GROUND REACTION FORCES, NEUROMUSCULAR AND METABOLIC RESPONSES TO COMBINED STRENGTH AND ENDURANCE LOADING IN RECREATIONAL ENDURANCE ATHLETES

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ABSTRACT

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Among recreational and elite endurance athletes strength and endurance loadings are often performed concurrently to improve neuromuscular capacity in order to enhance running economy and maximal running velocity (i.e. running performance). Measuring the ground reaction forces provides valuable information about the alteration of running technique. Therefore, this study investigated acute changes in ground reaction forces (GRFs) and running stride variables (RSVs) as well as changes in neuromuscular performance and in metabolic status in responses to a single session combined strength and endurance loading (S+E and E+S). Secondly it studied the order effect of the combined loading.

A group of 12 male (38±8 years) and 10 female (34±8 years) recreationally endurance trained subjects participated in the study. All subjects took part in two combined loading sessions; one with E loading followed immediately by S loading (E+S) and one with the opposite order (S+E). Prior to the measurements subjects were tested for their E (VO_2max) and S performance (maximal bilateral isometric leg extension force, MVC). The subjects then performed both loadings in a randomized order. E consisted of continuous running for 60 minutes (min) at a given intensity between aerobic and anaerobic thresholds. The S loading (45 min) included both maximal and explosive strength exercises (3 x 8 reps with 75 % of 1 RM and 3 * 10 reps with 40 % of 1 RM with 2 min rest between sets) for leg extensor muscles. Changes in ground reaction forces (in horizontal and vertical direction with impulses) and running stride variables, and neuromuscular (MVC, MVC500, CMJ) responses to combined loadings were measured before (PRE), following the first S or E (MID) and after completing the combined loading (POST) in both S+E and E+S. Metabolic changes in E were measured during the first and last 10 min of the endurance loading and determined as the average of minutes 6–8 and 56–58.

The main finding was that running biomechanics were altered significantly only after strength loading preceding endurance loading (S+E) but not after E+S. For men, stride length ($p < 0.05$), flight time ($p < 0.01$), vertical active peak force ($p < 0.01$) and total vertical impact ($p < 0.05$) decreased, while stride frequency ($p < 0.001$) increased in response to S+E loading order. There was an order effect in vertical active peak force between the loadings in men. For women, the only significant change was an increase in stride frequency ($p < 0.05$) in response to S+E loading order.

The present study showed that there was an order effect in running biomechanics (GRFs and RSVs) between combined loadings (S+E and E+S). Running biomechanics were altered only after strength loading preceding endurance loading (S+E), suggesting higher fatigue and increased changes in the running stride, after S+E loading compared to E+S loading. The neuromuscular and metabolic responses did not show the order effect and the associations were not unambiguous due to quite high intra- and inter-individual changes

Key Words: ground reaction forces, running biomechanics, contact time, acute responses, combined endurance and strength loading

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1 INTRODUCTION

To improve running performance endurance training is most irreplaceable. Although, one must remember that fundamentally running is continuous force production during consecutive running strides. One way to assess force production during running is to observe the ground reaction forces. The first major study among distance running and forces that occur during it was conducted by Cavanagh and Lafortune in 1980 and since then, alterations in running mechanics in response to endurance loading has been observed (e.g. Nicol et al. 1991; Morin et al. 2011a,b). Generally it seems that running stride patterns are highly individual and usually naturally chosen to be most economical (Kyröläinen et al. 2000; Hausswirth et al. 1997).

There have been observed substantial improvements in running economy or running performace by adding or replacing part of endurance training with strength training (Jung 2003). Paavolainen and colleagues (1999a) outlined that endurance performance is in relation not only to aerobic and anaerobic capacity but in addition to neuromuscular capacity. The maximal speed or running performance can be improved through strength and sprint training, which then also increase endurance performance. However, strength training and endurance training are well known to induce almost opposite training adaptations. Hickson already in 1980 reported some interference effect of combined strength and endurance training. Training responses for the cardiovascular system seemed to be as beneficial as by endurance only, but interference was noticed on neuromuscular training responses compared to strength only (Häkkinen et al. 2003; Wilson et al. 2012).

There is no previous study to assess the force production in submaximal running (ground reaction forces) and in isometric maximal leg press in response to combined single session strength and endurance loading. In addition, there is no data available whether the responses differ in response to different sequencing order of the combined strength and endurance loading (S+E vs. E+S). This information could offer practical application to recreational or even elite endurance athletes how to program the training.

2 GROUND REACTION FORCES IN RUNNING

Running is a typical locomotion, which contributes reaction and stretching forces to different body segments (Komi 2003, 184). The active stretch (eccentric contraction) followed by immediate shortening (concentric contraction) of the same muscle is called the stretch-shortening cycle (SSC) as presented in Figure 1.

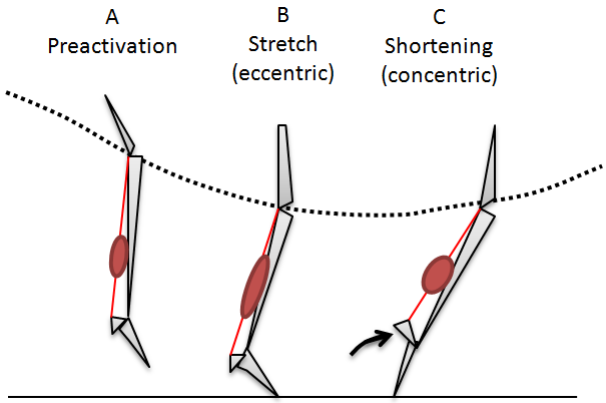

FIGURE 1. Pre-activation in tibialis posterior muscle group before ground contact (A). As the foot strikes the ground energy is stored to elastic structures of the muscle tendon unit (B). In propulsion phase the potential energy stored in elastic structures is released as a kinetic energy (C). (Komi 2003, 185.)

Whenever a part of the runner's foot is in contact with the ground, this part exerts a force on the ground and the ground reacts with an equal and opposite force, called *the ground reaction force* (GRF) (Nigg 2000, 255). In running, impact forces occur when the foot lands on the ground. The timing and magnitude of the impact force peak depend on various factors, including speed, material properties of the shoe sole and running style. (Nigg 1999, 276.)

2.1 Determining ground reaction forces

Ground reaction forces during running can be divided into three different components: the vertical, horizontal (anterio-posterior) and medio-lateral component. Most often,

there occur two impacts in the vertical force component, especially with heel-strike running pattern (Nigg 1999, 276 – 277). The first is called *impact peak* (5 - 30 ms after beginning of the contact), and the second *the active peak* (Nigg 1999, 276) as described in figure 2, left graph (Kluitenberg et al. 2012). In general, impact forces in human locomotion are forces that result from a collision of two objects reaching their maximum value earlier than 50 ms after the initial contact of two objects (Nigg 1999, 276). The magnitude of the impact peak is speed dependent and occurs during the first 10 % of contact phase (usually 10 – 30 ms) (Hreljac 2004). The active peak (maximal vertical GRF) is reached approximately during mid-stance and can last up to 200 ms (Kluitenberg et al. 2012). The vertical impact force peaks are earlier for barefoot running (5 – 10 ms after first contact) than for running with shoes, and earlier for running with harder shoe soles than running with softer shoe soles. Some individuals show more than one impact peak, one resulting when the heel strikes and one when the forefoot does. (Nigg 1999, 276.) The absence of a separate impact peak in the force-time curve is typical for non-heelstrike runners (Fig. 2 right graph) (Williams 1985).

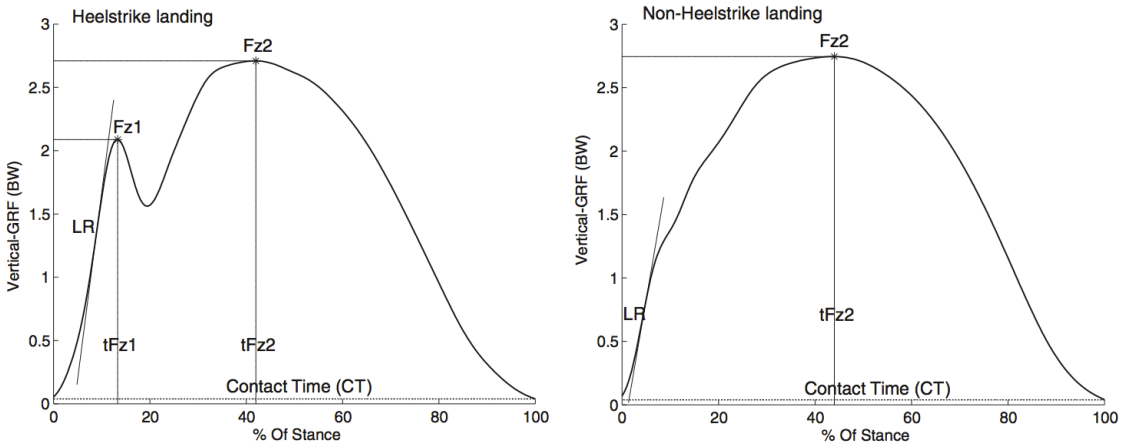

FIGURE 2. Typical vertical ground-reaction force (GRF) curve for a heelstrike (*left*) and non-heelstrike (*right*) runner. Fz1 and Fz2 stand for *impact peak* and *active peak*, respectively. The grade of line (LR) describes loading rate. (Kluitenberg et al. 2012.)

Loading rate. When studying how fast the force is increasing during landing, one variable describing this phenomenon is *the loading rate* (LR). The loading rate indicates how fast the force changes in time and can be depicted as the slope of the force-time curve (Fig 2.). (Kluitenberg et al. 2012.). It is often assumed that the loading rate of the force acting on the locomotor system is associated with the development of movement

related injuries (Nigg 2000, 254). Loading rate and GRF impact peak do not gain as great values when landing with the mid- or forefoot compared to heel-strike landing (Cavanagh & LaFortune 1980).

The force component in the horizontal (anterior-posterior) direction has two active parts, which defines the braking and the propulsion phase of ground contact. In the first half of the ground contact while braking, the foot pushes in the anterior direction causing the ground to react with an opposite, backwards pushing force (braking force). In the second half of the ground contact the foot pushes in posterior direction and propulsive force occurs. (Nigg 1999, 278.) Examples of vertical and horizontal GRF for running with slow pace (heel landing) and sprinting (toe landing) are illustrated in figure 3 (Nigg 2000, 255.)

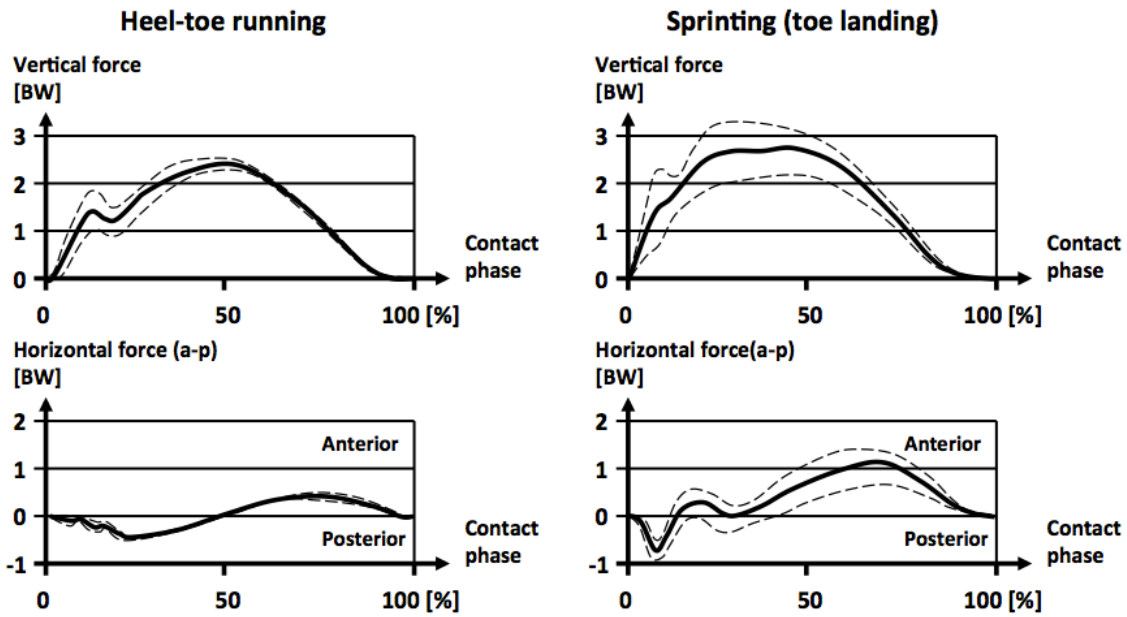

FIGURE 3. Illustration of ground reaction force (GRF) components (mean = solid line; Standard deviation = dashed line) in vertical and anterior-posterior (a-p) direction for running heel-toe (left) and sprinting (right) in units of body weight [BW]. Both curves are mean values with SD for five subjects (different for two tests) with three trial each. (Nigg 2000, 255.)

The medio-lateral GRF is the least consistent of the three GRF components and it often shows initial reaction force in lateral direction (Munro et al. 1987). On the contrary,

Kyröläinen et al. (2001) reported short initial inward (medial) force in the beginning of the contact. The intra- and inter-individual variability is much larger for the medio-lateral than the vertical and the anterior-posterior force-time curves. In addition, substantial differences may exist in the GRF components between the left and the right foot strike for one subject. (Nigg 1999, 278.) Kyröläinen et al. (2001) found the GRFs to be slightly higher than in earlier findings. Their values varied from 2.7 to 3.5 times body weight (BW) and from 0.4 to 1.1 times BW in vertical and horizontal direction, respectively. The medio-lateral force was slightly smaller (0.05 to 0.1 BW) as compared to previous results of Cavanagh & LaFortune (1980). Table 1 presents a summary of the vertical GRFs during running from different studies.

TABLE 1. Vertical impact force peaks (active peak) in walking and running. (* = Body weight assumed 700 N) (Nigg 1999, 277).

Movement	Shoe	Velocity (m/s)	Fzmax (N)	Fzmax/BW	Study
Walking	Barefoot	1,3	385*	0.55	Cavanagh 1981
	Army boots	1,3	259*	0.37	Cavanagh 1981
	Leisure shoes	1,3	189*	0.27	Cavanagh 1981
Running (heel contact)	Running shoe	4,5	1540*	2.2	Cavanagh 1980
	Running shoe "hard"	4	2000	2.9	Nigg 1980
	Running shoe "soft"	4	1100	1.6*	Nigg 1980
	Running shoe	3,4	1365	2.0	Frederick 1981
	Running shoe	3,8	1590	2.3	Frederick 1981
	Running shoe	4,5	1963	2.9	Frederick 1981
	Running shoe	3	1345	2.0*	Nigg 1987
	Running shoe	4	1521	2.2*	Nigg 1987
	Running shoe	5	1799	2.6*	Nigg 1987
	Running shoe	6	2070	3.0*	Nigg 1987
Running (toe contact)	Running shoe	4	300	0.4*	Denoth 1980

Impulses. Linear impulse (FΔt) or the time integral of a GRF, measures the change in momentum and quantifies the time course of the GRF (Heise & Martin 2001). Williams & Cavanagh (1987) pointed out several profound GRF measures, which included total vertical impulse (TVI), which can be considered as an indicator of overall muscular support during ground contact. The TVI is calculated as presented in formula 1, where F_v is the mean vertical force component, BW is subject's body weight, and t_c is the time of ground contact. (Heise & Martin 2001.)

$$TVI = \int_0^{t_c} \left\{ \frac{F_v}{\mathrm{BW}} \right\} \mathrm{d}t \qquad (1)$$

As the velocity increases, force production time during the contact phase decreases and the GRF increases significantly in vertical and anterior-posterior directions (Figure 4) (Kyröläinen et al. 2005). Weyland et al. (2000) concluded that the runner reaches faster top speeds by applying greater vertical support forces to the ground, not by more rapid leg movements.

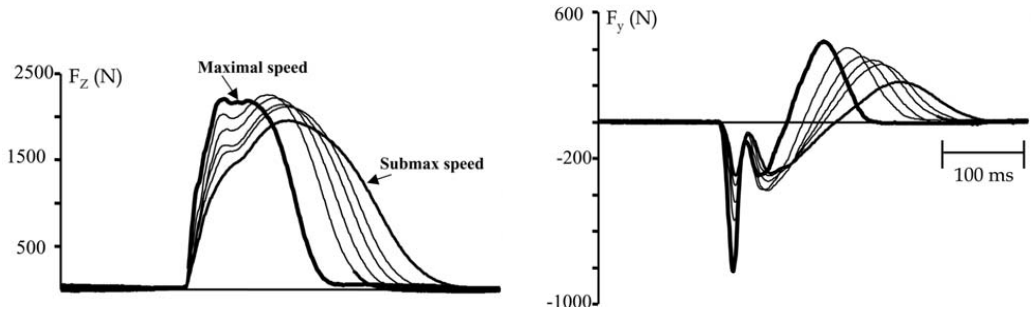

FIGURE 4. Vertical (F_Z) and horizontal (a-p) (F_Y) GRFs from submaximal speed (narrow line) to maximal speed (thick line), (Kyröläinen et al. 2005).

Contrary to this, Nummela et al. (2007) noticed that vertical effective force ($(F_z - F_{BW}) \cdot F_{BW}^{-1}$) increased until the speed of 7 m · s^{-1}. Thereafter the speed was increased without a further increase in vertical effective force (Fig 5.A). Nummela and his colleagues (2007) observed horizontal force increasing linearly with the running speed (Fig 5.B), suggesting that maximal running speed is more dependent on horizontal than vertical force production.

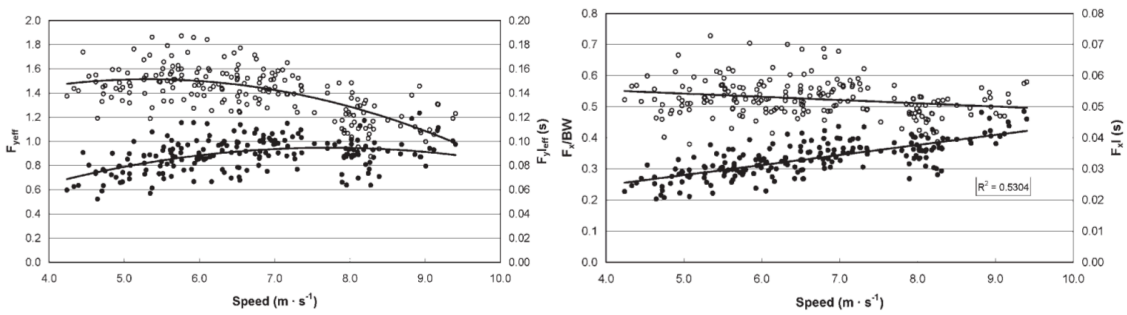

FIGURE 5. Running mechanics in relation to running speed. Left figure (A): Increase in vertical effective force (dots) and decrease in effective impulse (grey dots) with increasing speed. Right figure (B): increase in mass-specific horizontal force (black dots) and horizontal impulse (open circles) with increasing speed. (Nummela et al. 2007.)

In addition to increased GRFs contact time of running stride are decreasing simultaneously when running velocity is increased. Contact time was measured to last 0.203 (± 0.011) s at slow running pace in endurance trained men. Contact time was decreased progressively to 0.112 ± 0.007 s while running velocity increased to maximal. Stride frequency increased at the same time from 2.82 ± 0.13 to 4.16 ± 0.26 Hz and stride length from 1.51 ± 0.10 to 2.12 ± 0.15 m. (Kyröläinen et al. 2005.)

2.2 Ground reaction forces in relation to running economy

During ground contact, a runner activates muscles for the purpose of stability and maintenance of forward momentum. Excessive changes in the vertical and horizontal directions are wasteful in terms of metabolic energy. (Saunders et al. 2004.) Linear impulse measures the change in momentum and quantifies the time course of the GRF. Quantifying the magnitude of support and forces during ground contact may explain at least in part the variability in RE among individuals of similar fitness. (Heise & Martin 2001.) The greater GRFs in the beginning of the contact are related to increased oxygen consumption, but the findings have been controversial depending on the training status of the subjects (Williams 1990, 287). There is a correlation (r = 0.56) between vertical impact peak and submaximal oxygen consumption in recreational endurance runners, but the association is disappeared among athletes (Williams & Cavanagh 1987).

Heise & Martin (2001) observed the relation with GRFs and RE. Less economical runners exhibited greater total and net vertical impulse, indicating wasteful vertical motion. Correlation between total vertical impulse and VO2 were r = 0.62. The combined influence of vertical GRF and the ground contact time explained 38 % of the inter-individual variability in RE. In other words, the most economical runners exhibited greater force in relation with time. (Heise & Martin 2001)

On the contrary, Nummela et al. (2007) did not find any relation between GRFs and RE. The only association was observed between contact time and running economy (r = 0.49). Based on previous finding, Nummela et al. (2007) evaluated fast force production

to be crucial for economic running, even though GRFs were not measured at the same running pace than RE assessment. That could be the reason why Kyröläinen et al. (2001) did not find contact times to be in relation with submaximal oxygen consumption.

The relationship between running kinematics and running economy seems to be controversial. According to Williams and Cavanagh (1987), running economy is the sum of the influence of many variables. However, it appears that no single kinematic variable can fully explain the decrease in running efficiency (Hausswirth et al. 1997) or in running economy (Williams et al. 1987; Nicol et al. 1991a). Thus, one could conclude that individual changes in running kinematics, as measured at marathon-running speed, could only partially explain the drastically weakened running economy (Kyröläinen et al. 2000). Vertical GRF is the major determinant of the metabolic cost during running (Saunders et al. 2004). However, horizontal forces can substantially affect the metabolic cost of running (Chang & Kram 1997).

3 ACUTE RESPONSE TO STRENGTH LOADING

Single heavy resistance exercise leads to acute neuromuscular responses (e.g., temporary muscle fatigue) and induces acute increases in serum anabolic hormone concentrations (i.e., testosterone and growth hormone). The magnitudes of acute neuromuscular and hormonal responses are influenced by exercise variables such as the volume and intensity of the resistance exercise and recovery between sets. (Ahtiainen et al. 2003; Häkkinen 1993, Kraemer et al. 1990.) In addition the magnitude and the source of fatigue may vary when different contraction type (Babault et al. 2006) and contraction speed (Linnamo et al. 1998) are utilised. These acute responses are supposed to be primary stimuli for neuromuscular and hormonal adaptations that lead to muscle tissue hypertrophy and strength development during prolonged strength training (Kraemer et al. 1999).

Strenuous heavy resistance isometric (Babault et al. 2006) or dynamic (Linnamo et al. 2005; Ahtiainen et al. 2003) muscular work usually leads to momentary changes both in muscular strength and in the maximal voluntary neural activation (iEMG) of the exercised muscles. These changes are also related to acute neuromuscular changes which appear not only as a decrease in maximal peak force but also as remarkable shifts in the shape of force-time curve as well as a decrease in iEMG in maximal voluntary contractions. (Häkkinen 1993.)

3.1 Maximal isometric force and force – time characteristics

The magnitude of the acute, fatigue induced decrease in neuromuscular performance is related to the overall volume and the loading intensity of the training session as well as to the specific type of the fatiguing load (Häkkinen 1993). Heavy hypertrophic strength training (e.g. 5 * 10RM with 3 min rest between sets) induced an acute decrease in bilateral isometric leg extension in men and women of different ages ($p < 0.01$ - 0.001)

(Häkkinen & Pakarinen 1995). As one could expect, a heavy resistance exercise protocol such as 20 times one-repetition maximum (1RM) squatting with 3 minutes rest between sets resulted in remarkable decreases in maximal isometric force in men and women. However after the 9th set, the decrease in maximal strength was larger in males than in females (Figure 6), which might originate in different muscle fiber distribution between males and females. (Häkkinen 1993.)

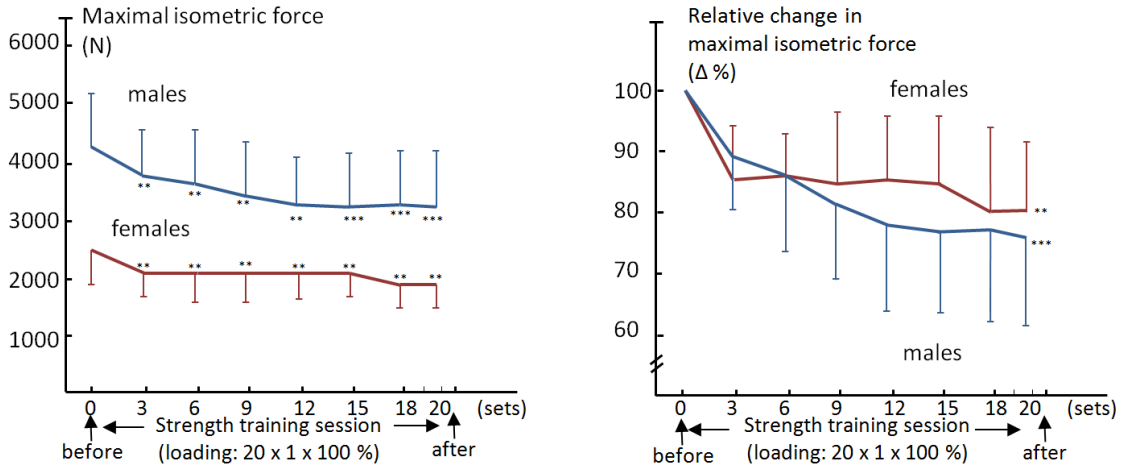

FIGURE 6. Maximal bilateral leg extension force (MVC) (left) and the relative changes in MVC (right) in male and female athletes. (** = p<0.01, *** = p<0.001) (Häkkinen 1993).

Similarly, Ahtiainen et al. (2003) observed significant decrease in isometric leg press as an acute neuromuscular response to heavy resistance strength loading. Strength levels decreased after 12RM and forced repetition (FR) sets to 62 % and 44 % of PRE values, respectively, ($p < 0.001$) (Figure 9). (Ahtiainen et al. 2003.) Findings of Ahtiainen & Häkkinen (2009) supported that strength athletes can evoke larger neuromuscular fatigue after heavy resistance loading than non-athletes due to greater motor-unit activation.

Table 2 presents a summary of acute responses to various heavy strength loadings in terms of reduction in maximal voluntary contraction in bilateral leg press. Generally, it appears that greatest reductions are achieved with hypertrophic loading pattern (10 RM or 12 RM) with nearly 100 repetitions totally (Ahtiainen & Häkkinen 2009; Ahtiainen et al. 2003; Häkkinen & Pakarinen 1993). Acute strength loss is greatest after assisted (i.e., forced repetitions) (Ahtiainen & Häkkinen 2009), but however also traditional

maximal strength loading (1 – 3 RM) appears to decrease MVC from 10 – 24 % (Häkkinen & Pakarinen 1993; Häkkinen 1993; McCaulley 2009). Explosive strength loading leads to minor reductions from 7 to 12 % (Linnamo et al. 2005, McCaulley et al. 2009; Table 2.)

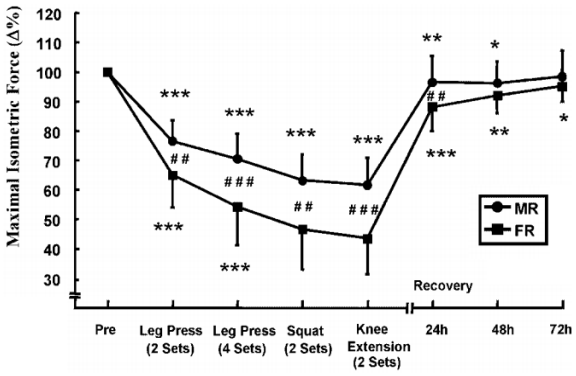

FIGURE 7. Relative change in MVC leg extension (mean ± standard error) during and after the maximal repetitions (MR) and forced repetitions (FR) strength loadings. Significantly different (*) from PRE and (#) between the MR and FR. (Ahtiainen et al. 2003.)

TABLE 2. Loss in maximal voluntary contraction in response to various (maximal, hypertrophic and explosive) strength loadings. * - *** = p 0.05 – 0.001.

	Strength loading			Loss in MVC (%)
Study	**Subjects**	**Type**	**Strength program**	
Häkkinen & Pakarinen 1993	M+	Maximal	20 x 1 RM/3' (100 % 1RM)	10 % ***
McCaulley et al. 2009	M+	Maximal	11 x 3/5' (90 % 1RM)	17 % *
Häkkinen 1993	M+	Maximal	20 x 1 RM/3' (100 % 1RM)	24 % ***
Häkkinen 1993	F+	Maximal	20 x 1 RM/3' (100 % 1RM)	22 % **
Peltonen et al. 2013	M	Maximal	15 x 1 RM/3' (100 % 1RM)	22 ***
Walker et al. 2013	M	Maximal	15 x 1 RM/3' (100 % 1RM)	16 % *
Häkkinen & Pakarinen 1993	M+	Hypertrophic	10 x 10 RM/3' (70 % 1RM)	25 % ***
McCauelley et al. 2009	M+	Hypertrophic	4 x 10/1.5' (75 % 1RM)	23 % *
Ahtiainen & Häkkinen 2009	M	Hypertrophic	8 x 12 RM/2' for leg ext.	34 % ***
Linnamo et al. 2005	M	Hypertrophic	5 x 10 RM/2' (100 % 10RM)	24 % *
Linnamo et al. 2005	F	Hypertrophic	5 x 10 RM/2' (100 % 10RM)	19 % *
Ahtiainen et al. 2003	M	Hypertrophic	8 x 12 RM/2' for leg ext.	38 % ***
Ahtiainen et al. 2003	M	Hypertrophic+	8 x 12 RM/2' for leg ext.	57 % ***
Ahtiainen & Häkkinen 2009	M	Hypertrophic+	8 x 12 RM/2' for leg ext.	44 % ***
Peltonen et al. 2013	M	Hypertrophic	5 x 10 RM/2' (80 % 1RM)	37 % ***
Walker et al. 2013	M	Hypertrophic	5 x 10 RM/2' (80 % 1RM)	44 % **
McCaulley et al. 2009	M+	Plyometric	8 x 6/3' (0 % 1RM)	7 %
Linnamo et al. 2005	M	Explosive	5 x 10 RM/2' (40 % 10RM)	11 % *
Linnamo et al. 2005	F	Explosive	5 x 10 RM/2' (40 % 10RM)	12 % *
Peltonen et al. 2013	M	Explosive	5 x 5 RM/3' (40 % 1RM)	5 %

M = male, **F** = female, **+** = strength training background, **hypertrophic+** = assisted repetitions.

A strenuous maximal strength session with multiple sets led to great shifts to the right in each part of the force-time curves both in males ($p < 0.001$) and in females ($p < 0.01$) though the shift was significantly ($p < 0.05$) greater in males, Also rate of force development (RFD) in first 100ms was significantly decreased already after 3 sets of 1RM in males ($p < 0.01$) and in females ($p < 0.05$). Maximal strength session led to clear shifts to the right in force-time curve in men ($p < 0.001$) and women ($p < 0.01$) in each portion during first 500 ms of isometric contraction (Figure 8). (Häkkinen 1993.)

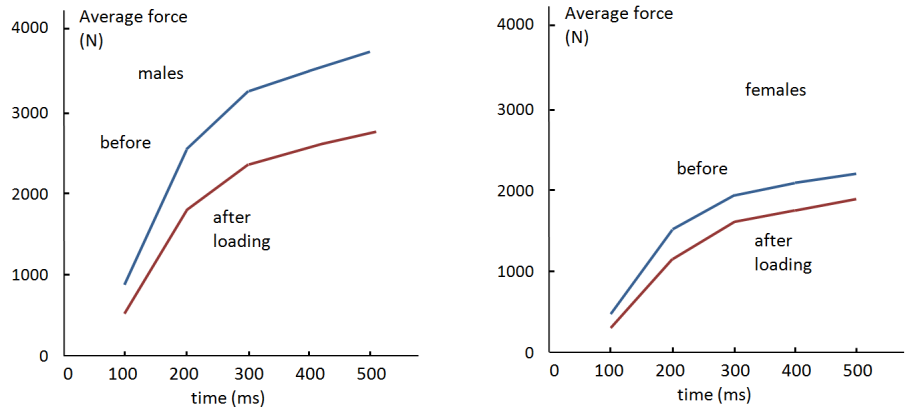

FIGURE 8. Average force-time curves of the leg extensor muscles in the rapidly produced MVC in men (left) and women (right) before and after maximal strength exercise. (Modified from Häkkinen 1993.)

3.2 Muscle activation

The type of strength exercise loading contributes very dramatically to EMG activity (Figure 9) (McCaulley et al. 2009). Ahtiainen et al. (2003) found a decrease in EMG after an ultimate hypertrophy loading. In contrast to the maximum strength type of resistance exercise the explosive strength loading is known to stimulate type IIa type of muscle fibers as well as increase motor unit activation to elicit neural improvements (McCaulley et al. 2009). Walker et al. (2013) observed EMG responses to maximal (15 × 1RM) and hypertrophic (5 × 10RM) strength loading. They found significant reductions in EMG amplitude in both vastus lateralis and vastus medialis muscles only after the maximal strength loading (-29 %, $p < 0.05$ and -22 %, $p < 0.05$) suggesting a decrease in the ability to activate the muscles (central fatigue) (Walker et al. 2013).

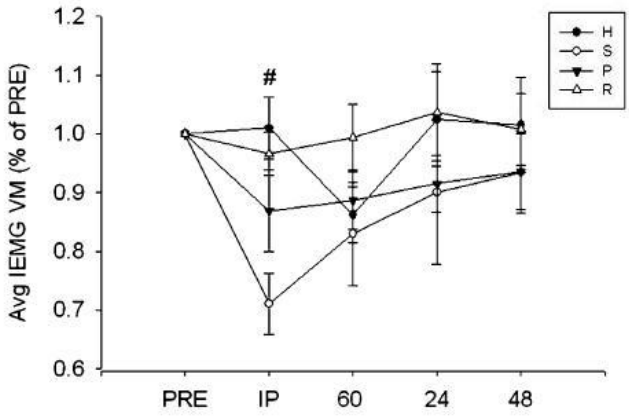

FIGURE 11. Averaged iEMG in isometric leg press between hypertrophy (H), maximum strength (S) and power type (P) loading and resting conditions (R) before (PRE), immediately after (IP), 60 min, 24 and 48 hours after loading. # = significantly ($p<0.05$) increased compared to S. (McCaulley et al. 2009).

Maximal strength. Häkkinen (1993) examined the effects of a heavy resistance exercise loading – 20 times one-repetition maximum (1RM) squatting with 3 minutes recovery between sets – on maximal isometric force and maximum iEMG during a strength session. The maximal strength session led to a significant decrease in knee extensors (*vastus medialis, vastus lateralis* and *rectus femoris*) iEMG ($p<0.05$-0.01) in male strength athletes, while the changes were minor in females and only significant ($p < 0.05$) for the vastus medialis muscle (Figure 10) (Häkkinen 1993).

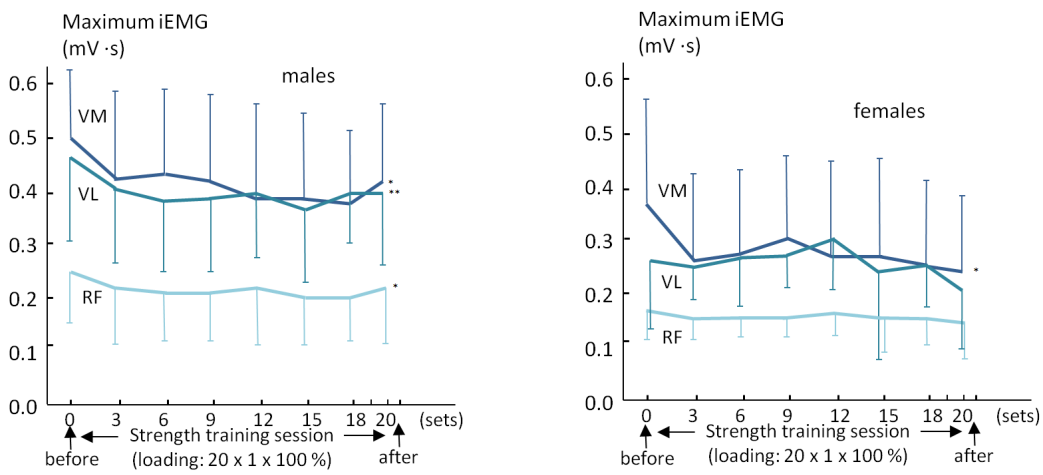

FIGURE 10. The mean (± SD) maximal integrated electromyography (iEMG) of the vastus medialis (VM), vastus lateralis (VL) and rectus femoris (RF) muscles in bilateral isometric leg press in male (left) and female (right) athletes. (* = $p < 0.05$ and ** = $p < 0.01$). Modified from Häkkinen 1993.

Hypertrophic strength. Heavy resistance exercise with sets of 12 repetition maximum (12RM) did not cause decreases in EMG activity during maximal voluntary contraction (MVC), but forced repetition maximum (FM) sets, where the load was on average 13 % higher than in RM sets, induced significant decrease in vastus lateralis and vastus medialis integrated EMG ($p<0.05 – 0.01$) (Figure 11) (Ahtiainen et al. 2003). Indeed, during heavy resistance exercise muscle activation tend to increase in dynamic 12 repetitions maximum leg extension exercise. When the load is increased to represent 8RM but still 12 repetitions are required, (so called forced repetition maximum), experienced strength athletes seem to experience a significant decrease in iEMG after 6 reps (Figure 13) due to exercise-induced neural fatigue. Otherwise recreational, non-strength athletes tend to maintain the same level even though forced repetition maximum. (Ahtiainen & Häkkinen 2009.) Similarly, in the study of Walker et al. (2013) 5 × 10RM did not cause significant reduction in EMG.

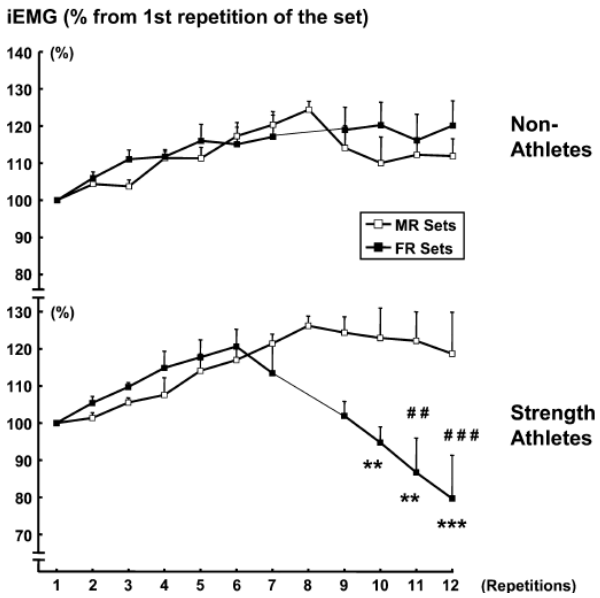

FIGURE 11. Integrated electromyogram activity (iEMG) during the concentric phases of the 12 rep knee extension exercises (mean of 4 sets ± SE). Significantly different (** = $p < 0.01$ and *** = $p < 0.001$) from the sixth repetition value. Significant difference (## = $p < 0.01$ and ### = $p < 0.001$) between the maximal repetition (MR) and forced repetition (FR) sets. (Ahtiainen & Häkkinen 2009).

Explosive strength. In explosive situations, the muscles are activated maximally (as in maximal strength exercise), but with shorter duration of each repetition, which is accompanied by a lower hormonal and metabolic response (Linnamo et al. 2005). Explosive type of strength exercise induces similar neuromuscular changes as maximal (hypertrophic) strength loading, but the magnitudes are lower and the recovery is faster after explosive strength loading (Linnamo et al. 1998). However, in another study of Linnamo et al. (2005) no significant changes in MVC occurred between men and women in heavy nor explosive loading. The fast force production ability might still be weakened after explosive strength loading. The decrease in iEMG for the early contraction phase (0 – 100 ms) in response to explosive strength loading was significantly greater ($p < 0.05$) compared to heavy (hypertrophic) strength loading. (Linnamo et al. 1998.) Furthermore, maximal EMG has observed to decrease (11 %, $p < 0.05$) in response to power loading protocol (5 sets of 5 × 40 % 1RM) (Peltonen et al. 2013).

3.3 Blood lactate accumulation

Acute metabolic changes may be related to hormonal responses during heavy resistance exercise. Blood lactate has been shown to increase more when number of repetitions is high with high loads compared to loadings where the number of repetitions and the loads are lower (Häkkinen & Pakarinen 1993; Bush et al. 1999). Peltonen et al. (2013) compared responses of the lactate accumulation to maximal, hypertrophic and explosive strength loading and confirmed significant change after hypertrophic loading, but the changes in lactate concentration were insignificant in response to maximal and explosive strength loadings. The number of repetitions is too low and the duration of the rest interval too long after maximal and explosive loadings.

In a study of Häkkinen (1993) blood lactate accumulation was measured during very strenuous high resistance loading. Although the present loading protocol (20*1RM / 3’) was very strenuous, the lactate accumulation was very low in both men and women

strength athletes up to values of 3.5 and 2.5 mmol/l, respectively. This points out that 3 minutes resting interval between sets is enough to keep ATP and CP stores as the primary energy store during each set. (Häkkinen 1993.) On the contrary to maximal strength loading, hypertrophic and explosive strength loading generally is performed with greater number of repetitions with a maximum load or maximal muscle activation, respectively. Blood lactate concentrations increase clearly more after hypertrophic strength loading (HL) in men and women ($p < 0.01$). In men the gains in blood lactate concentration were higher in response to specific, either hypertrophic or explosive strength loading ($p < 0.05$) (Figure 12). (Linnamo et al. 2005.)

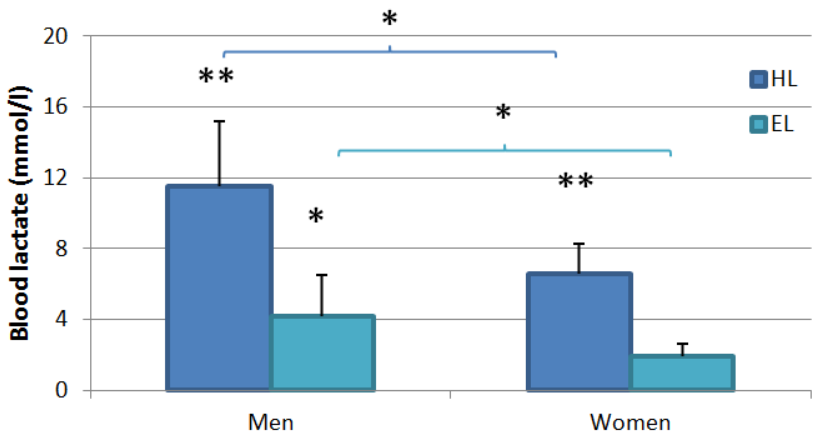

FIGURE 12. Mean (± SD) values in blood lactate concentrations after the hypertrophic strength (HL) or explosive strength (EL) loading in men and women. Modified from (Linnamo et al. 2005).

4 ACUTE RESPONSE TO ENDURANCE LOADING

During prolonged exercise it is generally believed that central fatigue may develop, and indeed, in running Millet et al (2002; 2003) have found lower level of activation due to prolonged running. In addition, metabolic (e.g. glycogen depletion or intracellular Ca2+ accumulation) as well as structural changes may be involved in muscle fatigue after long-duration exercise (Ostrowski et al. 1998; Kyröläinen et al. 2000; Overgaard et al. 2002; Rama et al. 1994).

Muscle fatigue depends largely on the type of muscular contraction (eccentric vs. concentric). It has been suggested that the excitation-contraction (E-C) coupling process is due, at least partly, to physical disruption of the membrane systems involved in the E-C coupling process. Low-frequency fatigue (LFF), also known as long-lasting muscle fatigue is connected to E-C coupling failure. (Millet & Lepers 2004.)

4.1 Changes in maximal force production

Continuous submaximal running induces a great stretch, which attenuates the regulation of muscle stiffness eventually decreasing the maximal voluntary contraction (Komi & Nicol, 2000, 399.) In prolonged running exercise of 2 hours or longer, the isometric strength loss seems to increase in a non-linear way in response to exercise duration (Millet & Lepers 2004) (Figure 13.)

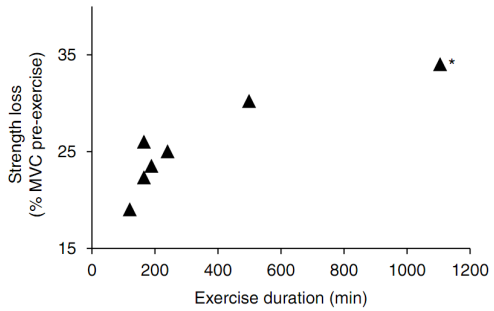

FIGURE 13. Relationship between the knee extensor muscle strength (MVC) relative reduction and the duration of running exercise (Millet & Lepers 2004).

There is a review of reductions in MVC and maximal EMG in response to various running loadings Table 3. According these studies the running distance of endurance loading is highly related to loss in MVC ($r = 0.85$, $p < 0.01$), which means in other words the longer distance the greater loss in maximal force production. In addition to the duration of endurance exercise, the intensity (%VO_2max) of running exercise and the method used to evaluate changes might affect the results of strength loss. (Millet & Lepers 2004.) The assessed response in isometric contraction seems to induce greater strength loss compared to concentric muscle contraction, 21 % vs. 11 %, respectively (Lepers et al. 2000). Respectively, with decreased force production capacity after prolonged running exercise, a decrease in iEMG activity during maximal voluntary contraction and/or during maximal running has been recorded for lower limb muscles in several studies (e.g. Avela et al. 1999; Millet et al. 2002; Nicol et al. 1991; Paavolainen et al. 1999b).

TABLE 3. Reductions in maximal voluntary contractions (MVC) and corresponding EMG activity in response to various running loadings.

		Endurance exercise		Loss in MVC	Loss in EMG
Study	Intensity	Time	Distance	(%)	(%)
Nummela et al. 2008	5 km time trial	17	5	16 % **	15 % *
Finni et al. 2003	10 km nearly max	48	10	19 % *	
Ross et al. 2010	20 km time trial	90	20	15 % *	20 % *
Saldanha et al. 2008	75 % vVO_2max	120	26,8	17 % *	
Lepers et al. 2000	75 % of vVO_2max	120	28,4	19 % **	13 % *
Millet et al. 2003	30 km cc-run race	189	30	25 % ***	21 % **
Avela et al. 1999	marathon	184	42,2	30 % ***	28 - 38 % **
Place et al. 2004	55 % vVO_2max	300	52,5	28 % ***	45 % ***
Millet et al 2002	65 km ultra race	511	65	30 % **	28 % ***

* = $p < 0.05$, ** = $p < 0.01$ & *** = $p < 0.001$

Ross and his coworkers (2010) observed leg extensor MVC and maximal EMG of VL to decrease 15 % ($p < 0.05$) and 18 % ($p < 0.01$) in response to 20 km of time trial. They also studied the time-course of fatigue by measuring the MVC in every 5 km interval, and concluded that the fatigue, in terms of strength loss, was significant only after completing the whole 20 km. The fatigue was induced by the decrease in voluntary muscle activation. (Ross et al. 2010.) Similarly, Place et al. (2004) found MVC reduction of 12 % after completing 2 h of totally 5 h running exercise. When the 5 h were completed the overall reduction had increased to 28 % ($p < 0.001$) while EMG

activity was decreased by 45 %, respectively (Place et al 2004). Avela et al. (1999) observed plantar flexor muscles to decrease maximal force production even 30 % ($p < 0.001$) in response to marathon loading. The reduction in the EMG of *Soleus* and *Gastrocnemius* were 38 % and 28 %, respectively, (Figure 14).

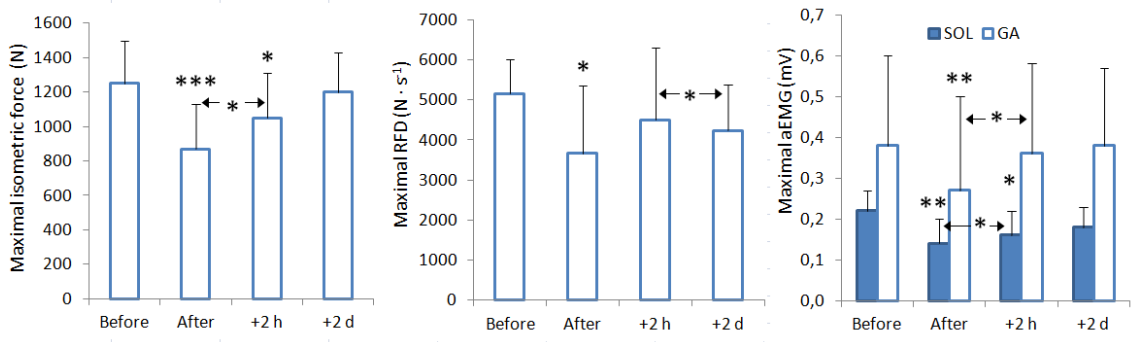

FIGURE 14. Maximal voluntary contraction B) rate of force development and C) maximal EMG activation in plantar flexion before, immediately, following 2 hours and 2 days after marathon. Sol = Soleus and Ga = Gastrocnemius. Modified from (Avela et al. 1999).

Contrary to nearly (or over) 2 hours of endurance loading the fatigue could be induced in similar magnitudes in shorter exercises as well (Nummela et al. 2008; Finni et al. 2003). A 5 km time trial reduced 20 m maximal velocity and MVC in leg press 16 % and 15 %, respectively, (both, $p < 0.001$). The reduction in maximum velocity was related to high initial maximum velocity and low VO_2max ($r = 0.58$, $p < 0.05$ and $r = -0.50$, $p < 0.05$, respectively). (Nummela et al. 2008). The force production capacity (MVC of plantar flexors) decreased 19 % ($p < 0.05$) already after submaximal 10 km. However, the decrease might be slightly greater because the subjects consisted of power and strength athletes, who did not have previous background of endurance training. (Finni ym. 2003).

However, the effects of fatigue on EMG activity in response to submaximal exercises are more controversial, than the findings of reduced muscle activation in maximal efforts. In submaximal constant speed endurance exercise, EMG ought to increase so that the given exercise intensity could be maintained. For example, at the end of marathon, greater neural input to the muscle is required to produce the same resultant force in the push-off phase of the ground contact. (Komi et al. 1987; Nicol et al 1991;

Kyröläinen et al. 2000). On the other hand, some studies (Avogadro et al. 2003; Paavolainen et al. 1999b) did not find any changes, while Nummela and his coworkers (2008) observed decrease in lower limb EMG during the pre-activation and the ground contact phase in 5 km time trial.

4.2 Changes in Ground reaction forces

Force production during running has been increasingly under interest among studies investigating the acute responses to endurance loading. There is a straight correlation between vertical active peak impact force and submaximal oxygen consumption. However, in elite runners, that connection was not conclusive. (Williams & Cavanagh 1987.) Still it can be concluded that higher ground reaction forces (GRFs) in the beginning of the contact are in relation to increased VO_2 (Williams 1990, 287). Studies of GRFs and running stride variables (RSVs) have reported contrasting results (e.g. Rabita et al. 2013; Gerlach et al. 2005; Hunter & Smith 2007; Dutto & Smith 2002; Slawinski et al 2008). The studies can be divided roughly into three groups by the duration and the intensity of endurance exercise. They can be categorized as middle (under 5 km), long (5 to 30 km) and ultra distance (over 30 km) (Table 4).

TABLE 4. Changes in ground reaction forces and running stride variables in response to various fatiguing running loadings. $F_z$max = Active vertical peak force, $F_x$min = Horizontal peak braking force, $F_x$max = Horizontal peak propulsion force, SL = stride length, SF = Stride frequency and CT = Contact time. * - *** = $p < 0.05$ - 0.001, respectively.

	Study	Intensity	Endurance exercise Time (min)	Endurance exercise Dist. (km)	Change in $F_z$max (%)	Change in $F_x$min (%)	Change in $F_x$max (%)	Change in SL (%)	Change in SF (%)	Change in CT (%)
Middle dist.	*Rabita et al. 2013*	95 % vVO_2max	6	1.8	-3 % ***	+3 %	-5 % *	-	-	+ 4 % *
	Slawinski et al 2008	2 km time trial	6.5	2	-	-		-	-	-
	Gerlach et al 2005	VO_2max test	?	?	-			+ 1 % **	-1 % ***	
	Fourchet et al. 2014	95 % vVO_2max	9	2.7	+23 % *			-	-	+ 13 % **
	Rabita et al. 2011	95 % vVO_2max	10.7	3.3	- 10 % *	-	+ 6 ***	- 2 % *	+ 1 % *	+ 4 *
Long dist.	*Nummela et al. 2008*	5 km time trial	17	5				- 3 % *	-	+ 6 % ***
	Girard et al. 2013	5 km time trial	17.5	5	- 2 % **	- 7 % ***	- 14 % ***	- 7 % ***	- 4 % **	+ 9 % ***
	Finni ym. 2003	10 km nearly max	47.5	10	-	- 16 % *	-	-	-	-
	Dutto & Smith 2002	80 % vVO_2max	57	13.8	-				-	-
Ultra dist.	*Kyröläinen et al. 2000*	3 h marathon	184	42.2	-	-	-	- 4 % **	+ 4 % **	-
	Morin et al. 2011a	24-h run	1440	153	- 4 % *			-	+ 5 % ***	-5 % ***
	Morin et al. 2011b	Mountain ultramarathon	2274	166	- 6 % ***				+ 6 % ***	-

Middle distance. Some studies have failed to observe any changes in the main RSVs or GRFs after a 7 min lasting maximal running (Slawinski et al 2008). Other authors have explored GRFs and RSVs during constant-pace maximal and exhaustive runs (Fourchet et al. 2014; Rabita et al. 2011; Rabita et al. 2013 Gerlach et al. 2005) but only Rabita et al (2011 and 2013) and Fourchet et al. (2014) assessed changes in vertical active peak force ($F_z$max) and contact time (CT) in nearly maximal endurance loading (i.e., 95 % of vVO2max). As a curiosity, Fourchet et al. (2014) observed $F_z$max to increase significantly (by 23 %) in adolescent boys with pressure insoles ($p < 0.05$). However in all the other studies conducted in adults and with force platforms the vertical active peak force has decrease. Rabita et al. (2011) reported as the previous researchers, that peak vertical GRFs are reduced under fatigue, but contrary to previous findings, Rabita et al. (2011) reported that higher step frequencies are developed near exhaustion.

Severe exhaustive running at velocity of maximal oxygen consumption (vVO_2max) led to a significant decrease (-3 %, $p < 0.001$) in vertical force production during running. In addition, contact times increased 4 % ($p < 0.05$) as stride length was kept unchanged. (Rabita et al. 2013.) Similarly Gerlach and colleagues (2005) found significant ($p < 0.001$) reductions in impact peak and loading rate -6.6 and -11.8 %, respectively, but not in the active peak ($p = 0.18$) after maximal, incremental running loading, with 3 minutes stages (Figure 15, left). Gerlach et al (2005) found stride frequency to decrease significantly ($p < 0.001$) and stride length to increase slightly due to endurance loading as well. Contrary to Gerlach and her colleagues, Rabita et al. found decrease in active peak in response to 95 % of vVO2max running. (Figure 15, right)

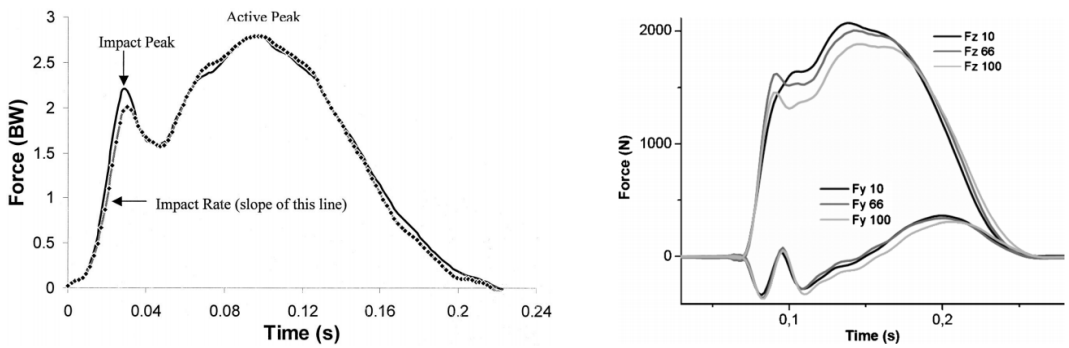

FIGURE 15. Changes occurred after maximal endurance loading in the impact peak and loading rate in female runners (*left*) and time-course of changes when 10 % (Fz10), 2/3 done (Fz66) and in the end of the exhaustive maximal running (*right*) (Gerlach et al. 2005; Rabita et al 2011).

Long distance. Fatigue assessed as a reduction of maximal sprinting velocity by 23 % ($p < 0.001$) after 10 km endurance running, result in a significant increase in contact times (both braking and propulsion phase) (Fig 16.A) and a decrease in mean vertical and horizontal GRFs (Fig 16.B). (Paavolainen 1999b). This indicates that fast force production and ability to tolerate repetitive GRFs diminish as a result of continuous stretch loading (running). In addition, maximal muscle activation (*Vastus Lateralis, Biceps Femoris, Gastrocnemius*) in maximal sprinting decreased significantly (29 – 57 %, $p < 0.001$) after 10 km of all-out running. (Paavolainen 1999b.)

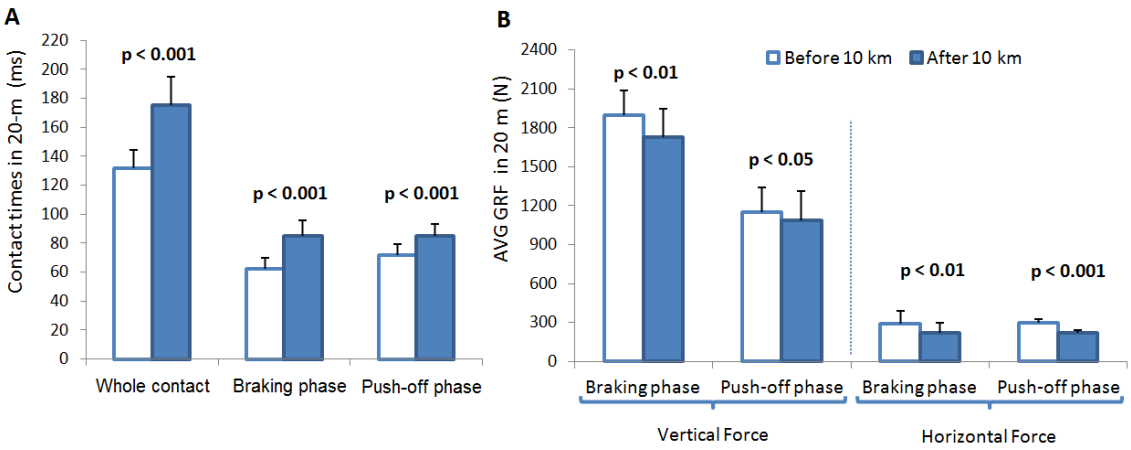

FIGURE 16. A) Contact times for braking and propulsion phase and B) mean vertical and horizontal GRFs in 20 m maximal sprinting before and after an all-out run of 10 km (n =19), p = significant difference before and after (Paavolainen 1999b).

Submaximal running of 10 km decreased significantly maximal sprinting ability and increased profoundly the contact time in men (unaccustomed to endurance training). This decrease in sprinting performance, appeared as impairment in muscle activation (*Soleus, Vastus Medialis & Rectus Femoris*) during concentric muscle work in the propulsion. (Finni et al. 2003.) During submaximal 10 km running mean vertical and horizontal GRF of braking phase decreased significantly already at the distance of 2 km, which was partly due to subjects changing running pattern in early phase of loading. (Figure 17). However, there were no significant changes in step frequency or length. Finni and her colleagues (2003) suggested that the decreasing braking forces produced lower deceleration effect, and consequently, improved running efficiency. Similarly, in a study among competitive triathletes, a 5 km time trial decreased horizontal GRF in the

braking phase, but contrary to Finni et al. (2003) $F_z$max was decreased – 2 % ($p < 0.01$) as well (Girard et al. 2013). In other studies conducted with endurance athletes there were no significant changes in ground reaction forces (Paavolainen et al. 1999b; Dutto & Smith 2002).

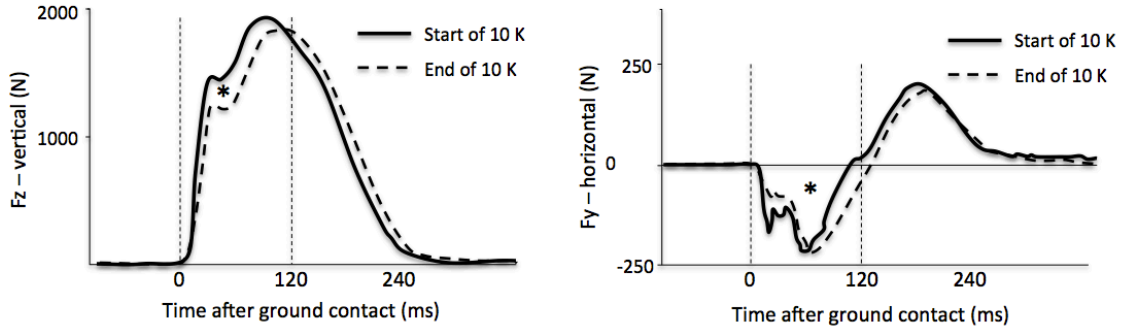

FIGURE 17. Group mean curves of vertical and horizontal ground reaction forces. Start and end of 10 K is collected during 0 – 300 m and 9600 – 9900, respectively. The dashed lines show the time of initial ground contact and the time of transition from braking to propulsion phase. (*) significant differences between start and end of 10 K, $p < 0.05$. (Modified from Finni et al. 2003).

Only minor changes were observed in running stride variables in response to submaximal ultra distance running. Mean stride frequency increased from 2.85 ± 0.15 Hz to 2.97 ± 0.14 Hz ($P < 0.01$), while stride length shortened ($P < 0.01$). The other kinematic parameters were fairly constant throughout the conditions. Mean contact time, external mechanical work, and power were maintained at a quite constant level in every test situation. Contact times, angular displacements and velocities, vertical displacements of the center of gravity of the whole body, mechanical cost and external mechanical energy (potential and kinetic) did not differ between the tests. Despite rather constant mean values, the inter-individual variability was quite large. (Kyröläinen et al. 2000.) The researchers suggested that in the future, a high-intensity velocity test should be utilized instead of conventional submaximal test to observe the true weakening of the neuromuscular function after submaximal running loadings.

Weakened running economy cannot be explained only by minor changes in submaximal running mechanics. Therefore, the increased physiological loading that occurs during a marathon run may be due to several mechanisms: increased utilization of fat as an energy substrate, increased demands of body temperature regulation, increased neural input to the muscle, and the acute effects of muscle damage. (Kyröläinen et al. 2000.)

Most of the changes observed in running mechanics are illustrated in Figure 18 through a representative running step before and after 24 h ultra long endurance loading. In submaximal extremely long endurance loadings the running pattern is modified by changes in leg stiffness (8.6 %, $p < 0.05$) and vertical peak ground reaction forces (- 4.4 %, $p < 0.05$). (Morin et al. 2011a.) Marathon induced changes in running stride parameters, such as stride frequency has been reported to increase significantly after long duration endurance loading (Kyröläinen et al. 2000; Morin et al. 2009; Morin et al. 2011a). In some occasions the changes has been minor or the inter-individual variations so high, that no significant changes has been observed in stride parameters (Nicol et al. 1991). On the contrary to increased step frequency, other factors, such as contact time has been significantly lower (Morin et al. 2009; Morin et al. 2011a).

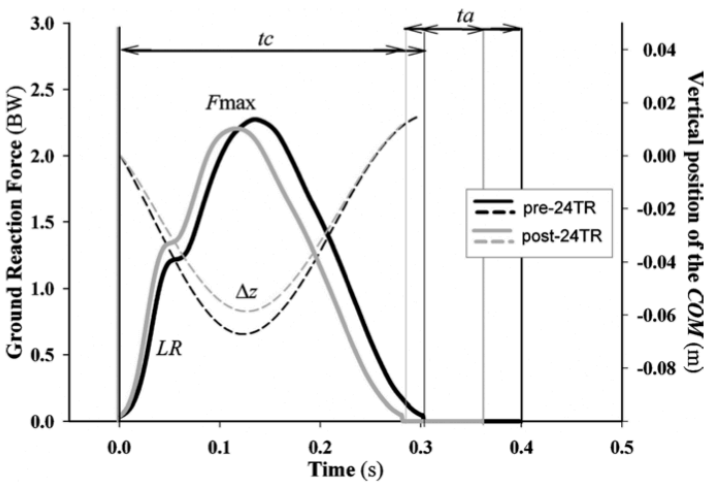

FIGURE 18. Typical running steps and changes in maximal vertical force, contact time (Tc), Aerial time (Ta), and vertical displacement of center of mass (Δz) and loading rate (LR) between pre 24 h run (black) and after 24 h run (grey). (Morin et al. 2011a).

Loading rate tended to increase even though $F_z$max is lower after a 24-h run (with a high inter-individual variation) (Fig. 11, Morin et al. 2011a). Vertical peak force and loading rate are both mechanical variables representing the initial impact peak of force, which is caused by the foot colliding with the ground and the active work against the ground at the mid-stance phase. Therefore, it is possible that a 24-h run E loading led to failing of muscle control and falling of lower limbs on the ground, which resulted in a heel impact shock (loading rate). (Morin et al. 2011a.) Runners attenuate the potentially harmful eccentric phase and overall load faced by their lower limb musculoskeletal system at each step; this event occurring roughly 200,000 times over a typical 24-h run (Morin et al. 2011a).

The changes in running mechanics observed in studies where loading protocol consists of submaximal but long-duration endurance loading are almost exactly opposite compared to middle distance loadings. These differences are due to much shorter (but, hence ran at higher velocities) running efforts. Morin and his colleagues (2011a) hypothesized that due to ultra long endurance loading, runners are willing to preserve the safety of their musculoskeletal structures and avoid pain by adopting a less vertically oscillating and force producing running stride, which may not be an issue of importance in short time-to-exhaustion runs (under 60 min).

4.3 Changes in metabolic variables

Fatigue induced by endurance exercise is highly dependent on the endurance loading intensity and the duration, as well as the training background of subjects. In experienced endurance athletes, a constant speed endurance exercise increased oxygen consumption (VO_2) throughout prolonged running (Fig. 19 A). Nevertheless the increase in VO_2 was significant only after completing the last third of a marathon. The running economy in terms of aerobic energy consumption i.e. oxygen consumption, was altered in the end of exercise, but lactate concentration did not alter throughout the endurance exercise. Respiratory exchange ratio (RER) decreased significantly throughout the running loading (Fig. 19 B), which referred to alteration in the energy metabolism to increase fat

oxidation as the glycogen stores were running out till the end of the marathon loading. (Kyröläinen et al. 2000.)

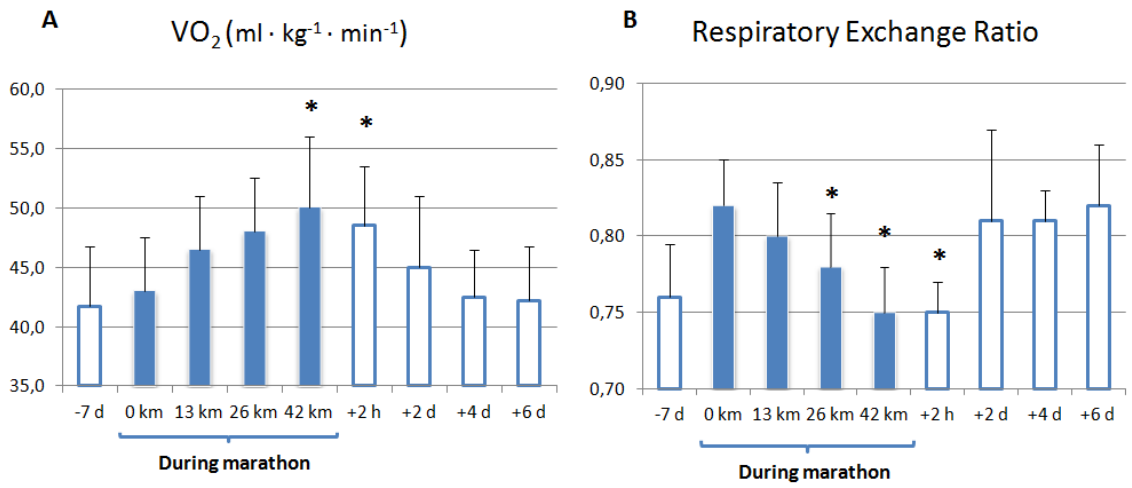

FIGURE 19. The oxygen consumption (VO_2) (A) and respiratory exchange ratio (B) before (-7d = a week earlier), during (blue columns; 0, 13, 26 and 42 km) and after a marathon loading (+2 h = 2 hours after, +2 d = 2 days after) in a submaximal running test. (Kyröläinen ym. 2000).

One estimator for the fatigue is the increase in lactate production which refers to changes in energy metabolism. Finni et al. (2003) found in inexperienced endurance athletes a 10 km of endurance loading to increase anaerobic energy metabolism, measures as lactate production increased from 1.8 (1.3) to 5.3 (1.8) mmol/l ($p < 0.01$). Oxygen consumption did not alter throughout the 10 km running, but together with lactate increase, the neuromuscular performance was decreased significantly in maximal performance measurements in response to the running exercise (Finni et al. 2003).

5 EFFECTS OF COMBINED STRENGTH AND ENDURANCE TRAINING

In theory, divergent training methods such as strength and endurance training, induce somewhat different and even antagonistic improvements in strength (Hickson 1980; Leveritt et al. 1999; Bell et al. 2000) and in endurance performance respectively (Nelson et al 1990; Bishop & Jenkins 1999). Strength training induces gains in muscle hypertrophy and contractile protein content, that is related to improved maximal force, but it also reduces mitochondrial density and activity of oxidative enzymes (Nelson et al 1990, Sale et al. 1990) On the other hand, endurance training induced adaptations are increased levels of oxidative enzymes, mitochondrial content and oxidative capacity. Endurance training have only little or no effect at all on muscle hypertrophy, and it increase muscle fibre conversion from fast to slow twitch. (Nelson et al. 1990; Bassett & Howley 2000.)

Due to quite opposite training responses concurrent strength and endurance training might cause interference for gains in strength or endurance performance. There has been a bunch of evidences (Hickson 1980; Dudley et al. 1985; Hunter et al 1987; Bell et al. 2000) that concurrent training leads to impairment especially in strength development when strength training is added to endurance training. This interference effect between strength and endurance training can be explained by following factors: a) the muscle cannot adapt to two different stimuli because of simultaneous requests from two different energy pathways during same training session (Bell et al. 1991; McCarthy et al 1995) b) the muscle is fatigued from previous training (Craig et al. 1991; Hennessy & Watson 1994) c) the volume and intensity of the concurrent trainings (Hickson 1980; Bishop & Jenkins 1999) d) the type of endurance loading (Bishop & Jenkins 1999; Schumann et al. 2014) and physical background of the subjects (Paavolainen et al. 1999a; McCarthy et al 1995; Taipale et al. 2010) e) the sequencing order, i.e. the order in which strength and endurance training are performed (Bell et al. 1988; Collins & Snow 1993; Gravelle & Blessing 2000; Schuman et al. 2014).

5.1 Changes in endurance performance

Many studies with combined training have shown that maximal aerobic power (VO_2max) has been improved in recreational athletes equally compared to normal endurance training (e.g. Bell et al. 2000; Hickson 1980, Chtara et al. 2005). In the same way Hunter et al. (1987) noticed an increase in VO_2max after 12 weeks of combined training in untrained subjects, but not in previously conditioned endurance runners. The underdevelopment of trained endurance runners resulted with strong possibility in the endurance training frequency and intensity being too low to induce training adaptation.

Hickson et al. (1988) found that endurance performance was improved by adding strength training (3 times/wk) to the traditional endurance training. Both long- and short-term cycling performance were improved, but only short-term endurance performance was changed after 10-weeks of intervention. These results showed improvements especially in fast-twitch fiber recruitment due to adding strength training concurrent to endurance training. (Hickson et al. 1988.)

Almost two decades later, Chtara et al (2005) found very convincing results about the benefits of concurrent training in developing endurance performance. They also explored if the sequencing order of the concurrent training session had any impact on the results. The most beneficial combination of training was endurance before strength (E+S) loading compared to the opposite order (S+E), to endurance only (E) or to strength only (S) in terms of improved 4-km time trial, velocity in maximal oxygen consumption (vVO_2max) and VO_2max (Fig. 20). (Chtara et al. 2005.)

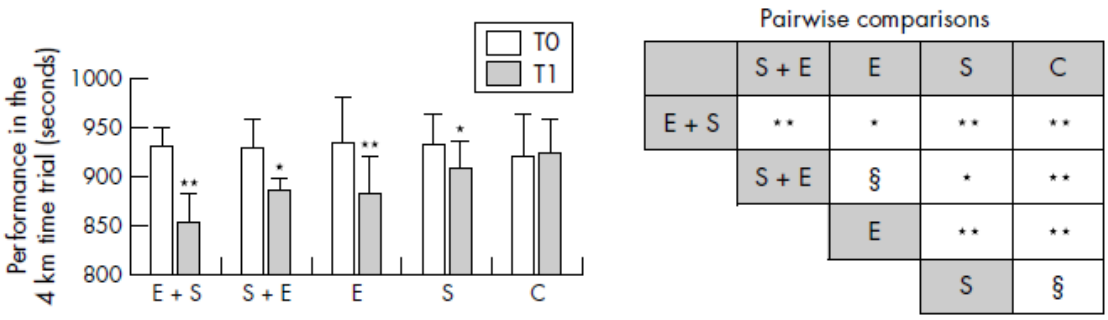

FIGURE 20. 4 km time trial performance before (T0) and after (T1) 12 weeks of training. E+S = endurance followed by strength training; S+E = vice versa; E = endurance only; S = strength only; C = control group. § = Non-sig. difference between PRE - POST, * = $p<0.05$, ** =, $p<0.01$. (Chtara et al. 2005).

The results considering cardiovascular adaptations during concurrent training are still very controversial. Gravelle & Blessing (2000) found in recreational fit women that S+E and even strength only training (S) improved VO_2max by 8.0 and 9.3%, respectively ($p < 0.05$), whereas – the above recommended sequencing order - E+S training group demonstrated only a 5.3% improvement. Collins & Snow (1993) noticed the improvements to be similar in VO_2max between S+E (6.7%) or E+S (6.2%) training groups of untrained subjects after a 7 weeks intervention.

Researchers such as Bell et al. (1991) and Nelson et al. (1990) have found combined training to limit improvements in VO_2max during last weeks of training. Also Taipale et al. (2010) noticed that VO_2max remained unchanged in endurance male runners during 8 weeks of combined endurance and explosive or maximal strength training, even though endurance training amounts were increased from preceding training. Although changes did not occur in terms of maximal aerobic power, other predictors of endurance performance, like vVO_2max and running economy (RE) can be improved by combined endurance and maximal strength training (Stören et al. 2008; Millet et al. 2000). Maybe even more effective results have been reached with the training interventions utilizing explosive strength training with additional load or plyometric training (Paavolainen et al. 1999a; Sedano et al. 2013; Saunders et al. 2006; Spurrs et al. 2003; Berryman et al. 2010). Table 5 represents a review of studies, where running economy is enhanced in consequence of strength training added to endurance training.

TABLE 5. A review of studies, where running economy is enhanced with utilizing strength training to endurance training.

Study	Subjects	Volume	Strength training	ΔVO_2max	ΔRE
Stören et al. 2008	17 male runners	4 sets * 4 reps	3 / wk for 8 wk	↔	↑ 5.0 %
Millet et al. 2000	15 triathlonist	3 – 5 sets * 3 – 5 reps	2 / wk for 14 wk	↔	↑ 6.9 %
Paavolainen et al. 1999a	22 male orienteers	Explosive strength + plyometrics	9 wk (2 h/wk)	↔	↑ 8.1 %
Sedano et al. 2013	6 elite runners	3 sets * 7 reps / 70%	2 krt / vk * 14 vk	↔	↑ 3 – 4 %
Saunders et al. 2006	17 elite runners	30 min plyometrics	3 krt / vk * 9 vk	↔	↑ 4.1 %
Spurrs et al. 2003	17 runners	30 min plyometrics	2 -3 krt / vk * 6 vk	↔	↑ 4.1 - 6.7 %
Berryman et al. 2010	11 male runners	drop jumps	1 / wk for 8 wk	↔	↑ 7 %
	12 male runners	3 - 6 sets * 8 reps	1 / wk for 8 wk	↔	↑ 4 %

5.2 Changes in neuromuscular performance

Concurrent strength and endurance training, relative to resistance training alone, has been shown to result in decrements in strength (Hickson 1980; Kraemer et al. 1995), hypertrophy (Hickson 1980; Kraemer et al. 1995; McCarthy et al. 2002), and power (Häkkinen et al. 2003; Hennessy & Watson 1994; Hunter et al. 1987; Kraemer et al.

1995; Leveritt & Abernethy 1999b). However, some of the studies have found only little to no reductions in strength training adaptations in response to concurrent strength and endurance training (McCarthy et al. 1995; Sillanpää et al. 2008). Furthermore, the neuromuscular response to concurrent training has been observed to be highly individual ranging from -12 to 87 % in terms of the gain in maximal voluntary contraction (Karavirta et al. 2011).

Pioneering work of Hickson (1980) revealed in recreational athletes that strength and endurance improvements during 10 weeks of combined training were not similar to those resulting after strength and endurance training only. VO_2max improved by 25 % in both the endurance only (E) and the combined strength and endurance training (S+E) groups, but combined training did not result in equal improvements in dynamic maximum force compared to strength only (S) training. The average improvements in maximum force for S and S+E groups were 42 kg (44 %) and 22 kg (25 %), respectively. In the 7th week, the S+E group had increased 1RM already by 30 kg (34%), but thereafter the S+E group decreased their leg press results as shown in Fig 21. (Hickson 1980.)

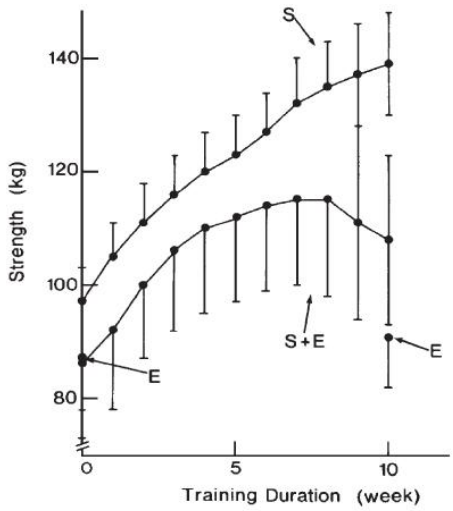

FIGURE 21. Development of 1RM squatting in three training groups. S = strength training only 5 times per week, E = endurance training only 6 times per week and S+E = combined strength and endurance training with same daily exercises as S and E groups. (Hickson 1980.)

In the studies of Hickson (1980) and Hunter et al. (1987), the combined strength and endurance training might have induced overloading of the given muscle groups employed in both training modes, strength and endurance, 5 + 6 and 4 + 5 times per week, respectively. The impairment in strength could thus have been seen as overtraining because of too strenuous training. Also it can be criticized, that the ratio of men and women were 7 to 1 and 5 to 2 in the S and S+E groups, a fact that might have influenced the results. On the other hand, strength training alone and concurrent training have been observed to induce similar improvements in strength after 10 weeks of training in 1RM squat and bench press (McCarthy et al. 1995) when training frequency was not over 3 times per week. The interference in strength, hypertrophy or power development has been noticed to be in relation to endurance training duration (r = -0.75) and frequency (r = -0.26 to -0.35) (Figure 22) in the profound review of Wilson (2012). Furthermore, strength training concurrently with running, but not with cycling, has been noticed to result in significant reduction in both hypertrophy and strength (Wilson et al. 2012.) This might be due to more similar biomechanical muscle work in cycling and strength training or higher muscle damage after running, which includes a high eccentric muscle activity (Komi 2003, 185; Gregor et al. 1991).

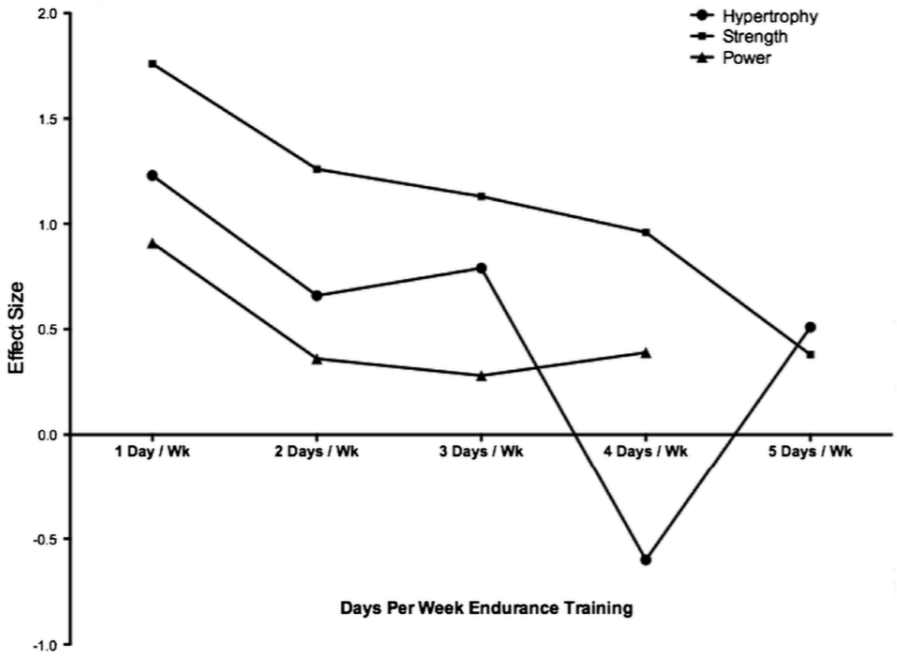

FIGURE 22. Dose-response effect size for frequency of endurance training in concurrent training strength and endurance training (Wilson et al. 2012).

Some authors suggest that concurrent training may impair the strength, power and muscle hypertrophy development, due to different neural adaptations (Kraemer et al. 1995; Leveritt et al. 1999a). Overreaching is currently thought to be caused by high-volume, high-intensity, or high-frequency endurance training bouts (Halson & Jeukendrup 2004), which stimulates competing training adaptations over a long-term training program (Leveritt et al. 1999b). Endurance training athletes demonstrate an increase in mitochondrial density (Nelson et al. 1990), and no change or a small selective hypertrophy of type 1 fibers, with maintenance or a decrease in type 2 fiber size (Bassett & Howley 2000). On the contrary, elite strength athletes train at relatively high percentages of their 1RM, which contributes to the hypertrophy of type 2 fibers, and have a decreasing effect on mitochondrial density (Sale et al. 1990).

Häkkinen and colleagues (2003) noticed especially differences in development of fast force production between combined strength and endurance training vs. strength training only. Interestingly there were no differences in development of dynamic or isometric maximal force production between only strength and concurrent training. They concluded that the interference might hold true in explosive strength development associated with limited changes in rapid neural activation. (Häkkinen et al. 2003.) The review of Wilson et al. (2012) confirms that concurrent training does not necessarily attenuate strength or hypertrophy development but power gains. Bell et al. (2000) assumed suppressed hypertrophy improvements to originate in increased catabolic hormonal response to concurrent strength and endurance training. Also this long-term catabolic state could be the reason behind the decrease in strength after 7 weeks (Fig 7. Hickson 1980). Nevertheless it seems that similar magnitude of aerobic improvements elicits despite of high-frequency training.

5.3 Order effect of combined training

There have been at least three kinds of sequencing of concurrent training: a) using periods of weeks when strength is always done before endurance or vice versa (Hickson 1980; Hunter et al. 1987), b) alternating training days for strength and endurance during

the training period (Sale et al 1990, Bell et al. 1988) and c) alternating the order of exercise bouts during the training session (Collins & Snow 1993; Gravelle & Blessing 2000, Chtara et al. 2005; Chtara et al. 2008; Eklund et al. 2014; Schuman et al. 2014).

According to Collins and Snow (1993), strength development seemed to be similar regardless of the sequencing order of exercises. There was just one significant difference in shoulder press between S+E and E+S groups in favour of E+S ($p < 0.05$) (Collins & Snow 1993). Neither Gravell & Blessing (2000) did find significant differences between the sequencing orders in strength development. Relative improvements in 1RM leg press were similar between the S+E and E+S groups (27 ± 8 % and 27 ± 6 %), respectively (Gravell & Blessing 2000). Concurrent endurance and strength training might diminish the strength gains if endurance exercise is conducted prior to strength exercise. Therefore high-velocity resistance training should be done prior to endurance training. (Bell et al. 1988.)

The studies, where strength and endurance exercise bouts are performed consecutively but in different order, have come up with somewhat controversial findings. (Chtara et al. 2008; Cadore et al. 2013; Eklund et al. 2014). In addition, results must be taken with great caution, because of many small but crucial differences in study design (i.e. training intensity) and subjects. Chtara et al. (2008) studied an interference effect on the strength gains in young men after 12 weeks of training but no effect of different intra-session sequences (i.e., strength + endurance S+E vs. endurance + strength E+S) were found. This finding was confirmed by Schumann et al. (2014). Eklund et al. (2014) observed concurrent strength and endurance training with different order of exercise bouts (E+S and S+E) together with different day (DD) combined training where the strength or endurance exercises are performed separately on different days. The gains in neuromuscular and endurance performance were significant during the 24-week training intervention (2 – 2.5 times/week for endurance and strength training) with no differences between training groups. The groups did not differ significantly after training, but E+S training order might diminish gains in neural activation. (Eklund et al. 2014.) Similarly, in elderly men, Cadore et al. (2013) observed greater ($p < 0.01$) lower-body strength gains as well as greater changes in the neuromuscular economy after 12-

week of concurrent training performing strength prior to endurance exercise (S+E) compared to opposite exercise order. On the contrary, in young women there were no differences between the groups that performed different exercise sequences (Gravelle & Blessing 2000).

5.4 Order effect of combined loading

Neuromuscular decrements did not differ significantly between different sequencing order of combined strength and endurance loading (Schumann et al. 2013). Although, it seemed that after completing both loading types (E+S and S+E) the reductions in explosive and maximal force were somewhat higher in E+S compares to S+E. More accurately neuromuscular performance decreased significantly in E+S from MID to POST whereas after E loading neuromuscular performance remained decreased in S+E after completing S (Schumann et al. 2013). It appears that higher reductions in neuromuscular performance are induced by the strength loading rather than the endurance loading. Although, attention must be paid to the endurance loading, which was performed by cycling for 30 min, before applying these finding to loading protocols which involves stretch-shortening mechanics as in endurance running (Nicol et al. 1991; Schumann et al. 2013).

6 PURPOSE OF THE STUDY

The purpose of the present study was to assess the acute changes in running biomechanics, i.e. ground reaction forces (GRFs) and running stride variables (RSVs) in response to a combined strength (S) and endurance (E) loading using two different loading orders in recreational endurance athletes. Furthermore, the aim was to compare the changes between different sequencing orders (*order effect*) of the combined strength and endurance loading. In addition, the final aim was to determine whether alterations in GRFs and RSVs were related to a change in the energy cost of running.

The specific research questions were the following:

1. Are GRFs ($F_z$max, $F_x$min and $F_x$max) and RSVs (CT, SF and SL) altered in response to a combined strength and endurance loading?

   Hypothesis: It is expected that GRFs and RSVs are altered. A majority of studies have shown a decrease in GRFs (Finni et al. 2013;Rabita et al. 2011; Girard et al. 2013). On the other hand, there is more variation in terms of RSVs but usually stride length and stride frequency are decreased and contact time increased in response to endurance loading (Rabita et al. 2011; Nummela et al. 2008)

2. Are the changes in running biomechanics similar between the different sequencing orders of the loading?

   Hypothesis: No studies have been conducted regards combined strength and endurance loading and GRFs or RSVs, which can be described as neuromuscular force measurements during endurance loading. In fact, it has been shown that aerobic exercise might acutely reduce strength performance (Lepers et al. 2001). However, S loading is known to reduce neuromuscular performance in greater magnitudes compared to E loading (Schuman et al. 2013). Though, it is hypothesized that decreased neuromuscular maximal performance by S loading will induce even

greater reductions in GRF and RSV during E following S loading (S+E) compared to E preceding S loading (E+S).

3. Are the changes in GRFs and RSVs during strength loading associated with neuromuscular changes?

   Hypothesis: There are no previous studies concerning the associations of changes in running biomechanics and neuromuscular alterations. However, both strength (both maximal and explosive) loading (e.g. Häkkinen 1993; Linnamo et al. 2005) as well as endurance loading (e.g. Saldanha et al. 2008, Lepers et al. 2000) has been noticed to attenuate MVC drastically. This reduction in MVC is no doubt one sign of the impaired neuromuscular capacity, and this might alter the running biomechanics that is a stretch-shortening cycle loading (Morin et al. 2011b).

4. Are the changes in GRFs and RSVs during endurance loading associated with metabolic changes?

   Hypothesis: Less economical runners have been proven to exhibit greater vertical impulses during ground contact (Heise & Martin 2002). Acute increase in energy cost of running (i.e. oxygen consumption) seems to be in relation to decreases in $F_z$max (Rabita et al. 2011).

7 METHODS

7.1 Subjects

A total of 10 female and 12 male recreational endurance runners with only little or no experience in strength training participated in this study. Subjects underwent a medical examination by a qualified physician, prior to the study including resting ECG and health questionnaires. Subjects with acute or chronic illness, injury and/or use of medications which would affect the physical performance or hormone levels, were excluded. Participants were carefully informed about the study design, including information about the possible study related risks before signing an informed consent document. The study protocol was approved by the Ethics Committee of the University of Jyväskylä and it conformed to the recommendations of the Declaration of Helsinki.

The anthropometric data of the subjects are shown in Table 6. In addition to standing height and subjects weight, percentage of body fat was determined using skinfold calipometry (Durnin & Womersley 1974) and fat free mass was analyzed using bioimpedance (In body 720 body composition analyzer, Biospace CO. Ltd., Seoul, South Korea).

TABLE 6. Anthropometric data for female and male subjects obtained during the initial pre-testing.

Sex	**Age** (yr)	**Height** (cm)	**Weight** (kg)	**Fat** (%)
Men (n = 12)	38.8 ± 7.1	177.4 ± 6.4	75.7 ± 3.6	12.9 ± 3.6
Women (n = 10)	33.5 ± 8.3	165.9 ± 7.6	59.8 ± 5.1	22.0 ± 3.8

7.2 Design

The study was conducted using a cross-over research design with all subjects participating in two loading conditions (Figure 23). Prior to the loadings maximal performance level (basal measurements) was tested in maximal strength and endurance performance. At earliest one week after assessing maximal performance levels, subjects performed, in a random order, two loadings of strength and endurance exercise carried through in a single session. One loading started with strength exercise loading followed by endurance loading (S+E), and the other with endurance loading followed by strength (E+S). The duration between the accomplishment of the basal measurements and the first loading was 2.4 ± 1.9 weeks and 3.1 ± 2.4 weeks for men and women, respectively. The duration between both loadings in men and women was 3.6 ± 2.3 and 2.9 ± 2.0 weeks, respectively. The performing order of combined loadings was randomized before the first combined loading. Time of day variations were controlled by scheduling of each subjects loading to be ± 1 hour from their basal measurement testing time.

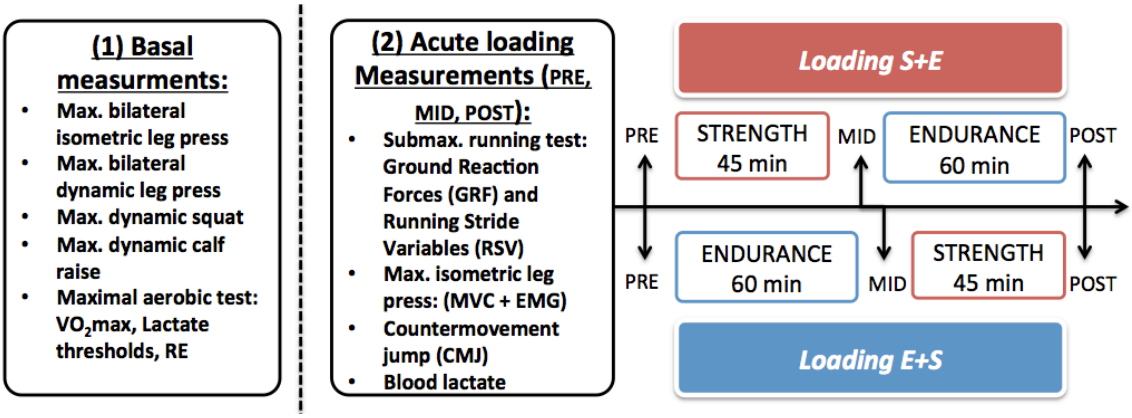

FIGURE 23. Study design and physical measurements (1) to define basal performance level and (2) to measure acute responses during combined strength and endurance (S+E) and endurance and strength (S+E) loading.

Acute loading measurements were used to quantify responses during combined single-session loadings. These included: submaximal running test, maximal strength and power measurements were conducted prior the loading (PRE), after the first exercise - strength or endurance, (MID) and after completing strength and endurance exercises (POST) (Figure 23) as explained in detail in a later chapter (see paragraph 7.4). In addition, blood lactate concentrations were determined from a fingertip blood draw at

seven occasions during each combined loading: pre strength loading, mid strength loading, post strength loading, pre endurance loading, at 10min and at 50min during the endurance loading and post endurance loading (Figure 24). Subjects' body weight was measured before and after each combined loading in order to monitor sweating/hydration status.

7.3 Strength and endurance loading

Combined strength and endurance loadings (S+E and E+S) lasted totally 2.5 hours, including preparation of wearable measurement equipments, warm-ups and all the actual acute loading measurements (PRE, MID and POST). The accurate order of events in both loading conditions is presented in figure 24.

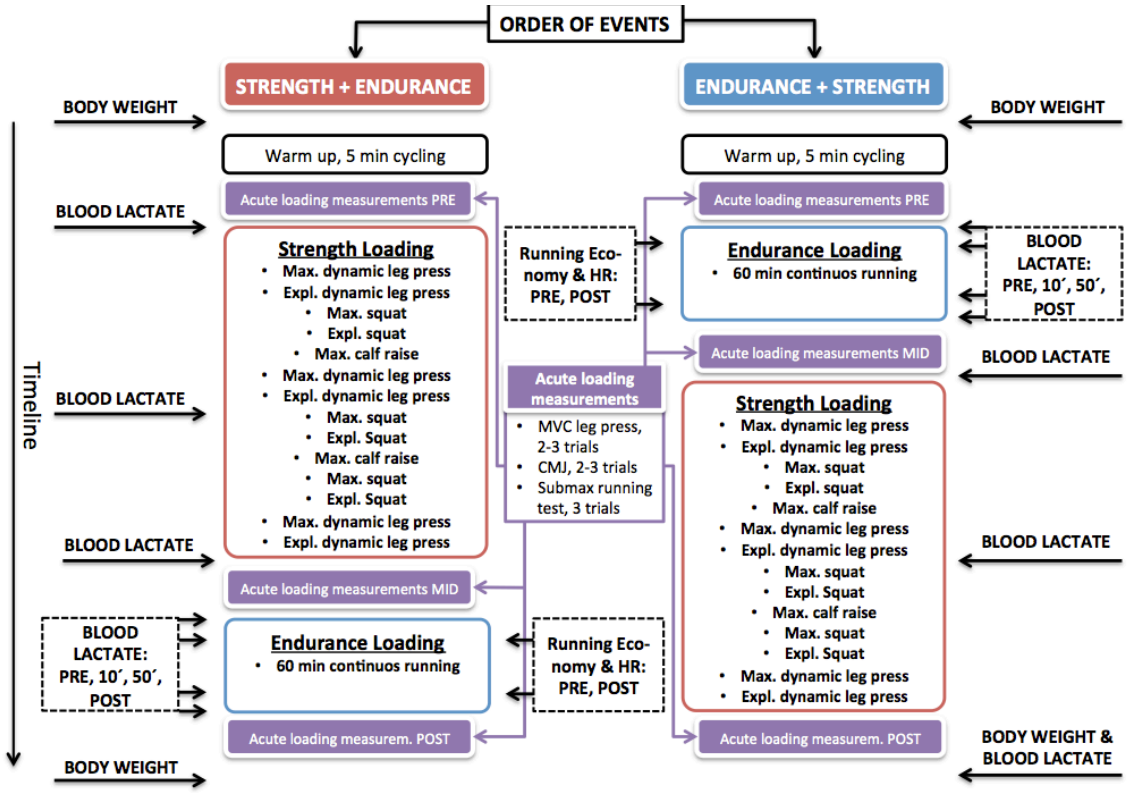

FIGURE 24. Order of events in both S+E and E+S loadings. Black vertical arrows (→) describe the various acute measurements taken during combined loadings. Purple arrows (→) represent a set of acute loading measurements described in the middle of the figure.

Strength loading. The strength loading focused primarily on the lower extremities and included both maximal and explosive strength exercises lasting totally 40 minutes. Strength exercises were conducted in a circuit where maximal and explosive sets varied and followed each other (figure 24). Maximal strength exercises were performed using 8 repetitions per set with a load of 75 % of 1RM, and in explosive strength exercises using 10 repetitions per set with a load of 40 % of 1RM. The rest interval between the sets was always 2 minutes. The subjects were advised to perform maximal sets with slow velocity over the whole range of movement and the final repetition of each set was performed near to failure. In explosive exercises subjects were informed to perform the concentric phase as fast as possible. Exercises performed included leg press (3 sets of maximal and 3 sets of explosive strength), squats (3 sets of maximal and 3 sets of explosive strength) and calf raises (2 sets of maximal strength). The performing order of the strength exercises is shown in Figure 21. Subjects were allowed to wear a belt around their waste to stabilize their lower back.

Endurance Loading. The endurance loading consisted of constant speed continuous running for 60 minutes on a 200 m indoor track. The intensity during endurance running was determined according to previously defined aerobic and anaerobic thresholds (basal measurements) as exactly at the level of 2/3 of the gap between aerobic and anaerobic thresholds. For instance, if the anaerobic threshold was at the pace of 13 km/h and respectively aerobic threshold at 10 km/h, the pace for the endurance loading will be at the pace of 12 km/h. The light rabbit system integrated into the running track paced the subjects at the given velocity during the endurance loading. Oxygen consumption (ml/kg/min) and running economy (ml/kg/km) was measured during the first and last 10 minutes period of the endurance loading, whereupon the subjects wore a portable gas analyzer, the Oxycon Mobile®, Jaeger, Hoechberg, Germany). Initial “resting” values were collected from 6th to 8th (PRE), and respectively, 56th to 58th minute (POST) presented as averages of 2 minutes from breath-by-breath data. In addition heart rate was recorded throughout the endurance loading (Suunto t6, Vantaa, Finland) but compared between first (minute 15) and second (minute 45) half of the exercise.

Formula 2: Endurance loading pace = vAer [km/h] + 2/3(vAn [km/h] – vAer [km/h])

7.4 Measurements

Prior to the loadings anthropometric data were collected and a specific set of basal measurements including maximal isometric leg extension (MVC), explosive force production in counter movement jump (CMJ) and dynamic one repetition maximum (1RM). In addition, subjects were familiarized with the strength exercises to be performed in the following two loadings. Therefore, the four repetition maximum (4RM) in dynamic squat and calf raise was assessed and based on the result 1RM was estimated (Häkkinen & Ahtiainen 2007). Following strength testing, maximal oxygen uptake (VO2max) was measured using a treadmill running protocol.

7.4.1 Basal measurements

Dynamic leg extension. One repetition maximum (maximal dynamic bilateral horizontal leg press in a seated position) was measured using a David 210 dynamometer (David Sports Ltd., Helsinki, Finland) (Häkkinen et al. 1998). Prior to attempting 1 RM, subjects completed a warm-up consisting of 6 x 70 % and 4 x 80 – 85 % of estimated 1 RM with one minute of rest between the sets. Following this warm up, no more than 5 attempts to reach 1 RM were made. The load was increased by 2.5 to 5.0 kg per each attempt. Subjects were instructed to grasp the handles located by the seat of the dynamometer and to keep constant contact with the seat and backrest during leg extension to a full extension of 180 degrees. Verbal encouragement was given to promote maximal effort. The greatest load, that the subject could successfully lift from knee angle of approximately 65° to knees fully extended (180 °), to the accuracy of 2.5 kg was accepted as 1RM.

Isometric leg extension. Maximal isometric bilateral leg extension force (MVC) was measured on a horizontal dynamometer (Häkkinen et al. 1998) in a seated position with a knee angle of 107°. Subjects were instructed to generate maximum force as rapidly as possible through the entire foot against the force plate for a duration of 2 to 4 seconds. Subjects were asked to produce maximum force through the ball of the foot as rapidly

as possible against the force plate for the same duration. In addition, subjects were instructed to grasp handles located by the seat of the dynamometer and to keep constant contact with the seat and backrest throughout each measurement trial. Verbal encouragement was given to promote maximal effort. In the pre-test subjects performed a minimum of 3 and a maximum of 5 trials with 1min rest in between. Maximal force was accepted when the difference between two subsequent trials did not exceed 5%. During the actual loading measurements, subjects performed 3 trials each at PRE, 24h and 48h with 1 min rest whereas at MID and POST only 2 subsequent trials without rest were performed. The force signal of both measures was low pass filtered (20 Hz) and analyzed (Signal software Version 4.04, Cambridge Electronic Design Ltd, Cambridge, UK). In addition, rapid force production of 500ms (MVC500) was measured during MVCmax.

Counter movement jump. Counter movement jump (CMJ) was performed on the force platformes (Komi & Bosco 1978) on normal standing position, and the subjects were informed to keep their feet shoulder width. The jump started with slight downward movement (knee angle minimum to 90°) followed by a maximal vertical jump as high as possible. The subjects were allowed to time the jump when feeling themselves ready. The signal generated by the CMJ was transferred from the force plates via amplifier to Signal software in a computer (Signal software Version 4.04, Cambridge Electronic Design Ltd, Cambridge, UK). The jump height were meant to be analyzed from the force – time -curve as the impulse using the formula ($h = I/2gm^{2,}$, where I = impulse, g = gravity and m = mass). Due to problems with force the platforms the jumping height was defined from the flight time.

Dynamic squat and calf raises. 1RM in dynamic squat and calf raises were estimated from the subjects' 4RM (Häkkinen & Ahtiainen 2007). Squats and calf raises were determined using a Smith strength loading device with a tracked bar. For the squat exercise subjects were asked to keep their feet shoulder width apart. During the eccentric phase subjects were instructed to bend their knees up to an angle between 80° and 90° and ensure that their knees did not bend forward beyond the level of the toes. For safety reasons subjects were allowed to use a hip-belt in order to support the lower

back muscles. Prior to attempting 4RM, subjects performed 2 to 3 sets of light weights in order to familiarize with the technique. After that, 4RM was approached with no more than 5 trials. If, however, the subjects were able to exceed 4RM, but reported lower back pain, a maximum of 6RM was accepted and based on that the 1RM predicted. The greatest weight that the subject could successfully lift with the correct knee angle to the accuracy of 2.5 kg was accepted as 4RM or 6RM, respectively.

Maximal aerobic test – VO_2max. Maximal oxygen uptake (VO2max), anaerobic and aerobic thresholds were determined during treadmill running. The initial speed for men and women was 8 $km \cdot h^{-1}$ and 7 $km \cdot h^{-1}$, respectively. The velocity was increased by 1 $km \cdot h^{-1}$ after every 3 min stage until exhaustion. According to the subjects' training background the initial velocity was 1 $km \cdot h^{-1}$ higher in subjects who reported a training background higher than the average. The incline for all subjects was kept at a constant 0.5° during the whole test. Fingertip blood samples were taken after each stage during a 20 seconds stop of the treadmill to determine blood lactate concentrations with Biosen lactate analyzer (S_line Lab+, EKF Diagnostic, Magdeburg, Germany). Heart rate was monitored (Suunto t6, Vantaa, Finland) continuously during the test but collected as average values from the last minute at each stage. Oxygen consumption (VO_2) and ventilation (VE) were determined continuously breath-by-breath using a portable gas analyzer (Oxycon Mobile®, Jaeger, Hoechberg, Germany). The VO_2max was taken as the highest averaged VO_2 value in a time period of 60 seconds. Running speed at the anaerobic threshold was determined from lactate and pulmonary variables using the same method as Aunola & Rusko (1986). Before each test, air flow calibration was performed using the automatic flow calibrator and the gas analyzer was calibrated against a certified gas mixture of 16 % O_2 and 5 % CO_2.

7.4.2 Acute loading measurements.

Running economy, blood lactate and heart rate. Oxygen consumption (VO_2) and running economy (RE) [ml(O_2)/kg/km] during the endurance loading was measured as the average of 3 minutes between minute 6 and 8 and minute 56 and 58, respectively. Oxygen consumption was determined continuously breath-by-breath using a portable

gas analyzer (Oxycon Mobile®, Jaeger, Hoechberg, Germany). Before each test, air flow calibration was performed using the automatic flow calibrator and the gas analyzer was calibrated against a certified gas mixture of 16 % O_2 and 5 % CO_2. Heart rate average was recorded throughout the whole endurance running duration (Suunto t6, Vantaa, Finland) but compared from minute 15 and 45 respectively.

Submaximal running test. Ground reaction forces (GRFs) and running stride variables (RSVs) were measured during submaximal running test on the running track. Subjects performed three consecutive submaximal runs over 50 m running course at the same velocity than in the endurance loading. The subjects were allowed to accelerate 30 m to ensure a normal and steady state running gait throughout the 20 m measurement section. The running speed was regulated and kept same by small lights placed on the next lane (Naakka Ltd., Lappeenranta, Finland) and obtained with photocell gates (Newtest Inc., Oulu, Finland) connected to an electronic timer. The runs were performed over a special 8.8 meters long force platform system, which consisted of five two-dimensional (2D) and three 3D force plates (0.9 × 1.0 m each, TR Test Inc., Finland, natural frequency in the vertical direction 170 Hz) and one Kistler 3D force platform (0.9 × 0.9 m, Honeycomb, Kistler, Switzerland, 400 Hz) connected in series and covered with a tartan mat. Each force plate registered both vertical (F_z) and horizontal (F_x) components of the ground reaction force. Because mechanical work in the medio-lateral direction is negligible during running (Cavagna et al. 1964) medio-lateral forces were not analyzed (Avogadro et al 2003). Two successful ground contacts of the right leg were selected for analysis. Contact and aerial phases (i.e., contact time, CT (s), and aerial time, FT (s)) were defined when the vertical force was more than and less than 50 N, respectively. Active peak amplitude of vertical force ($F_z max$), peak braking ($F_x$min) and push-off ($F_x$max) forces, step frequency ($SF = (FT + CT)^{-1}$, in hertz), and step length ($SL = v \cdot SF^{-1}$, in meters) were also determined. Anterio-posterior forces (F_x) were used to determine the braking and push-off phases during ground contact when the anterio-posterior force was negative and positive, respectively. Braking and push-off impulse (B_{Imp} and P_{Imp}, respectively) values were determined from the product of the effective force applied to the running surface and foot–ground contact times of these respective phases. (Rabita et al. 2011.)

7.5 Training

In order to standardize the training status of subjects, they were required to record their training volume and intensity for both strength and endurance training carried out in the period between both loadings. Subjects were informed to maintain their normal levels of physical activity and training throughout the whole study design. The analysis of available training results for women and men showed an average of 3.7 ± 1.2 h (n = 7) and 4.2 ± 2 h (n = 9), respectively. All subjects were asked to record their training conducted during three days prior to both loadings and maintain this preparatory training prior both combined loadings. It was required not to perform any intense exercises during this time.

In addition to subjects' training, the nutritional intake was controlled on loading and follow up days. The subjects were required to ingest the similar breakfast in terms of the total amount and quality on both loading occasions. During each loading, subjects were allowed to ingest a total amount of 4 dl of pure tap water, with 2 dl given separately right after the strength and after the endurance loading before the venous blood sample was drawn.

7.6 Statistical analysis

Traditional statistical methods were used for the calculation of mean and standard-deviation (SD). The normal distribution of variables was observed (*name of the test*) and within group differences analyzed using a dependent-samples T-test (comparison of loading conditions within all the subjects and within gender groups). Difference between the three measured time-points were analyzed for both protocols using repeated measures ANOVA with 3 levels (PRE, MID, POST) with appropriate post-hoc comparison of means (Bonferronis significance test). In addition, the interactions gender * time and protocol * time were evaluated. If significant p-values were observed, the difference in the change between genders or protocols was analyzed by paired T-

tests. The criterion for significance was set at * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$. Statistical analysis was completed with PASW 18.0 (SPSS Inc., Chicago, IL, USA).

8 RESULTS

8.1 Basal measurements

Altogether 22 subjects were included into the final statistical analysis (men n = 12, women n = 10) due to inadequate participation or failure to schedule another loading at the timeline reserved to this study. Men's and women's cardiovascular fitness is represented in Table 7.

TABLE 7. The basal measurement in VO2max test. vAnT = running speed at the anaerobic threshold, vAT = running speed at the aerobic threshold * = $p < 0.05$ refers to significant difference compared to males.

Sex	VO2max ($ml \cdot kg^{-1} \cdot min^{-1}$)	vAnT ($km \cdot h^{-1}$)	vAT ($km \cdot h^{-1}$)
Men (n = 12)	54.5 ± 4.0	13.1 ± 1.1	10.4 ± 1.0
Women (n = 10)	48.5 ± 4.6 **	11.8 ± 1.0 *	9.3 ± 0.7 *

The baseline strength and power variables were significantly higher in men compared to women (Table 8).

TABLE 8. Maximal and explosive dynamic and isometric strength values in men and women in the baseline measurements. *** = $p < 0.001$ refers to significant differences compared to males.

Sex	1RM (kg)	MVC (N)	MVC500 (N)	CMJ (cm)
Men (n = 12)	175.8 ± 23.0	2920 ± 487	1909 ± 372	32.9 ± 3.6
Women (n = 10)	106.6 ± 17.8 ***	1954 ± 441 ***	1235 ± 33 ***	23.7 ± 4.1 ***

8.2 Running stride variables and ground reaction forces

In running stride variables S+E loading led to slight changes in stride frequency and stride length. Stride frequency at POST measurement increased both in men and women compared to PRE (+2.2 %, $p < 0.001$ and + 1.7 %, $p < 0.05$, respectively) (Figure 25). No changes occurred in stride frequency after S alone in S+E. In men and women the relative difference from MID to POST was significant ($p < 0.05 – 0.01$) between the loading orders. Stride length decreased in S+E only for men (-4.1 %, $p < 0.05$) (Figure 26). In the E+S loading there were no significant changes in stride frequency or stride length (Figure 25 and 26). Running speed was kept unchanged during all the GRF measurements in both loading conditions.

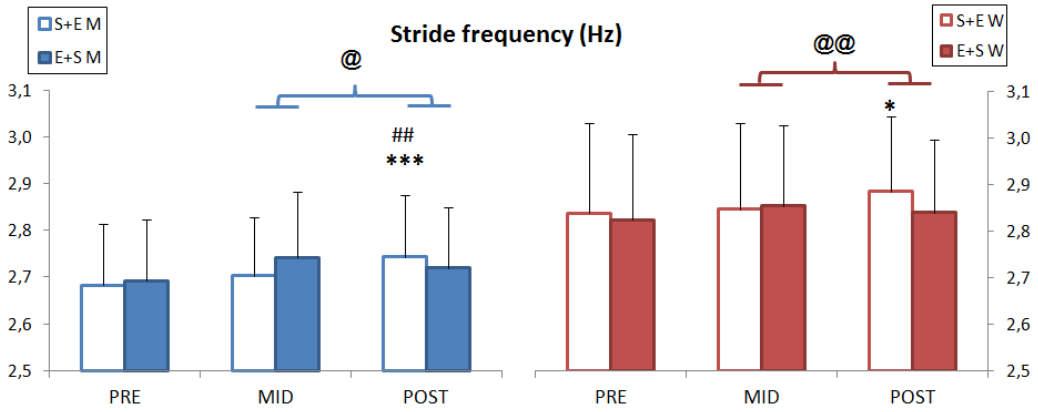

FIGURE 25. Stride frequency in both combined loadings for men (left) and women (right). * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$ represent significant change from the PRE. ## $p < 0.01$ is significant change from the MID and @ $p < 0.05$ and @@ $p < 0.01$ significantly different change between loadings.

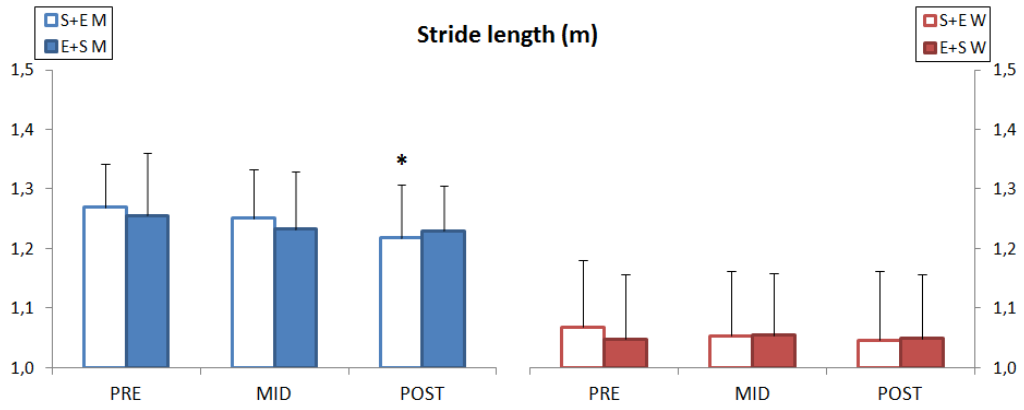

FIGURE 26. Stride length in both combined loadings for men (left) and women (right). * = $p < 0.05$ represents significant change from the PRE.

Stride patterns in terms of times of the contact phases were not altered significantly except for flight time (FT), which decreased 8.4 % ($p < 0.001$) after the completion of S+E in men (Figure 27).

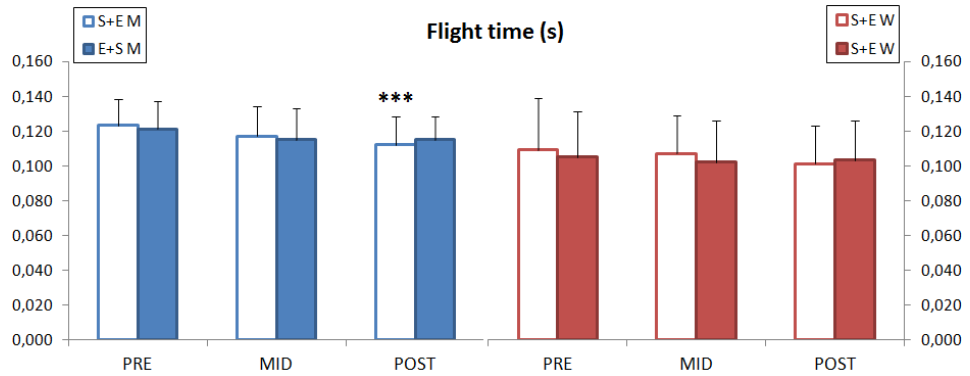

FIGURE 27. Flight time compared to PRE-values in both combined loadings for men and women. *** = $p < 0.001$ represents significant change from the PRE.

In both genders the vertical active impact peak ($F_z$max) decreased only after S+E and more accurately after the completion of E (MID to POST). In men the two different combined loading protocols S+E and E+S decreased $F_z$max by -6.2 %, $p < 0.01$ and -2.0 %, n. s., respectively. The overall change from PRE to POST differed significantly ($p < 0.05$) between the loading models in men (Figure 25). In women $F_z$max were decreased -4.2 % and -4.4 % (n.s. both) during the S+E and E+S loadings, respectively, but there were no difference between the loading models. In the S+E loading there were significant decrease from MID to POST in women (-3.8 %, $p < 0.05$) (Figure 28).

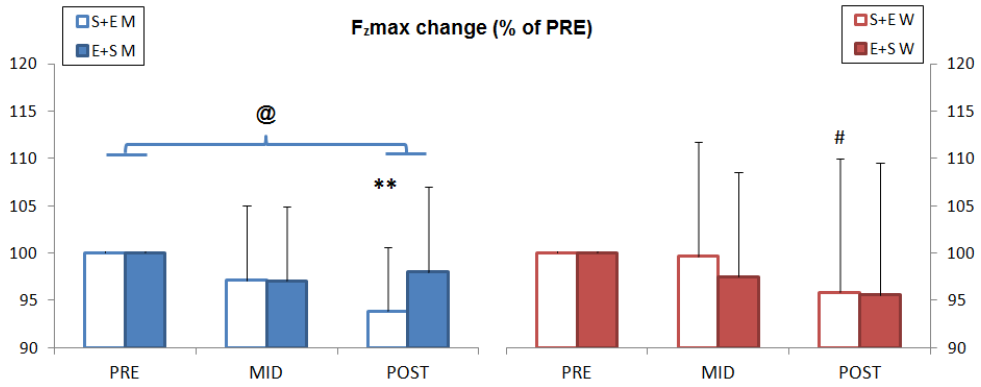

FIGURE 28. The relative changes in active peak ground reaction force compared to PRE-values in both combined loadings for men and women. ** = $p < 0.01$ represents significant change from the PRE, # = $p < 0.05$ represents significant change from the MID and @ = $p < 0.05$ significantly different change between loadings.

The total vertical impact (TVI) during the whole ground contact decreased only after the S+E loading and especially after the completion of E. In men S+E and E+S decreased TVI by -3.9 %, ($p < 0.05$) and -1.4 %, (n.s.), respectively. The MID-POST change differed significantly ($p < 0.05$) between the loading models (Figure 26). In women TVI decreased -4.2 % and -1.2 % during the S+E and E+S loadings, respectively, but the overall change was not significant. In the S+E loading 60 minutes of running decreased women's total vertical impact by -5.2 % ($p < 0.01$) (Figure 29).

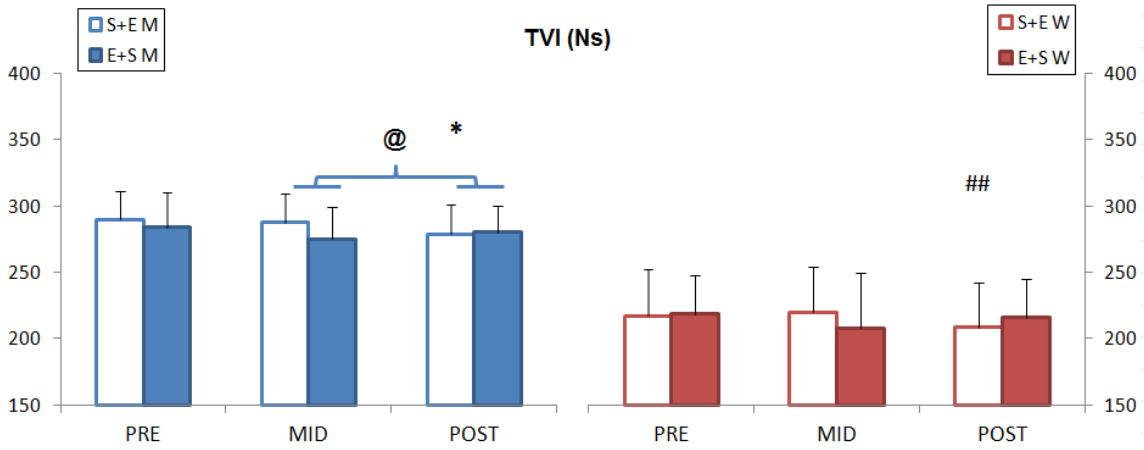

FIGURE 29. Total vertical impact during ground contact compared to PRE-values in both combined loadings for men and women. * = $p < 0.05$ represents significant change from the PRE, ## = $p < 0.01$ represent significant change from the MID and @ = $p < 0.05$ significantly different change between loadings.

There were no significant changes in horizontal GRFs or impacts during the braking or the propulsion phase in either loading order. The summary of responses in ground reaction forces and running stride variables is listed in Table 9.

TABLE 9. The running stride variables and ground reaction forces in both combined loading conditions. * represents significant change from the PRE and # represents significant change from the MID.

		MEN			WOMEN		
		PRE	MID	POST	PRE	MID	POST
SF (Hz)	S+E	2.68 ± 0.13	2.70 ± 0.13	2.74 ± 0.13 ***##	2.84 ± 0.19	2.85 ± 0.18	2.89 ± 0.16 *
	E+S	2.69 ± 0.13	2.74 ± 0.14	2.72 ± 0.13	2.82 ± 0.19	2.85 ± 0.17	2.84 ± 0.16
SL (m)	S+E	1.27 ± 0.07	1.25 ± 0.08	1.22 ± 0.09 *	1.07 ± 0.11	1.05 ± 0.11	1.05 ± 0.12
	E+S	1.26 ± 0.10	1.23 ± 0.10	1.23 ± 0.08	1.05 ± 0.11	1.05 ± 0.10	1.05 ± 0.11
CT (s)	S+E	0.251±0.022	0.253±0.022	0.253±0.022	0.245±0.029	0.246±0.020	0.247±0.024
	E+S	0.251±0.020	0.251±0.020	0.254±0.018	0.250±0.027	0.249±0.022	0.250±0.024
FT (s)	S+E	0.123±0.015	0.117±0.017	0.112±0.016 ***	0.109±0.030	0.107±0.022	0.101±0.022
	E+S	0.121±0.016	0.115±0.018	0.115±0.013	0.105±0.026	0.102±0.024	0.103±0.023
$F_z$max (N)	S+E	1916 ± 131	1860 ± 147	1798 ± 122 **	1421 ± 207	1416 ± 171	1362 ± 192 #
	E+S	1850 ± 132	1796 ± 141	1813 ± 164	1424 ± 191	1387 ± 154	1361 ± 190
$F_x$min (N)	S+E	-298 ± 63	-281 ± 59	-282 ± 55	-204 ± 93	-186 ± 53	-184 ± 77
	E+S	-287 ± 53	-276 ± 45	-288 ± 42	-175 ± 66	-189 ± 60	-194 ± 55
$F_x$max (N)	S+E	209 ± 28	203 ± 35	197 ± 37	149 ± 34	161 ± 43	152 ± 28
	E+S	204 ± 37	206 ± 30	195 ± 33	151 ± 33	150 ± 28	148 ± 29
TVI (N · s)	S+E	290 ± 21	287 ± 22	279 ± 23 *	217 ± 35	220 ± 34	208 ± 34 ##
	E+S	284 ± 26	275 ± 24	280 ± 20	218 ± 30	208 ± 42	216 ± 29

SF = Stride frequency, **SL** = Stride length, **CT** = Contact time, **BT** = Braking time, **$F_z$max** = Vertical active impact peak, **$F_x$min** = Horizontal ground reaction force in braking phase, **$F_x$max** = Vertical ground reaction force (in relation to body weight) in braking phase, **TVI** = Total vertical impact

8.3 Neuromuscular performance

Both loadings induced significant reductions in MVC. In men MVC decreased at MID (-18.3 %, $p < 0.01$ and -8.2 %, $p < 0.01$) and at POST (-20.5 %, $p < 0.001$ and -21.1 %, $p < 0.001$) for S+E and E+S, respectively (Figure 30). There were significant changes between PRE-MID ($p < 0.05$) and MID-POST ($p < 0.01$) in men, whereas in women the relative changes between time points were not significant ($p = 0.090$). In women S+E and E+S induced reduction at MID (-14.4 %, $p < 0.01$ and -6.7 %, n.s.) and at POST (-10.9 %, $p < 0.05$ and -11.9, $p < 0.05$, respectively). There was a significant sex by time interaction ($p < 0.05$). In men S loading induced significant reduction regardless of if performed before (S+E) or after the E loading (E+S) (-18.3 %, $p < 0.01$ and -14.0 %, $p < 0.001$, respectively), whereas the reduction in women after S was significant only when performed first -14.4 %, $p < 0.01$ and in E+S -5.6 %, n.s., respectively. The E loading alone induced a significant decrease in MVC (-8.2 %, $p < 0.01$) only in men and when E was performed as a first loading (Figure 30).

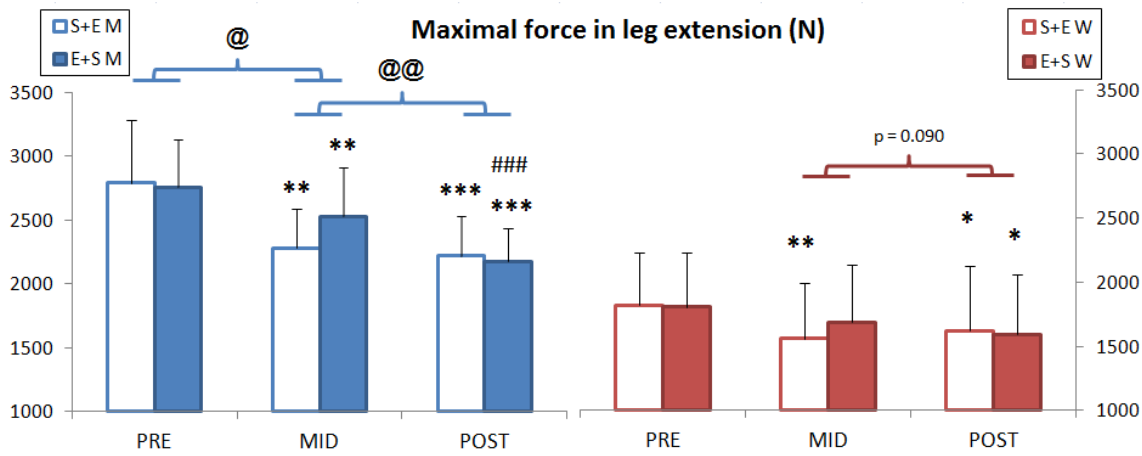

FIGURE 30. Maximal force in leg extension (MVC) during both combined loadings for men and women. * represents significant change from the PRE, # represents significant change from the MID and @ $p < 0.05$ and @@ $p < 0.01$ significantly different change between loadings.

In fast force production (during first 500 ms) significant changes occurred only in men. S+E and E+S decreased MVC500 by -25.9 %, $p < 0.001$ and -20.7 %, $p < 0.01$, respectively. The E loading alone induced a significant decrease (-12.0 %, $p < 0.001$)

and after S loading it decreased further (-3.4 %, $p < 0.01$) regardless the already impaired fast force production. (Figure 31).

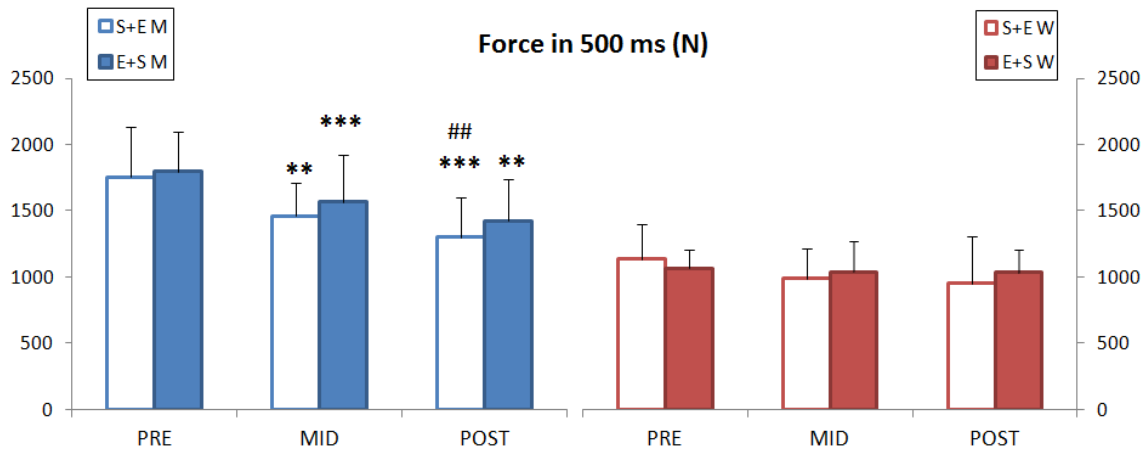

FIGURE 31. Maximal voluntary force within first 500 ms in both combined loadings for men and women. *represents significant change from the PRE and # represents significant change from the MID.

CMJ results decreased -7.1 %, $p < 0.05$ and -5.0 %, $p < 0.05$ in response to the combined loading in men S+E and E+S, respectively. No significant changes occurred in women (Figure 32). The summary of neuromuscular responses in combined strength and endurance loading is listed in Table 10.

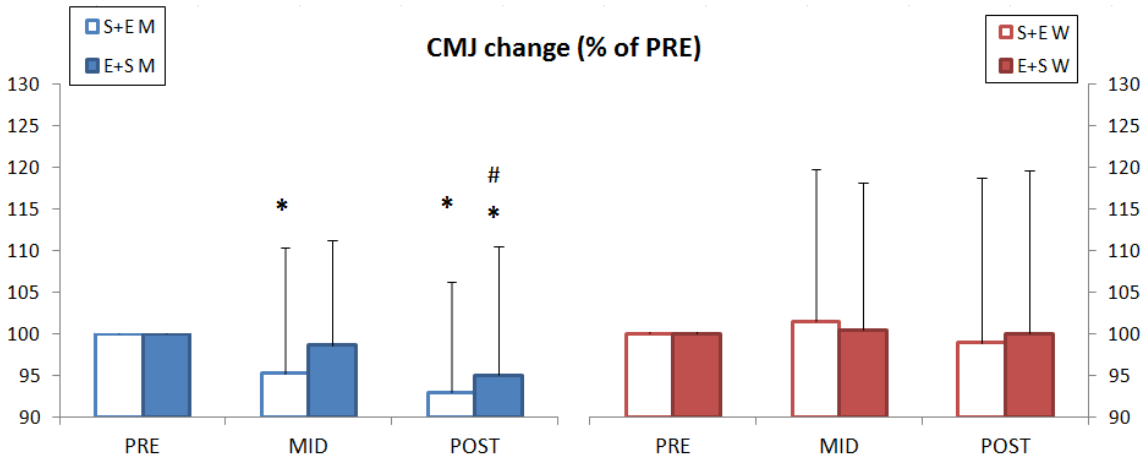

FIGURE 32. Relative changes in maximal counter movement jump (CMJ) in both combined loadings for men and women. *represents significant change from the PRE and # represents significant change from the MID.

TABLE 10. Neuromuscular responses during both combined loading protocols in men and women. * = significant change from PRE # = significant change from MID.

		MEN			WOMEN		
		PRE	MID	POST	PRE	MID	POST
MVC (N)	S+E	2794 ± 496	2282 ± 306**	2220 ± 307 ***	1821 ± 414	1558±434**	1622 ± 507*
	E+S	2757 ± 371	2530 ± 382**	2175 ± 262***###	1808 ± 423	1686 ± 452	1592 ± 465*
MVC500 (N)	S+E	1752 ± 382	1459 ± 253**	1298 ± 306***##	1132 ± 268	985 ± 233	952 ± 354
	E+S	1795 ± 304	1564 ± 360***	1423 ± 31**	1063 ± 137	1036 ± 229	1034 ± 174
CMJ (cm)	S+E	33.9 ± 5.1	32.3 ± 4.9 *	31.5 ± 4.2 *	22.7 ± 3.7	23.0 ± 4.2	22.4 ± 4.5
	E+S	33.3 ± 4.8	32.8 ± 4.1	31.6 ± 4.9 *#	23.2 ± 3.4	23.3 ± 4.1	23.2 ± 4.6

MVC = Maximal voluntary force in bilateral leg extension, **MVC500** = Force production in leg extension during first 500 ms, **CMJ** = Counter movement jump.

In combined strength and endurance loading (S+E) in men, there were no associations between overall changes in the running biomechanics and neuromuscular responses. In S+E in women there were few significant correlations between the change in fast force production (MVC500) and the change in horizontal braking force and braking impact ($r = -0.875$, $p < 0.01$ and $r = -0.829$, $p < 0.05$), respectively. Also the change in MVC and stride frequency were correlated ($r = -0.721$, $p < 0.05$) as well as the change in CMJ and horizontal braking force ($r = 0.838$, $p < 0.01$). In the opposite loading order, only the change in CMJ and change in contact time and flight time were significantly correlated ($r = 0.839$, $p < 0.01$; $r = -0.749$, $p < 0.05$).

When the S loading was compared separately the change in vertical active peak force ($F_z$max) was correlated negatively ($r = -0.676$, $p < 0.05$) with the change in CMJ in the S+E loading in men. In S+E in women the change in CMJ was correlated with the change in braking impact ($r = 0.742$, $p < 0.05$). During the S loading alone in men

during the E+S, the change in the horizontal braking and propulsion force were correlated with the change in MVC ($r = -0.742$, $p < 0.01$; $r = 0.651$, $p < 0.05$). During E+S in women the change in stride length was negatively correlated with the change in CMJ ($r = -0.671$, $p < 0.05$) during S.

8.4 Metabolic responses

During 60 min of running in both loading conditions cardiovascular and metabolic variables remained quite stable except heart rate and respiratory exchange ratio (RER) which changed significantly in both men and women. These results are shown in Table 11. Heart rate increased significantly during the 60 minutes of submaximal running in the S+E loading for men and women (4.3 %, $p < 0.001$ and 3.0 %, $p < 0.01$, respectively). The changes were similar in magnitude for both genders during the E+S loading when endurance loading was performed first (4.7 %, $p < 0.001$ and 3.4 %, $p < 0.001$). RER decreased in both loading conditions significantly ($p < 0.01 – 0.001$) for men and women. When the endurance loading was performed first (E+S loading) oxygen consumption increased in men in relation to time unit (VO2) and distance (RE) (2.4 %, $p < 0.05$ and 2.2 %, both $p < 0.05$, respectively). No significant changes were observed in women in the same combined loading, or in men and women during S+E loading order (Table 11).

TABLE 11. Cardiovascular and metabolic responses for both combined loadings. Heart rate is recorded at minutes 15 and 45 during endurance loading, respectively. Breathing gas variables are listed as mean of minutes 6 – 8 and 56 – 58 during endurance loading, respectively. * = $p < 0.05$, ** = $p < 0.01$ and *** = $p < 0.001$ refers to significant differences compared to start of endurance loading.

	Loading S + E				Loading E + S			
Sex	**Men**		**Women**		**Men**		**Women**	
Time-point	**start**	**end**	**start**	**end**	**start**	**end**	**start**	**end**
HR (bpm)	153 ± 11	159 ± 10 ***	159 ± 16	164 ± 16 **	150 ± 9	157 ± 10 ***	155 ± 16	161 ± 15 ***
VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$)	45.0 ± 4.0	45.3 ± 4.4	39.1 ± 3.4	39.3. ± 3.5	43.6 ± 3.7	44.7 ± 3.7 *	37.9 ± 3.3	38.2 ± 3.9
RE ($ml \cdot kg^{-1} \cdot km^{-1}$)	223 ± 12	224 ± 11	220 ± 8	221 ± 9	214 ± 10	219 ± 10 *	215 ± 6	216 ± 8
RER	0.93 ± 0.03	0.90 ± 0.03 **	0.88 ± 0.04	0.84 ± 0.04 ***	0.93 ± 0.03	0.89 ± 0.03 ***	0.90 ± 0.03	0.85 ± 0.04 ***
BLa ($mmol \cdot l^{-1}$)	2.7 ± 1.0	2.5 ± 1.1	2.1 ± 1.1	2.2 ± 1.4	2.2 ± 0.5	1.9 ± 0.7	1.7 ± 0.7	1.6 ± 0.5

In the S+E loading order the acute changes in heart rate were positively correlated with the change in the horizontal peak force during propulsion and with the change in the stride length ($r = 0.714$, $p < 0.05$; $r = 0.675$, $p < 0.05$, respectively). S+E in women there were no significant associations between any metabolic and biomechanical changes.

In the opposite loading order, E+S in men, the change in the running economy (ml/kg/km) was negatively correlated with the change in the horizontal impulse during propulsion ($r = -.632$, $p < 0.05$). E+S in men, also the change in RER was positively correlated with the change in the stride length ($r = .667$, $p < 0.05$). In the corresponding loading order in women, the change in the heart rate was negatively correlated with the change in the horizontal impulse during propulsion, total vertical impulse and horizontal peak force during propulsion ($r = -.881$; $r = -.800$; $r = -.819$; all, $p < 0.01$, respectively).

9 DISCUSSION

The present study investigated acute changes in ground reaction forces (GRFs) and running stride variables (RSVs) as well as changes in neuromuscular performance and in metabolic status as a response to a single session combined strength and endurance loading (S+E and E+S) in recreationally trained male and female endurance runners. Secondly it studied the order effect of the combined loading. Thirdly, it investigated the associations between running biomechanics and neuromuscular performance, and the last, the associations between running biomechanics and metabolic responses. The main finding was that running biomechanics were altered only after strength loading preceding endurance loading (S+E) but not after E+S. This suggests a higher fatigue in running biomechanics after S+E loading than after E+S loading. For men stride length ($p < 0.05$), flight time ($p < 0.01$), vertical active peak force ($p < 0.01$) and total vertical impact ($p < 0.05$) decreased, while stride frequency ($p < 0.001$) increased in response to S+E loading order. For women, the only significant change was a small increase in stride frequency ($p < 0.05$) in response to S+E loading order. There were some associations between changes in running biomechanics, neuromuscular and metabolic responses but these were not unambiguous due to high inter-individual variation in GRFs and RSVs.

9.1 Changes in running biomechanics in response to combined loading

There is no data available on how running biomechanics are affected by strength loading, not to mention combined single session endurance and strength loading. Generally, in the current study only S+E loading order induced significant changes in GRFs and RSVs, but when looking at separate exercises (S or E), it seemed that endurance loading alone induced greater changes in running biomechanics compared to

strength loading alone. In women in S+E the changes in running biomechanics seemed to choose different direction, whereas the overall change remained insignificant. E following S in women induced similar changes as S+E in men. However, in men, both S+E confirmed each other, thus making overall change more significant. Nevertheless, none of these separate changes were statistically significant in the PRE-MID timeline.

The possible reason for the changes observed, especially after S+E loading, might be related to the fact that the strength loading alone induced alterations in neuromuscular capacity. When the endurance loading was conducted immediately after the strength loading, this induced the greatest overall changes in running biomechanics. In previous studies where stretch-shortening cycle exercise (e.g. running) has been studied separately, the exercise has been noticed to induce neuromuscular impairment as the isometric MVC has been noticed to decrease from 15 to 30 % depending on the intensity and duration of running exercise (e.g. Avela et al. 1999; Finni et al. 2003 Millet et al. 2002). The overall effect of S+E loading on running biomechanics in the current study is similar to those observed after these long distance running exercises. Because there are no reports of the change in running biomechanics during a combined strength and endurance loading, the interpretation comparison of the current data in light of existing studies is limited.

Running stride variables. Stride length decreased (4.1 %, $p < 0.05$) and stride frequency increased (2.2 %, $p < 0.001$) in men in response to the S+E loading, whereas there were no statistically significant changes in the opposite loading order. In women, there was a slight increase ($p < 0.05$) only in stride frequency after S+E loading, while no changes were observed in the opposite loading order. Contact times remained unchanged in both sexes and loading orders, but flight times decreased significantly (8.4 %, $p < 0.001$) after S+E in men only.

As mentioned earlier, the study design was unique in terms of strength loading effect on running biomechanics. On the other hand, there are fairly many studies that have measured running biomechanics in various endurance exercises (e.g. Rabita et al. 2011; Rabita et al. 2013; Kyröläinen et al. 2000; Finni et al. 2003). There has been observed

altered stride frequency in many studies; either decreased SF (Hunter & Smith 2007; Dutto & Smith 2002) or increased stride frequency (Rabita et al. 2011; Kyröläinen et al. 2000; Morin et al. 2011a; 2011b) during constant velocity running. The current results are in line with findings of Kyröläinen and colleagues (2000), who similarly found increased stride frequency (+ 4 %, $p < 0.01$) while stride length (-4 %, $p < 0.01$) was decreased after running a constant speed marathon. In addition, in a shorter but a more intensive endurance loading, Rabita et al. (2011) found similar changes among nine elite triathletes, however, they found contact times to be increased by 4 % ($p < 0.05$). Rabita and colleagues (2011) concluded that the increase in contact times allowed the runners to maintain a constant horizontal impulse despite of fatigue development. One must be cautious to compare the current and the previous results because different measurement methods have been used (i.e. force platforms, mounted force treadmills and pressure insoles) and the subjects' training backgrounds were different (recreational vs. elite endurance athletes).

Buckalew et al. (1985) found that, as fatigue increases, the support leg knee bends more during ground contact, decreasing body's center of mass (COM) height. A lowered COM in turn can decrease stride length (Buckalew et al. 1985; Hauswirth et al., 1997). Though, the stride length decreased as a response to S+E this can be seen as an origin of fatigue even though an increase in oxygen consumption did not occur (more accurately on paragraph 9.3).

Ground reaction forces. Ground reaction forces were measured in vertical and horizontal direction, and as described earlier, most of the changes occurred only after the S+E loading. Vertical active peak ($F_z$max) was decreased by 6.2 % ($p < 0.01$) after the S+E loading in men, but no changes were observed in the opposite loading order (2.0 %, $p = 0.67$). This was seen as order effect, i.e. a relative significant change ($p < 0.05$) from PRE to POST between the loading models. In women, the overall change was insignificant because of quite large individual variation in both loading conditions, but women's $F_z$max decreased 3.8 % ($p < 0.05$) during the endurance loading (following S loading). In men, the reduction in $F_z$max by 6.2 % is well in line with previous findings, where various endurance loadings have been utilised e.g. intensive

middle distance (Rabita et al. 2013; Rabita et al. 2011) or long distance endurance loading (Girard et al. 2013; Morin et al. 2011a; Morin et al. 2011b).

In total vertical impulse (TVI) (i.e. time integral of a GRF during a ground contact), there was a decrease of 3.9 % ($p < 0.05$) after S+E in men, whereas in women the inter-individual variation was quite high thus decreasing the statistical power. The reduction in total vertical impulse after S+E illustrates the reduced force production or support demand during the ground contact (Heise & Martin 2001). More often in the literature the maximal active peak force is used and in longer endurance events the reduction in vertical active peak force is well established (Morin et al. 2011a; Morin et al. 2011b). It has been concluded that the neuromuscular function is impaired and the overall behaviour of the lower limb considered as a spring-mass system shifts toward a higher stiffness and oscillating frequency, allowing for reduced vertical force during each support phase and lower vertical displacements of the centre of body mass. (Morin et al. 2011a.)

In the horizontal direction there were no changes either during braking or propulsion phase independent of sex or the loading order. This might be due to the magnitudes in horizontal direction are much lower in relation to body weight and it is much more sensitive for inter- and intra-individual variation.(Cavanagh & LaFortune 1980.)

Millet et al. (2011) studied responses to ultra endurance running and concluded that runners had significantly higher stride frequency, reduced flight time without change in contact time, decreased maximal force ($F_z$max) and loading rate (LR) in response to ultra-distance running. These changes were remarkably similar to those observed in the current study, where the loading was completely different (combined strength and endurance loading vs. ultra distance running). Millet et al. (2011) suggested the higher SF and reduced FT to be due to impairment in the neuromuscular function by extremely long exercise duration. $F_z$max and FT seemed to decrease most in response to ultrarunning attenuating the potentially painful eccentric (braking) phase and overall load faced by their locomotor system at each step (Morin et al. 2011b). Those changes in running pattern were interpreted to lead to a smoother and safer running style (Millet

et al. 2009; Martin et al. 2010). This phenomenon has also been observed by Kramanidis and Arampatzis (2005), who found old men to run with a lower vertical displacement of the centre of the body mass during contact, a higher stride frequency (caused in both studies by a reduced flight time with no change in contact time), and a reduced maximal vertical peak force. Karamanidis and Arampatzis (2005) also interpreted these changes as a reaction to the reduced capacities of subject's muscle–tendon unit to increase the running safety.

9.2 Neuromuscular changes and the associations between the running biomechanics.

The neuromuscular response to combined loading protocols was a significant decrease in the maximal leg extension force (MVC) in both genders and loading protocols. In men the decrease was 20.5 % ($p < 0.001$) and 18.3 % ($p < 0.01$) in the S+E and E+S loading orders, respectively. In women the decrease was smaller, 10.9 % and 11.9 % ($p < 0.05$ in both). Only in men the change in MVC was significantly different between the loading orders. MVC was significantly decreased from PRE to MID in both combined loadings (18.3 %, $p< 0.01$ in S+E and by 8.2 %, $p < 0.05$ in E+S). However, from MID to POST the reduction was significant only in E+S (14.0 %, $p < 0.001$). Interestingly in women the change in MVC was not significantly different between loading protocols even though MVC already after S decreased more than after the S+E loading overall, because their force production improved slightly (but insignificantly) during the latter E loading.

Based on previous literature, both strength (both maximal and explosive) loading (e.g. Häkkinen 1993; Linnamo et al. 2005) as well as endurance loading (e.g. Saldanha et al. 2008, Lepers et al. 2000) has been noticed to attenuate MVC drastically. In the study of Linnamo et al. (2005) there were reductions of 11 % and 12 % ($p < 0.05$ in both) after explosive strength exercise in men and women, respectively. Endurance loadings have been noticed to decrease MVC between 15 – 30 % (e.g. Ross et al. 2010; Millet et al.

2002) depending on running intensity and duration. The finding of relatively bigger decreases in MVC in the current study is fairly reasonable, suggesting a cumulative effect of fatigue. The strength loading included both heavy and explosive strength exercises and together with endurance loading (60 minutes) the total duration of the combined loading protocol with acute measurements was approximately 2.5 hours.

In men, the separate parts of the combined loadings contributed to a decrease in MVC. However, in women only the S loading separately decreased MVC. This can be due to different muscle fiber distribution between males and females, in favour of men having more fast-twitch fibers (Häkkinen 1993). In addition, in athletes a greater baseline strength level can lead to a larger neuromuscular fatigue after heavy resistance loading due to greater motor-unit activation (Ahtiainen & Häkkinen 2009). Similarly in the training study of Schumann et al. (2014) the loss in MVC, as an acute response to combined strength and endurance loading, increased from 22 % to 27 % after 24 weeks of combined strength and endurance training. This indicates a greater reduction in MVC due to developed ($p < 0.05$) strength levels. Therefore it can be assumed that the greater reduction in MVC in men is due to higher strength level compared to women.

Also based on previous studies the rapid force production is greatly attenuated in men ($p < 0.001$) and women ($p < 0.01$) though the shift has been noticed to be greater in men ($p < 0.05$) (Häkkinen 1993). In addition, maximal rate of force development has been observed to attenuate ($p < 0.05$) in response to submaximal marathon loading (Avela et al. 1999). In the current study, in fast force production during first 500 ms in maximal voluntary force production (MVC500), statistically significant changes occurred only in men. The overall changes between the loading orders were almost similar, but the S+E attenuated rapid force production more than E+S. Independent of the loading type performed first in the combined loading, the loss in MVC500 was greater between PRE – MID than MID-POST time points. This acute reduction in rapid force production can be seen as muscle fatigue, which might rise not only because of peripheral changes at the level of muscle, but also because central nervous system fails to drive the motor neurons adequately (Nummela et al. 2008). It has also been suggested that in exercise

such as running (stretch-shortening cycle) performance may be impaired partly due to alterations in muscle stiffness regulation (Avela & Komi 1998).

Even though the S+E loading in men was the order where most of the significant changes in running biomechanics occurred, there were no associations between the changes in running biomechanics and the changes in neuromuscular performance in S+E in men. However, in S+E in women the change in rapid force production was significantly correlated with the change in horizontal braking force and braking impact ($r = -0.875$, $p < 0.01$ and $r = -0.829$, $p < 0.05$), respectively, indicating an increase in braking support force while fast force production decreased suggesting that fast force production during fits 500 ms could offer valuable information about increases in braking forces. Although, neuromuscular impairment due to eccentric actions in the running loading might attenuate fast force production, and furthermore, lengthen the braking phase (Komi & Nicol 2000).

In addition, in S+E in women stride frequency was increased most in them whose maximal force production decreased most. After exercise involving long-term running, the isometric strength loss is related in a nonlinear way to the exercise duration. Muscular fatigue can be defined as an inability to maintain a level of force production or a reduction in the maximum force that a muscle can exert. (Millet & Lepers 2004). In the E+S loading order in women, only the change in CMJ and change in CT and FT were significantly correlated ($r = 0.839$, $p < 0.01$; $r = -0.749$, $p < 0.05$). Women tended to increase CMJ results with the increased CT or decreased FT, which is a little bit controversial. Although, Vuorimaa et al. (2005) have proved elite endurance athletes improve their CMJ results in response to an intensive endurance loading. It must be noted that the subjects in the previous mentioned study were elite athletes. Increase in vertical force production can be seen as enhanced fast force production, however increased contact time is usually a sign of fatigue (Nicol et al. 1991). Although, the associations need to be considered with caution since the change in CMJ or CT were not significant in either of the loading orders in women.

In conclusion, because the changes in neuromuscular responses in men were not correlated at all with the changes in running biomechanics, it rises a question is the bilateral isometric leg extension force the best way to measure fatigue in endurance running loading. Similarly Nummela et al. (2008) doubted the application of MVC as a measurement of fatigue in endurance running loading, because the maximal force in MVC was not correlated with fatigue responses during running.

9.3 Metabolic changes and the associations with the running biomechanics.

Oxygen consumption increased both in relation to time (VO_2) ($p < 0.05$) and distance (RE) ($p < 0.05$) in men when the endurance loading was performed prior to the strength loading. However, in women during the E+S there were no significant increases, and further, there were no changes in the opposite loading order in men or in women. The strength loading performed first probably attenuated excess post-exercise oxygen consumption (EPOC) which might be the reason for slightly elevated oxygen consumption levels already in the beginning of the endurance exercise in the S+E loading order. Nevertheless, the relative changes in oxygen consumption or running economy between the loading orders were not significant either in men or in women.

The breathing data was collected during the first and the last 10 minutes of the totally 60 minutes lasting endurance exercise. It was surprising that running economy altered slightly only for men in E+S. The mean coefficient of variation in running economy varies between 1 to 4 % in the meta-analysis of four reports (Morgan & Craib 1992). However, if various factors such as time of the day during measurement, footwear, training status and performance level are controlled, as in the present study, the coefficient of variation will be under 2.5 %. Further, more precise energy expenditure can be calculated with the application of respiratory exchange ratio (RER) and lactate metabolism as in the study of e.g. Kyröläinen et al. 2000 and Kyröläinen et al. 2001. RER was observed to decrease significantly ($p < 0.01 – 0.001$) in both loading orders in men and women, which refers to a slight change in energy metabolism towards an

increased fat oxidation. This means a lowered energy expenditure in relation to O_2 liters consumed (McArdle et al. 2001, 183). In addition to lowered RER data the blood lactate levels did not increase at all, which only emphasize the high energy expenditure already after 10 min of running compared to last 10 min of loading. In conclusion, even trying to find some alternative methods for compensating RER and blood lactate accumulation, the changes were insignificant. It is possible, though, that during the first 10 minutes of endurance loading when breathing gases were collected there might have been overbreathing. The overbreathing seems as an increase in CO_2 production in relation to consumed O_2, which increases RER and VO2 values as well (McArdle et al. 2001, 185). Thus, the differences of PRE-POST comparison in oxygen consumption remained unchanged

There were few associations between changes in the running biomechanics and metabolic alterations during the running loading in either S+E or E+S. It is not worthwhile to compare the total change during combined strength and endurance loading due to the fact that metabolic changes have been measured only in the beginning and in the end of the endurance loading. Thus, comparing these two loadings is in this case more precisely done by comparing the E loading immediately after strength exercise (S+E) with the E loading with no previous fatigue (E+S).

Most of the associations observed between metabolic changes and running biomechanics were between the changes in heart rate and horizontal force production during propulsion phase. This is reasonable because only few time interactions occurred in metabolic variables like oxygen consumption and running economy throughout the combined loadings in men and women. Instead, heart rate increased significantly ($p < 0.01 – 0.001$) in response to both combined loadings in both sexes, but there were no time interactions in horizontal force production during the ground contact. In S+E loading in men, acute changes in heart rate were positively correlated with the changes in the horizontal peak force during propulsion and with the changes in stride length ($r = 0.714$, $p < 0.05$; $r = 0.675$, $p < 0.05$, respectively). In women in S+E there were no associations between any metabolic and biomechanical changes. More precise observation of the significant correlations in men revealed that usually one or two

outliers might have been the reason for the correlation. Especially in the horizontal direction the GRFs are relatively small (0.4 – 0.5 time body weight), thus already a small alteration in running technique could change the horizontal force production drastically (Kyröläinen et al. 2001).

In the opposite loading order, E+S, there were small changes in metabolic variables as oxygen consumption increased and running economy weakened ($p < 0.05$), but changes took place only in men. Alterations in running economy were inversely correlated with the change in the propulsion impact (P_{Imp}: $r = -0.632$; $p < 0.05$). In addition, reduction in RER was related to decreased contact time ($r = 0.667$, $p < 0.05$). In E+S in women, the associations were visible between increased heart rate and decreased horizontal propulsion force and decreased propulsion impact ($r = -.819$, $p < 0.01$ and $r =-.881$, $p < 0.01$, respectively). In other words, the female runners who fatigued most in terms of increased heart rate were those whose horizontal force production decreased most.

According to previous results the relationship between running biomechanics and running economy seems to be controversial. According to Williams and Cavanagh (1987), running economy is the sum of many variables. It seems that no single kinematic variable can fully explain the decrease in running efficiency (Hausswirth et al. 1997) or in running economy (Williams et al. 1987; Nicol et al. 1991). Kyröläinen et al. (2000) concluded that individual changes in running kinematics could only partially explain the drastically weakened running economy. There are still some evidence of the association between running biomechanics and running economy. In the cross-sectional study of Heise & Martin (2001), researchers noticed that running economy was correlated with total vertical impulse ($r = 0.62$). However, in the current study, there were no relationship between the changes in total vertical impact and running economy.

One of the reasons for few associations was the minor changes in metabolic variables even though there were statistically significant differences in the running biomechanics. This could also have been the opposite way – Slawinski et al. (2008) found no changes in GRFs and RSVs even though the cost of running increased 11 %. However, these

associations in the current study should be interpreted with caution because of the high inter- and intra-individual variability, which has an effect on the results.

9.4 Limitations of the study

Some of the weaknesses in the current study were the small number of subjects and few ground contacts analysed for each subject even though Karamanidis et al. (2003) outlined that a single trial can provide reproducible vertical GRF data. Despite rather constant mean values, the inter-individual variability was quite high but this seems to be the case in earlier studies as well (Buckalew et al. 1985; Williams et al. 1987). In addition, it is possible that the awareness of measurements might have affected RSVs as well as GRFs. The RSV and GRF measurements were done separated by 60 minutes of endurance running on the 200-m running indoor track, thus the subjects became conscious of the measurements. Indeed, Morin et al. (2009) concluded that subjects' running pattern significantly changed with the increasing level of information given, with a higher stiffness and stride frequency, a reduced contact time and a lower change in leg length during contact. Subjects changed their running pattern when knowing that a sampling was performed and what mechanical parameter was studied (Morin et al. 2009).

This "sampling effect" might be even more emphasized when running biomechanics (longitudinal responses) are measured with a force-plate system by the aid of a light-rabbit system, in a single 50-60-meters long running course separately from the running loading, as in the current study. Even though subjects were informed to maintain the normal stride patterns and the pace was controlled by the photocell gates, it is possible that they altered their running stride patterns and force production unconsciously when approaching or "aiming at" the force plate system, which instantly modifies the GRF pattern (Challis 2001). However, this was partly due to the aim to measure acute responses as fast as possible after the cessation of loadings.

In addition, the striking pattern (rear-, mid- or forefoot) was not controlled, which might alter the GRF variables remarkably. This surely have an effect on how fast the initial impact peak occurs (Kluitenberg et al. 2012). The loading rate or the initial impact peak were not analysed, because the striking pattern of the subject was unknown. However, roughly 90 - 95 % of them were rear-foot strikers, which is well in line with the previous findings among recreational runners in the study of Larson et al. (2011).

In addition to above mentioned limitations, no muscle activation was analyzed, thus leaving questions about the origin of fatigue or alterations. In submaximal constant speed endurance exercise, EMG ought to increase so that the given exercise intensity could be maintained. Greater neural input to the muscle is required to produce the same resultant force in the push-off phase of the ground contact. (Komi et al. 1987; Nicol et al 1991).

10 CONCLUSIONS

The present study showed that there was an order effect in running biomechanics (GRFs and RSVs) between combined loadings (S+E and E+S). Running biomechanics were altered only after strength loading preceding endurance loading (S+E), suggesting higher fatigue and increased changes in the running stride pattern after S+E loading compared to E+S loading. Most of the changes in running biomechanics occurred in men whereas women preserved the initial stride patterns. The changes described above were similar than in previous studies considering much longer running loadings, but the reason of the change might be the same: aim to find a safe and economic running stride under the fatiguing condition after S+E.

No order effect between loadings was found in the neuromuscular or metabolic changes. Not even in S+E in men, where alterations in terms of running biomechanics were found. The associations between changes in neuromuscular and biomechanical responses showed a decrease in fast force production to be related with increase in horizontal braking forces.

This was according to my knowledge the first study to assess running biomechanics and running economy in response to a combined strength and endurance loading and therefore it is obvious that more studies are needed in order to fully understand the effect of a combined single session loading protocol. Furthermore, it is too early to outline whether S+E would be a more beneficial way to improve running performance by utilising single session combined training. More longitudinal studies that focus on combined strength and endurance running training are needed to publish reliable training implications. However, the results of this study imply that E+S training induces less fatigue and should therefore be considered as the way to combine strength and endurance training for endurance athletes. It might be more ideal in regards to unaltered running stride patterns after E preceding S loading and thus, no alterations in the running technique due to fatiguing effect of S.

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