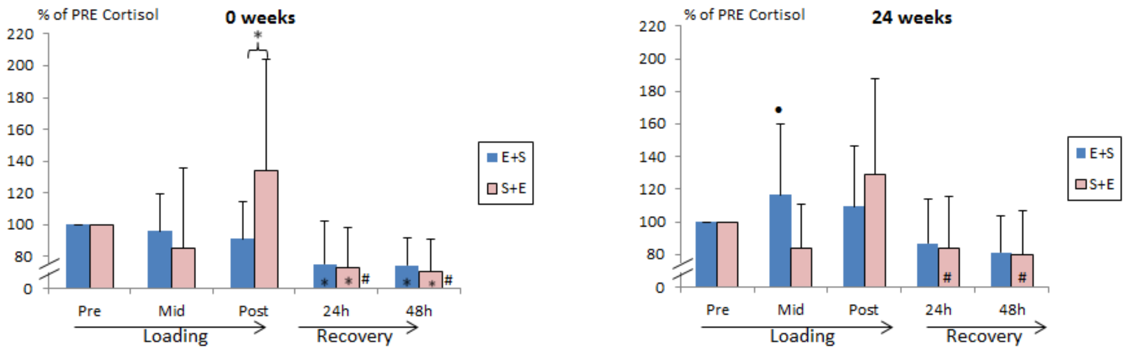

Fig. 30. Cortisol responses for E+S and S+E during loading and recovery. * = significant from pre, # = significant from post. . ⌐ Indicates between-group difference. • Indicates within-group difference to corresponding time point at 0 weeks. *p<0.05, #p<0.05 and •p<0.05.

9 DISCUSSION

The present study investigated the acute hormonal and muscular responses to a combined strength and endurance loading, their adaptations over the course of 24 weeks of combined training as well as the possible effects of the intra-session loading sequence. The main findings were:

1) The combined loading was similarly strenuous for both E+S and S+E groups in terms of acute decreases in force production variables at both 0 and 24 weeks.

2) There were differences in decreases of MVC at Post after 24 weeks so that the level of fatigue for the S+E group at post was significantly greater at 24 weeks than at 0 weeks.

3) The time differences in recovery between the endocrine system and the force production capability that were noted in the acute responses for the E+S group at week 0 were no longer observed at week 24. Recovery of MVC and MVC 0-500ms was found to be complete at 48h, while serum testosterone levels were lowered at the same time point at week 0, both variables were recovered at the same time point (48h) at week 24.

4) The fatigability of the strength loading in terms of MVC 0- 500ms increased during the course of 24 weeks of combined training. This was evident when considering the between-group difference in MVC 0-500ms found at Mid at week 24 but not at week 0. Furthermore, the S+E group experienced a statistically more significant decrease at Mid and was more fatigued at Post at 24 weeks than at 0 weeks.

5) There were differences between the effects of the present strength and endurance loadings on fatigue in terms of the measured force production variables. Between-group differences at the Mid-time point for MVC (0 and 24 weeks) and MVC 0-500ms (24 weeks) revealed a significantly greater contribution to fatigue from the present strength loading. However, the present endurance loading performed after the strength loading did not further fatigue the force production capabilities.

The results of the study thus suggest, that should the order effect to the acute responses to single-session combined loadings exist, it may be more pronounced after a prolonged period of combined training. The differences in relative contributions to acute fatigue in terms of MVC at 0 weeks and 24 weeks suggest that the different training orders may result in different training adaptations.

9.1 MVC and force production

Some recent findings (Cadore et al. 2012) suggest that the first loading in a combined strength and endurance session, independent of the loading sequence, would produce notable acute fatigue responses and possibly lead to the second loading being performed in a compromised state. In addition, a continuous low-intensity endurance loading lacks interference on subsequent strength performance (de Souza et al. 2007). In the present study, the strength loading contributed significantly to the total fatigue in terms of MVC. At both 0 and 24 weeks, the contribution of S was about 50% for E+S and about 90% for S+E. The S+E group did not experience any further significant impairment in maximal force or force production following their endurance loading, suggesting that the endurance loading did not contribute to further neuromuscular fatigue. As for rapid force production, the strength loading produced significantly greater impairments for both groups at week 24, underlining the increased strenuousness of the strength loading, possibly due to adaptations in response to prolonged strength training.

Despite the different relative contributions to the decreases in MVC and MVC in 0-500ms, the level of fatigue at Post did not differ between the groups. Furthermore, recovery after 24 weeks of training was similar for both loading orders, whereas the recovery for E+S was slower at the beginning of the study (week 0). These findings suggest that the adaptability of the acute responses to a certain type of loading order is possible. It should, however, be noted, that there were no significant differences between the groups in training induced adaptations in dynamic maximal 1RM. In previous studies (Hickson 1980; Kraemer et al. 1995), training for strength and endurance concurrently with high volume and intensity has proven to be disadvantageous in terms of strength gains in comparison to training for strength only.

Furthermore, it has been found that the time course of adaptations differs between combined training and strength training only (Bell et al. 2000) and that explosive force production is more vulnerable than maximal strength over prolonged maximal training (Häkkinen et al. 2003). The present study did not provide a possibility to monitor these but instead suggests that the order of intra-session loading sequence might not be of importance. However, as other studies (Hickson 1980; Kraemer et al. 1995) have used higher training frequencies than the present study, this opens up questions about the optimal training frequency for combined training.

9.2 Endocrine responses

Despite that the strength loading of the combined session was strenuous from the neuromuscular point of view and causing notable decreases in force production and maximal voluntary isometric contractions, it did not produce a significant testosterone response in either of the groups, as would typically be seen after a strength loading (eg. Häkkinen & Pakarinen 1993; Linnamo et al. 2005). It may well be, that the overall intensity and / or volume were diluted by the inclusion of explosive and maximal sets, as sub-maximal and explosive protocols that are less taxing on the metabolic system do not seem to provoke significant acute hormonal responses (Linnamo et al. 2005; McCaulley et al. 2009).

As the magnitude of the endocrine responses to a strength loading are dependent on the amount of muscle mass activated, intensity, type of resistance loading and the number of sets and repetitions performed as well as recovery between sets (Vanhelder et al. 1984; Vanhelder et al. 1985; Häkkinen & Pakarinen 1993; Kraemer et al. 1999; Smilios et al. 2003; Ahtiainen et al. 2004; Linnamo et al. 2005), it may be that the present overall strength loading was not metabolically demanding enough (Häkkinen & Pakarinen 1993; Raastaad et al. 2000) to elicit remarkable testosterone responses. It is thus also left unclear, whether a continuous endurance loading can interfere with the endocrine responses of a subsequent loading. However, other factors affecting the amount of circulating testosterone were not possible to monitor with the methods used in the present study. Serum testosterone concentrations are mediated by the production of luteinizing hormone (Vermeulen et al., 1972), increased testosterone secretion (Cumming et al., 1986) or reduction in clearance rates (Cadoux-Hudson et al., 1985). The reduction of testosterone clearance has even been suggested to be the foremost reason for acute, exercise-induced elevations of testosterone levels. As this process is regulated from both within and outside of the liver (Cadoux-Hudson et al., 1985), the methodology of the present thesis presents itself as insufficient in providing an answer to whether clearance levels fluctuated throughout the loading or not. Thus, the actual causes of the magnitudes of serum testosterone concentrations are left unclear. Nonetheless, as a similar trend in testosterone response to the endurance loading was noted independent of the loading sequence, this may suggest that a mixed strength exercise protocol does not interfere with the elicited testosterone responses to subsequent exercise. It may also give an implication of the strenuousness of the present endurance loading and raises a question whether or not a workload-controlled endurance loading is to be preferred over ranges of heart rate relative to maximum or blood lactate concentrations (de Souza et al. 2007; Seiler 2010).

The temporal differences in recovery between the endocrine system and the force production capability that were observed in the acute responses for E+S, were no longer observed at week 24. This may be an implication of the order of endurance preceding strength overall being more fatiguing for an untrained person who embarks to complete a combined loading. However, the presence of androgen receptors (AR) in relation to the available amounts of testosterone must be taken into account. A higher volume of a single resistance exercise bout has been found to initially down-regulate the AR content (Ratamess et al., 2005) before an up-regulation takes place (Bamman et al., 2001). This is to be considered when circulating testosterone concentration is measured in terms of the timing of the drawing of blood samples. In the present study, the timing was consistent between all the subjects, but unfortunately we were unable to take any additional blood samples during the moments immediately following the completion of the entire loading in order to reveal the possible time course of changes in AR availability (Ratamess et al., 2005). This might have been informative since the hypertrophic part of the mixed strength loading constituted for the last part of the strength loading. The phenomenon may have actually been in part reflected as the decline of serum testosterone concentrations until 48 hours post-loading in the E+S group as noted at week 0. Nonetheless, as hormonal responses to endurance exercise have a tendency to be related to training background (Viru et al. 2001; Vuorimaa et al. 2008), the faster recovery of testosterone for the E+S group after 24 weeks of training may suggest an adaptation in various components of the recovery processes of the endocrine system.

9.3 Strengths and limitations of the present study

The strengths of the present study can be attributed to the thorough overall methodology with the measurements of acute responses, adaptations to acute responses, as well as long-term adaptations of basal strength. The design of the acute loading session provided an outstanding opportunity to monitor the level of fatigue during and after the loading session as well as during recovery, and attributed both endocrine and muscular responses. The 24-week duration of the study also provided sufficient time for adaptations to develop, which provides novel information of the current research problem. Highly supervised training ensured correct execution of individual training sessions in terms of technique and intensities, and thus laid a proper foundation for long-term adaptations.

One of the flaws of the present study was related to the monitoring of endocrine behavior. The absence of fasting blood samples from the two days following the combined loading may not provide the appropriate information needed for precise monitoring of the recovery status of an individual. Considering the time-of-day-dependent, circadian patterns of testosterone and cortisol secretion (Veldhuis et al 1987; Van Cauter et al 1996), morning blood samples would have been needed in order to monitor more thoroughly the hormonal status of each subject, eg. in terms of T/C-ratio, which would have brought further information with regard to the state of the anabolic milieu and recovery status.

The statistically significant differences for the measured variables observed at the Mid-time point reveal a significant difference between the strength and endurance loading. Although it is closely related to the strength and endurance protocols respectively, it may on the other hand complicate the interpretation of a possible order and / or interference effects, when the loadings where non-equal in terms of inducing fatigue.

The strength loading was the more fatiguing of the two loadings in the current study design, especially for the S+E group at 24 weeks, which, on the other hand, can be seen as a training adaptation of overall improved strength performance. This in turn may question the sufficiency of the endurance training, and thus, adaptations in endurance performance. However, as a 20% increase in cortisol was noted following the endurance loading in the E+S group at 24 weeks compared to 0 weeks, indications exist for the endurance loading being even more strenuous. This might be attributed to an adaptation in endurance training exclusive to the E+S group. Explanations for the different amount of fatigue produced by the loadings might also lie in different sites of fatigue. However, the present study was not able to provide thorough answers for this within the methodology utilized.

9.4 Conclusions and practical applications

The present study provides some evidence for an order effect in terms of adaptations to the acute responses of a combined strength and endurance loading, since the observed adaptations seem to be order-specific. However, no order effect was found for training induced adaptations in maximal dynamic 1 RM. These findings indicate that despite order-related adaptations in acute responses, the magnitude of chronic adaptations in performance may not be related to the intra-session loading order with the present loading and training protocols and previously untrained subjects.

Without any prior experience of combined loadings, recovery appeared to be slightly delayed after the E+S loading in comparison to S+E, but 24 weeks was enough for adaptation that led to faster recovery for the E+S group. As the recovery follow-up revealed that 48 hours was sufficient for recovery for both groups and the present training frequency was 2-3 combined sessions per week, it may be an explanation for the significant gains in strength despite different loading orders. However, the present study did not provide an opportunity to monitor the effect of the addition of endurance loading to supplement strength loading, and the magnitude of a strength-only training protocol is thus left unclear. Nevertheless, this finding bears practical relevance when prescribing training frequencies for combined training and emphasizes the importance of full recovery.

It should be born in mind, that the application of the obtained results to other protocols of combined training may not be reasonable per se, as acute training variables for both endurance (Vanhelder et al. 1984b; Gray et al. 1993; Van Bruggen et al. 2011) and strength loadings as well as rest (Häkkinen et al. 1988; Häkkinen & Pakarinen 1993; Häkkinen 1994; McCaulley et al. 2009) all affect the acute outcome of a loading. In addition, as observed in this study, inter-individual variation may be large and may grow even larger with training, underlining the importance of individually designed loadings for both training and research purposes. However, the study does provide evidence for improved overall strength (1 RM) independent of the loading order and without between-group differences, despite the adaptations to acute responses being order-specific in nature. These findings have practical relevance for individuals aiming to improve strength while training for strength and endurance simultaneously.

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