ACUTE EFFECTS OF FATIGUE TO STRENGTH AND POWER VARIABLES IN ENDURANCE TRAINED ATHLETES

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ABSTRACT

Ville Vähäkoitti (2015). Acute effects of fatigue to strength and power variables in endurance trained athletes. Department of Biology of Physical Activity, University of Jyväskylä, Bachelor Thesis of Science of Sport Coaching and Fitness Testing, 39 p, 5 appendices.

The purpose of this bachelor thesis was to investigate how fatigue affects strength and power in endurance trained athletes. This thesis is written for the athletes, coaches and researchers in the field of sport. Total of 7 endurance athletes (age 23.3 years ± 1.3, height 174.7 cm ± 6.4, weight 66.5 kg ± 8.4) volunteered for the study, 4 male and 3 female. Hypotheses were that measured variables do not decrease after fatiguing protocol and that the potentiation may counteract fatigue. Fatigue was induced in a continuous maximal treadmill running, where speed was increased every five minutes by one km/h. When necessary, after 45 minutes of running, speed was increased every minute by one km/h till exhaustion. Strength and power were tested before, during and after running with countermovement jump (CMJ), dynamic leg press power and maximal force of isometric leg press, respectively.

Results showed statistical increase in CMJ height at every measurement point, between pre run and 15 min ($p = 0.005^{**}$), pre run and 30 min ($p = 0.009^{**}$), pre run and post run ($p = 0.033^{*}$) and pre run and post 10 ($p = 0.049^{*}$). Changes in CMJ and lactate did not correlate between each other. Dynamic leg press and isometric leg press results stayed levelled, or increased, but the changes were not statistically significant. Post run heart rate (HR) was 186 (± 5.6) and post run lactate (LA) 11.2 (±1.9), which both demonstrate maximal effort. No changes were found between control and pre run values in any of the strength tests. From these results it can be concluded that maximal running did not induce fatigue in any of the strength measurements. Endurance athletes seems to be fatigue resistant and are able to maintain their strength levels during and after fatigue. Based on prior studies, CMJ results may have increased because of the potentiation in muscles. Data obtained here could be used in developing warm-up, training and competition protocols for endurance athletes.

Key words: endurance athletes, postactivation potentiation, fatigue, countermovement jump

TABLE OF CONTENTS

ABSTRACT

APPENDICES

1 INTRODUCTION

VO_2 max have been considered as the defining factor in endurance performance (Hausswirth & Le Meur 2012). However both lactate threshold (LT) (Sunde et al. 2010) and exercise economy (Aagaard & Raastad 2012) contribute to the endurance performance. The higher LT and exercise economy are the longer the desired pace during training or competition can be maintained longer (Sunde et al. 2010).

Whereas VO_2 max and LT are mostly trained with repeated actions, like running or cycling, exercise economy can be improved with strength training. Concurrent strength and endurance training improve the performance of average to top-level endurance athletes (Millet et al. 2002; Mikkola et al. 2007; Aagaard & Raastad 2012), without compromising endurance capabilities (Taipale et al. 2014). Increments in performance are from the adaptations that enhance the economy of endurance performance, for example desirable muscle fiber changes (Aagaard & Andersen 2010).

During and after prolonged exercise fatigue increases. Fatigue is task dependent (Enoka & Stuart 1992), and it differs according to the exercise duration and intensity, types of contractions and among tested muscle group (Škof & Strojnik 2006a). Postactivation potentiation (PAP) implies action where muscle performance is temporary enhanced because of the previous contractions (Boullosa et al. 2011). PAP can be used for example in jumping, sprinting or throwing (Xenofondos et al. 2010). Hodgson et al. (2005) propose that fatigue and potentiation can co-exist. Thus PAP could enhance performance by decreasing the amount of fatigue, or move the point of fatigue forward.

This bachelor thesis examined how fatigue affect strength and power production in national level endurance athletes. They were tested before, during and after a running protocol, i.e. in different points of fatigue. Hypotheses were that endurance athletes can maintain their strength and power production in a fatigued state, and that PAP could counteract fatigue in endurance athletes.

2 FACTORS AFFECTING ENDURANCE PERFORMANCE

2.1 Importance of VO_2 max

Traditionally maximal oxygen uptake (VO_2 max) has been considered to be the most important factor defining endurance capability (Hausswirth & Le Meur 2012). VO_2 max equals the highest rate at which oxygen can be absorbed and used in muscles during exercise (Hausswirth & Le Meur 2012). VO_2 max and heart rate (HR) rise somewhat linearly with the increase in the exercise intensity (ACSM 2010, 159). Female athletes have 8-10 % lower VO_2 max than male athletes (Hausswirth & Le Meur 2012). VO_2 max can be raised with endurance training but it is greatly affected by the genetics. Genetics affect both the innate VO_2 max and the capability of VO_2 max to respond to training. (Hausswirth & Le Meur 2012.)

Differences in VO_2 max between normal population and trained athletes are connected to differences in maximal cardiac output and approximately 70 to 85 % of limitations in VO_2 max is explained by maximal cardiac output (Hausswirth & Le Meur 2012). This is due to that in maximal exercise almost all of the arterial oxygen is extracted from the muscles (Hausswirth & Le Meur 2012). Though heart capacity to deliver oxygen defines VO_2 max it is not the only mechanism. Mitochondria's capacity can be enhanced with endurance training which increases the pressure gradient between the muscle capillaries and the intracellular medium (Hausswirth & Le Meur 2012). Blood capacity to transport oxygen increases with haemoglobin. Haemoglobin responds to endurance training, but can also be manipulated with altitude training or blood doping, from witch last one is strictly forbidden (Hausswirth & Le Meur 2012).

Hausswirth and Le Meur (2012) point out four ways that may limit VO_2 max in performance since oxygen has to travel from air to the cells mitochondria. The ways are 1) the pulmonary diffusion capacity 2) the maximal cardiac output 3) the blood's capacity to transport oxygen and 4) the muscle's capacity to consume oxygen. For normal individuals diffusion capacity is not a limiting factor in exercise, but for elite endurance athletes performing in high-intensity exercise it maybe. Elite endurance athletes have relatively high cardiac output and therefore time for red blood cells in the pulmonary capillaries to exchange oxygen is limited and may result for some athletes to reach their maximum ventilatory capacity during high-intensity exercise. (Hausswirth & Le Meur 2012.)

Another important factor in endurance capacity is the lactate threshold (LT) (Sunde et al. 2010). Hausswirth and Le Meur (2012) define LT as a highest intensity where muscle oxygenation capacity is able to maintain energy production without increase in lactate concentration. As the exercise intensity increases, lactate will not generally increase before the LT, which is around 60 % of VO_2 max in trained athletes, and up to 75 to 90 % of VO_2 max in elite endurance athletes (Hausswirth & Le Meur 2012). As the exercise intensity rises above LT pyruvate production exceed the mitochondria capacity to produce oxygen for the working muscles and therefore lead to production of lactic acid (Hausswirth & Le Meur 2012). Both mitochondria's capacity to deliver oxygen and LT respond well to endurance training. Elite endurance athletes have higher LT than normal people, which allow them to maintain higher VO_2 max for a longer time (Hausswirth & Le Meur 2012).

2.2 Strength training for endurance athletes

Strength training has been controversial in endurance training. Researches have shown results in favour of incorporating strength training to improve endurance performance, but also vice versa (Aagaard & Raastad 2012). Traditionally strength training has not been considered beneficial for endurance athletes, but new research shows that concurrent strength and endurance training improve the performance of average to top-level endurance athletes (Millet et al. 2002; Mikkola et al. 2007; Aagaard & Raastad 2012). Maximal and explosive strength training improved performance more than circuit training in recreational runners (Taipale et al. 2014).

Also, combined strength and endurance training does not alter VO2 mechanics (Millet et al. 2002; Mikkola et al. 2007; Sunde et al. 2010; Taipale et al. 2014) which has been a concern for endurance athletes and coaches. This even when part of the endurance training is replaced with strength training (Bastiaans et al. 2001). Taipale et al. (2014) point out in their study that strength increases plateau in the final phase, possibly because of either too low volume or intensity or both. Therefore it seems that strength training need to produce enough stimulus for body for adaptations, which means that intensity or volume of strength training should be increased progressively (Taipale et al. 2014). Research shows that endurance athletes should incorporate strength training to their training programs (Bastiaans et al. 2001).

Aagaard and Raastad (2012) list four different ways how strength training can improve endurance performance. They are 1) improved exercise economy, 2) improved anaerobic capacity, 3) reduced or delayed fatigue, and 4) improved maximal speed. Aagaard and Raastad (2012) divide benefits of strength training to short-duration (less than 15 minutes) and long-duration (more than 15 minutes) endurance performances.

In short-duration endurance performance improving maximal speed or anaerobic capacity leads to better results. Better maximal speed improves performance in mass start competitions (Aagaard & Raastad 2012), which is an advantage in, for example, sprint cross-country skiing competition. Strength training provokes optimal muscle fibre changes from type IIX to IIA and enhances maximal voluntary contraction (MVC) and rate of force development (RFD), which all lead to improvement in short-duration endurance performance (Aagaard & Raastad 2012). Type IIA fibres are more fatigue resistant than IIX fibres but are able to produce high forces (Aagaard & Andersen 2010; Aagaard et al. 2011). If strength training improves types I and IIA fibres that would ultimately leads to more powerful contraction, and thus smaller amount of muscle must be activated to produce certain power. This may prevent fatigue or shift the point of fatigue forward, and also decrease the amount of energy used (Aagaard & Raastad 2012).

Effects of strength training to long-duration endurance performance have been mainly studied in untrained or moderately trained people, but not much with elite athletes (Aagaard & Raastad 2012). In one study, Aagaard et al. (2011) examined young top level cyclists and concluded that concurrent heavy strength and endurance training led to an improved endurance capacity in 45 minute time trial. Research group suggested that improvement was due to increase in IIA muscle fibre capacity and improvements in muscle strength (MVC) and RFD (Aagaard et al. 2011) and are alike than in previous adaptations in short-term endurance performance.

Strength training does not bring increases in body mass nor decreases capillary density (Aagaard & Andersen 2010: Aagaard et al. 2011). Increased capillary density could lead to a better delivery of O_2 and FFA uptake to the muscle cell because of the shortened diffusion distance (Aagaard & Andersen 2010). Elevated free fatty acid (FFA) uptake can diminish glycogen breakdown which may prolong the time to fatigue and thus improve performance (Aagaard & Andersen 2010).

Mikkola et al. (2007) combined endurance and explosive type of strength training and noted a small increase in muscle mass, a small decrease in body mass which summarized to no changes in body mass. Same changes in body weight was measured in another research combining explosive strength training and endurance training (Paavolainen et al. 1999), and combining heavy strength training and endurance training (Aagaard & Andersen 2010). Endurance training prevents the muscle hypertrophy stimulus that would normally exist from high intensity strength training, when trained simultaneously (Aagaard & Andersen 2010). Many endurance athletes are concerned that strength training would add their muscle mass, which could decrease performance in sports that require moving body against gravity, for example running (Aagaard & Andersen 2010).

Aagaard and Raastad (2012) conclude that concurrent strength and endurance training have been proved to improve long-duration endurance performance in untrained-to-well trained individuals more than mere endurance training. Strength training has to be high on intensity (> 85 % 1-RM) to improve endurance performance (Aagaard & Andersen 2010; Aagaard & Raastad 2012). This also means that hypertrophy type of training is not as effective as maximal strength training for endurance athletes, nor is the low-resistance, power type of strength training (Aagaard & Andersen 2010).

Also, strength training can improve sprinting ability after short- or long-duration endurance performance (Aagaard & Raastad 2012). In many endurance competitions the winner is decided in the end, where improved sprinting ability or speed may be a key factor over other competitors. This is true in both short-duration and long-duration competitions. For cyclists, increasing maximal strength means that applying force to the pedal represents lower load compared to maximum prior strength training (Aagaard & Andersen 2010). As well, increased RFD could mean faster muscle contraction (pushing the pedal), and therefore longer relaxation time in each individual pedalling, thus decreasing the local muscle exhaustion (Aagaard & Andersen 2010). Sunde et al. (2010) found that 8 weeks of maximal strength training improved cycling economy and time to exhaustion in group of competitive cyclists.

Concurrent strength and endurance training may improve exercise economy in both short-duration and long-duration performance, compared to endurance training alone (Aagaard & Andersen 2010; Aagaard & Raastad 2012). Paavolainen et al. (1999) mention that running economy can be more important predictor of endurance capability in well-trained endurance athletes than VO_2 max. Improvements in exercise economy have been reported in different level of athletes and also in different fields of endurance sport after concurrent strength and endurance training (Aagaard & Raastad 2012). For the top level endurance athletes exercise economy may already be so optimized that improvements are hard to demonstrate in short concurrent training researches (Aagaard & Raastad 2012). Improvements in endurance performance and in VO_2 max after years of endurance training seems to become limited at some point, but explosive type of strength can improve endurance performance by improving muscle power and running economy in well-trained endurance athletes (Paavolainen et al. 1999).

2.3 Plyometric training and endurance

Plyometric training is defined as explosive strength training involving the stretch-shortening cycle and actions like bounding, jumping and hopping (Saunders et al. 2006). One advantage of plyometric training is that it generates neural adaptations rather than muscle hypertrophy, which is more likely outcome after heavy strength training and usually not desirable for endurance athletes (Saunders et al. 2006). Plyometric training can improve muscle stiffness in muscle-tendon system and therefore enable body to store and release elastic energy more effectively (Spurss et al. 2003).

Running economy (RE) is one of the best indicators of running performance (Spurrs et al. 2003). Plyometric training has been reported to improve running performance by improving

RE (Paavolainen et al. 1999; Spurrs et al. 2003; Saunders et al. 2006). RE is defined as a steady-state oxygen requirement in certain submaximal running speed (Spurrs et al. 2003). Better RE corresponds to lower oxygen cost at a given running speed, and is used as a marker of RE (Saunders et al. 2006).

6-week plyometric training program increased both CMJ and 5-bound distance test in moderately trained endurance athletes (Spurrs et al. 2003). RE and running performance were both improved after plyometric training program, without compromising VO_2 max (Spurrs et al. 2003). In another study by Saunders et al. (2006) 9 weeks of added plyometric training improved running economy at high speed (18 km/h) but not in lower speeds in highly trained runners without compromising VO_2 max. Endurance athletes improved their running time (5-km), RE and maximal velocity in maximal anaerobic running test (MART) after 9-weeks of concurrent plyometric and endurance training (Paavolainen et al. 1999).

In the researches by Spurrs et al. (2003) and Saunders et al. (2006) plyometric training was added to normal endurance training, whereas in the research by Paavolainen et al. (1999) part of the normal endurance training was replaced with plyometric (explosive-type strength training). Based on these studies both adding plyometric training, or replacing part of normal training with plyometric training, seems to improve endurance performance. Saunders et al. (2006) propose that better RE are due to improvements in muscle power and elastic energy return. Well-trained endurance athletes reach after years of training their VO_2 max, but performance can still be developed with plyometric training (Paavolainen et al. 1999).

3 FATIGUE IN ENDURANCE PERFORMANCE

Nummela et al. (2008) define fatigue as an inability to maintain muscle force production, or as a reduction in the maximal force that a muscle can exert. To keep the desired force level, perceived effort increases before the force declines (Enoka & Stuart 1992; Barry & Enoka 2007). During prolonged exercise fatigue increases. Fatigue rises from the peripheral changes in the muscle level, or from the central nervous systems inability to control the motor system adequately (Nummela et al. 2008). Therefore fatigue impair both neural and muscular mechanisms (Garrandes et al. 2007). It seems that instead of a single mechanism that affects fatigue, it is task dependent (Enoka & Stuart 1992; Barry & Enoka 2007), and that fatigue differs according to exercise duration and intensity, types of contraction and the tested muscle group (Škof & Strojnik 2006a).

In endurance performance fatigue can be either central or peripheral (Škof & Strojnik 2006a; 2006b). Peripheral fatigue is further divided into high- and low-frequency fatigue (HFF and LFF, respectively) (Rassier & MacIntosh 2000; Škof & Strojnik 2006a; 2006b). HFF results in a decrease in maximal force, and LFF decrease in submaximal force, both from prior activity (Rassier & MacIntosh 2000). Prolonged fatigue is caused by interference in Ca^{2+} cycle which affects excitation-contraction linkage (Škof & Strojnik 2006b; Morana & Perrey 2009) and is peripheral fatigue. Performance can decrease from repeatedly muscle actions in running which strain the stretch shortening cycle and affects muscles stiffness regulation (Nummela et al. 2008).

Different muscles fatigue earlier than other muscles. Hanon et al. (2005) found that hip mobilising muscles rectus femoris (RF) and biceps femoris (BF) fatigued before other lower limb muscles. Those muscle showed and increased activation in parallel with increased running speed which introduced earlier fatigue (Hanon et al. 2005). Vesterinen et al. (2009) found decreased EMG activity in triceps brachii and vastus lateralis during simulated cross-country skiing sprint competition, but no changes in EMG activity in latissimus dorsi or pectoralis major. Noteworthy is that, regardless of the muscle, the higher the force, the faster the muscles fatigue (Enoka & Stuart 1992).

After prolonged running at maximal speed and during MVC lower limb muscles have been recorded decreased electromyography (EMG) activity (Nummela et al. 2008). During submaximal exercise the effects of fatigue to EMG are not as clear as in maximal exercise (Nummela et al. 2008). Nummela et al. (2008) noticed that AEMG (rectified EMG) and ground contact phase increased during 5-km run but that the decrease in AEMG was not related to the decrease of velocity. Decrease in EMG and concurrent decrease in in isometric force seems to describe central fatigue (Nummela et al. 2008). Nummela et al. (2008) suggest that analysing pacing strategies during running provide information of muscles fatigue mechanisms. In a simulated cross-country skiing sprint fatigue was present as an increased poling and recovery phases, and decrease in cycle rate (Vesterinen et al. 2009).

Different types of athletes have different fatiguing profiles. In a study by Häkkinen and Myllylä (1990) endurance, power and strength athletes were tested to maintain isometric force production at 60 % level. Time for submaximal force production and the maximal rate of force production were lower in endurance athletes compared to the other groups, but time to fatigue was longer for endurance athletes (Häkkinen & Myllylä 1990). Maximal isometric force decreased after fatiguing, smallest decrease was in endurance athletes compared to other groups (Häkkinen & Myllylä 1990). From the data from Häkkinen and Myllylä (1990) we can conclude that endurance athletes have lower isometric force, and longer force production time, but weakening of the force is lesser and it recovers faster, compared to power and strength athletes. Garrandes et al. (2007) noted also greater isometric MVC for power trained athletes compared to endurance athletes due to bigger muscle mass (cross-sectional area), different muscle fiber type (more type II) and higher RFD.

Häkkinen and Myllylä (1990) investigated fatigue in isometric conditions, whereas Garrandes et al. (2007) compared endurance and power trained men in isometric, concentric and eccentric contractions after fatiguing concentric exercise. Power trained men’s torque production capacity was clearly impaired after fatigue, whereas no changes were noted in endurance trained men (Garrandes et al. 2007). In concentric contractions endurance trained men values did not differ pre- and post-fatigue, whereas for power trained men the decrease was major (Garrandes et al. 2007). However, after the eccentric contractions torque was decreased in both endurance and power trained groups (Garrandes et al. 2007). Possible explanation given by the authors was that elastic component of muscle and connective tissue may assist torque generating during eccentric contraction (Garrandes et al. 2007).

3.1 Postactivation potentiation

Postactivation potentiation (PAP) signifies an event when muscular performance is temporary increased because of the muscles earlier contractions (Boullosa et al. 2011). Two different mechanisms have been proposed to induce PAP. The first is muscle phosphorylation of myosin light chains, which affect the sensitivity of actin and myosin to Ca^{2+}, and this lead to increased force (Xenofondos et al. 2014). Increased sensitivity of Ca^{2+} means that less Ca^{2+} is needed to perform work (Xenofondos et al. 2014). Fast muscle fibers have more myosin light chain kinases and therefore PAP is greater in muscles with more fast fibers (Sale 2002; Xenofondos et al. 2010; Xenofondos et al. 2014). Fast twitch fibres demonstrate higher potentiation possibility, and power athletes have been shown to have bigger percentage of fast twitch fibres than endurance athletes (Morana & Perrey 2009). Also, endurance athletes demonstrate better fatigue resistance than power athletes (Morana & Perrey 2009).

The other mechanism is neural factors. Increase in motor neuron activity and motor unit recruitment could increase the RFD (Xenofondos et al. 2014), through better motor unit synchronization or decrease in presynaptic inhibition (Xenofondos et al. 2010). Nervous system can modify the muscle contraction by altering the amount of recruited motor units or by changing the firing rate (Xenofondos et al. 2014). PAP itself does not increase strength yet it increases RFD (Sale 2002; Xenofondos et al. 2010).

PAP affects explosive types of movements like jumping, sprinting and upper body (for example throwing) performance (Xenofondos et al. 2010). It seems that highly trained athletes produce more PAP than recreational people (Xenofondos et al. 2010). This is due to that more trained athletes can recruit more motor units faster and at a higher firing rate (Xenofondos et al. 2010). Endurance trained athletes were found to have bigger PAP in trained muscles compared to sedentary people which points out that the phenomena is due to training adaptations (Hamada et al. 2000). Also, PAP seems to be greater in a concentric and in an eccentric-concentric contraction than in an isometric contractions (Sale 2002). Most activities in sport involve dynamic muscle action, which increase the importance of PAP. Gender does not seem to have effect on PAP response (Xenofondis et al. 2010).

Advantages of PAP have been used in training by doing plyometric exercise after strength set, for example jumping after set of heavy squats (Hodgson et al. 2005; Xenofondos et al. 2010). Combined strength and jumping training induced adaptations in the whole muscle level, and in addition, combined training improved all types of jumping (Xenofondos et al. 2010). Esformes et al. (2010) found that CMJ height was improved after set of half squats, compared to plyometric exercise or rest. Although in repeated trials CMJ height did not improve after either mode of exercise (Esformes et al. 2010).

Endurance performance include repeated submaximal muscle actions (Sale 2002). Endurance athletes have greater percentage of slow muscle fibers in their trained muscles (Hamada et al. 2000). Because of the submaximal contractions, motor units discharge in low rates and the force can be increased with PAP (Sale 2002). Previously mentioned, impairment in excitation-contraction coupling induces low-frequency fatigue (LFF), which is opposite of the PAP because LFF is loss of low- frequency tetanic force and PAP increment in low-frequency tetanic force (Sale 2002). PAP cannot compensate high-frequency fatigue (HFF) which is force decline from motor units firing at high rates (Sale 2002). The benefit from PAP to endurance athletes would be better fatigue resistance (Hamada et al. 2000; Sale 2002), for example lower motor unit firing rate to maintain the desired pace during performance.

3.2 Concurrent fatigue and potentiation

Muscle’s performance is affected by its contractile history, which include both PAP, which improves performance, and fatigue which impairs performance (Sale 2002; Hodgson et al. 2005). The previous muscle contractions can either increase (PAP), or decrease performance (fatigue) (Sale 2002; Hodgson et al. 2005). Hodgson et al. (2005) review that although concurrent PAP and fatigue can co-exist, the research on the topic is contradictory due to differences in study methods and designs, and that more research is needed. Rassier and MacIntosh (2000) also state that the potentiation and fatigue can co-exist because they both depend on the previous contractions.

Boullosa et al. (2011) measured concurrent fatigue and potentiation with running track test (Université de Montréal Track Test, UMTT), sprint test and countermovement jump (CMJ). Results showed that CMJ increased after track running test, athletes maintained their sprinting ability, and at the same time peak power increased and concurrently peak force decreased (Boullosa et al. 2011). Boullosa et al. (2011) concluded that PAP possibly replaced the force loss after exhaustion, and therefore allows enhancement in CMJ performance.

Vuorimaa et al. (1996) compared different runners in anaerobic running test, namely sprinters, middle distance runners and marathon runners. They measured maximal 20 meter running test and CMJ as an indicator of fatigue (Vuorimaa et al. 1996). CMJ decreased during anaerobic running test in sprinters and middle distance runners, but increased in marathon runners (Vuorimaa et al. 1996). Authors noted that marathon runners had lower power production (CMJ, sprint time) prior the anaerobic running test, and that values of CMJ on sprinters and middle distance runners remained higher than of marathon runners after anaerobic running test regardless of greater decrease in power production (Vuorimaa et al. 1996).

Vuorimaa et al. (2006) have reported enhanced power and jumping performance after a running protocol done to the exhaustion in elite long-distance runners. When muscles fatigue and Ca^{2+} release is impaired in muscles, potentiation of force happens by increased rate of phosphorylation of the myosin light chains and thus leading that proteins become more sensitive to Ca^{2+} (Morana & Perrey 2009). This will counteract the reduction of Ca^{2+} release in fatigue (Morana & Perrey 2009). This is true in low frequency fatigue (LFF) which is result from long lasting, repeated muscle actions (Škof & Strojnik 2006a; 2006b; Morana & Perrey 2009). Morana and Perrey (2009) state that both fatigue and potentiation change the skeletal muscle’s characteristics.

Morana and Perrey (2009) researched two different groups of athletes, endurance and power athletes, and PAP in fatiguing isometric contractions. They concluded that both endurance and power athletes benefited from potentiation during fatigue although the level of fatigue and its accumulation differed between the two groups (Morana & Perrey 2009). In power athletes force loss was significantly greater than in endurance athletes, and endurance athletes countered fatigue with potentiation earlier (Morana & Perrey 2009). Authors suggest that potentiation may have a role in countering, or preventing, fatigue in repeating moderate intensity contractions in sports like cycling, running, swimming and cross-country skiing where the same muscle actions happen repeatedly for a given time (Morana & Perrey 2009).

4 RESEARCH QUESTIONS

Research question 1: Does strength variables decrease after exhaustion in endurance trained athletes?

Hypothesis 1: Strength variables do not decrease in exhaustion in endurance trained athletes.

Argument 1: Vuorimaa et al. (1996) found that after exhausting running test countermovement jump (CMJ) value remained or increased post-running in marathon runners. Boullosa et al. (2011) also found an improvement in CMJ and maintaining in 20 m sprint after exhaustion in endurance athletes. Garrandes et al. (2007) measured no statistical decrease in maximal voluntary torque after concentric knee extensions in endurance athletes.

Research question 2: Can postactivation potentiation (PAP) counteract the effects of fatigue in endurance trained athletes?

Hypothesis 2: PAP can delay or prevent fatigue in endurance trained athletes.

Argument 2: Hodgson et al. (2005) state that fatigue and PAP can co-exist, and that PAP improves performance. Endurance athletes countered fatigue with potentiation in 10-minute intermittent exercise and thus prevented fatigue (Morana & Perrey 2009). Boullosa et al. (2011) found that PAP countered loss of peak force after exhaustion and improvement in CMJ and maintenance in sprint ability. PAP increased jumping capacity (CMJ) after running protocol in endurance athletes (Boullosa & Tuimil 2009).

5 METHODS

5.1 Subjects

The subjects consisted of 7 (age 23.3 ± 1.3 years; height 174.7 ± 6.4 cm; weight 66.4 ± 8.4 kg), both male and female, endurance trained athletes who train and compete in the national level. There were 4 male and 3 female athletes who volunteered for the study. Total number of contacted athletes were 15 and the participation rate to the study was 47 %. Also, one athlete completed the first measurements but then dropped out from the study. Male athletes (age = 23.3 ± 1.7 years; height = 179 ± 4.5 cm; mass 71.8 ± 4.1 kg) and female athletes (age = 23.3 ± 0.6 years; height = 169 ± 4.0 cm; mass 59.2 ±7.1 kg) performed the same study design. All of the athletes had minimum of 5 years of endurance training and competition experience. Pre-endurance values were not measured, but VO_2 max was estimated from the running speed after the running test. Criterion for the participation was that the athlete competed in the national level. Athlete's sports were cross-country skiing (3), endurance running (3) and orienteering (1). The physical characteristics of the subjects and pre-measured strength test results (control values) are presented in table 1. This study was approved by the Ethics Committee of the University of Jyväskylä, Jyväskylä, Finland.

TABLE 1. Mean (± SD) values of physical characteristics and control strength test results for all the subjects.

Age (year) (n=7)	Height (cm) (n=7)	Mass (kg) (n=7)	CMJmax (cm) (n=7)	dynamic leg press (W) (n=7)	isometric leg press (kg) (n=7)
23.3 ± 1.3	174.7 ± 6.4	66.4 ± 8.4	36.2 ± 10.1	702 ± 241	309 ± 91

In table 2 each subject's running time, last running speed, and estimated VO_2 max is shown. Running speed is given from the last load subject was capable of running, and if he or she ran more than half of the load, speed is shown with a point five increase (table 2). Based on the maximal speed, VO_2 max is estimated using two different formulas, ACSM (2010) and

Londeree (1986), respectively. Estimations from ACSM (2010) appear to be excessively great and therefore estimations from Londeree (1986) are used here.

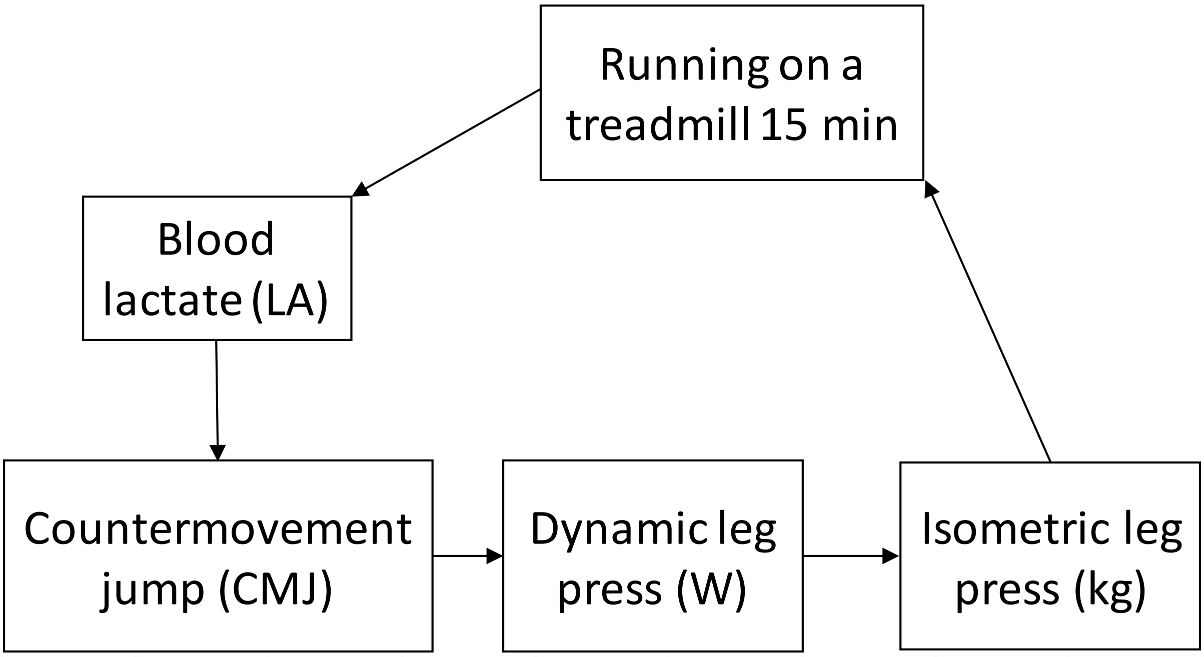
TABLE 2. Running time, maximal speed and estimated VO_2 max from maximal speed based on formulas from ACSM (2010) and Londeree (1986). E = 4 means national level runner.

Subject	Time (min.sec)	Speed (km/h)	VO2 max (ACSM 2010)	VO2 max, E = 4 (Londeree 1986)
Man1	43.00	17.5	66.4	60.3
Woman1	40.26	17	64.6	58.4
Woman2	43.05	17.5	66.4	60.3
Man2	48.00	19	71.8	65.9
Woman3	36.35	16	61.0	54.7
Man3	49.15	21	79.0	73.4
Man4	48.16	20	75.4	69.6
Mean ± SD	44.37 ± 4.45	18.3 ± 1.8	69.2 ± 6.4	63.2 ± 6.6

5.2 Procedures

Participants were evaluated individually on two occasions. The first time included anthropometric evaluation, familiarization to the research protocol and strength tests for control values. The second time included both data and health questionnaires and the running (fatiguing) protocol. The participants were advised not to do speed or maximal endurance training, or heavy strength training for legs two to three days prior the second session. During the running protocol, strength measurement were done before, during and after the running.

The running protocol started with measuring pre values of lactate (LA), resting heart rate (HR) and all three strength tests, respectively. Strength tests were countermovement jump (CMJ), dynamic leg press power and isometric leg press force, respectively. Each strength test was executed three times in each set with given rest intervals: 30 s for CMJ, 15 s for dynamic leg press and 30 s for isometric leg press. One set of strength tests included total of 9 repetitions. After 15 and 30 minutes of running treadmill was stopped. LA sample was taken instantly, and after that strength tests were conducted immediately with given rest intervals (picture 1). Strength measurements took approximately 5-7 minutes.



PICTURE 1. Organization of the measurements. After treadmill running lactate was measured and then all three strength measurements were made, respectively. After the last strength measurement running was continued immediately.

After the pre run values were measured, athlete started the running on a treadmill in speed of 9 km/h and 1° angle. Angle was kept the same during whole running and speed of the treadmill increased every five minutes by one kilometre per hour (appendix 1). Long 5 minute loads were chosen to imitate long prolonged endurance performance. Purpose was that different parts of running would represent approximately different endurance running characteristics. Between 0-15 minute's basic endurance, between 15-30 minutes speed endurance and from 30 minutes forward maximal endurance.

If an athlete completed 45 minutes of running (last 5 minutes speed 17 km/h), LA sample was taken, and he or she performed strength tests normally, and returned to the treadmill. From 45 minutes onwards the speed of the treadmill increased one kilometre every minute until exhaustion (appendix 1). At this point purpose was to find subject's maximum, and the treadmill load time was decreased to one minute because the speed had increased notably. After exhaustion in running, LA sample and strength tests were performed as fast as possible, and one more time 10 minutes post running from the time running ended. Depending on the fitness level of the athlete, he or she performed 4 to 6 times the strength tests. Heart rate was monitored on average of the last half minute of every 5-minute load. LA was measured from the fingertip and analysed with EKF Diagnostics’ Biosen S-line lactate analyser.

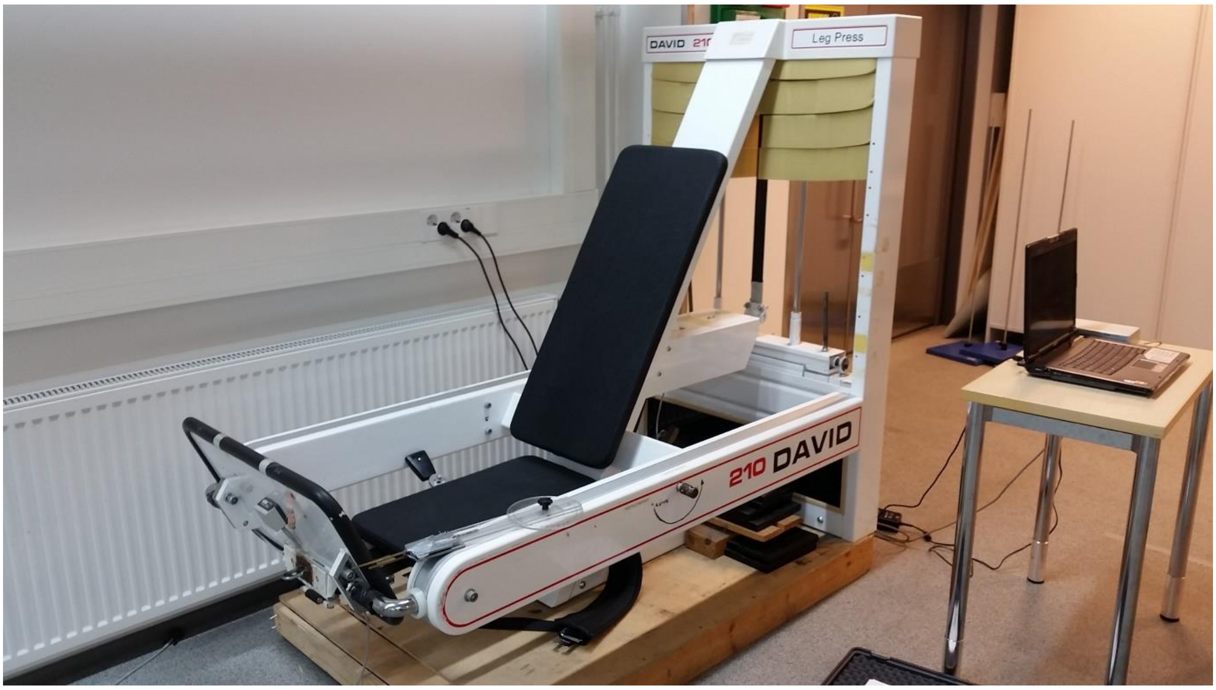
5.3 Measurements

Treadmill used for running was Rodby’s RL 3500E (picture 2). Safety tacks were used whole time during running. Speed and angle was controlled manually from the treadmills control panel.

PICTURE 2. Rodby RL 3500E treadmill used in the study.

CMJ was measured in a force platform from the net impulse. USB-4716 program was used for the recording and programs own ANALYCE option for measuring the results. Each jump was recorded and analysed automatically by the ANALYCE program and then saved. All jump measurements were verified manually for possible errors in automatic recording.

Dynamic leg press power was David’s 210 Leg Press and analyse program MuscleLab V7.18 (Ergotest Technology as). Computer was attached to the sensor that measured change of vertical distance in time (power) when leg press was pushed and the weight pack moved (picture 3). All subjects and their information were imported to the MuscleLab program. Resistance in the leg press was 1.5 times bodyweight for all the subjects and ranked between 80-115 kg. When needed, the weight was rounded up to the next five kilogram mark.



PICTURE 3. Dynamic leg press and the analyse system.

Isometric leg press was measured with Legforce v1.3. The angle was constant 107° and was measured for each subject in the first session using goniometer. Force measurement was done by Dataq Instruments Model DI-149 and it recorded the peak force in kilograms of each performance. Subject were advised to keep their back close to the bench and they were not allowed to lift their body when pushing against the platform. Hands were held in the handles and subjects were advised to grip handles at the same time when pushing with legs. Top of the toes were placed top of the platform for all the subjects to ensure the same protocol.

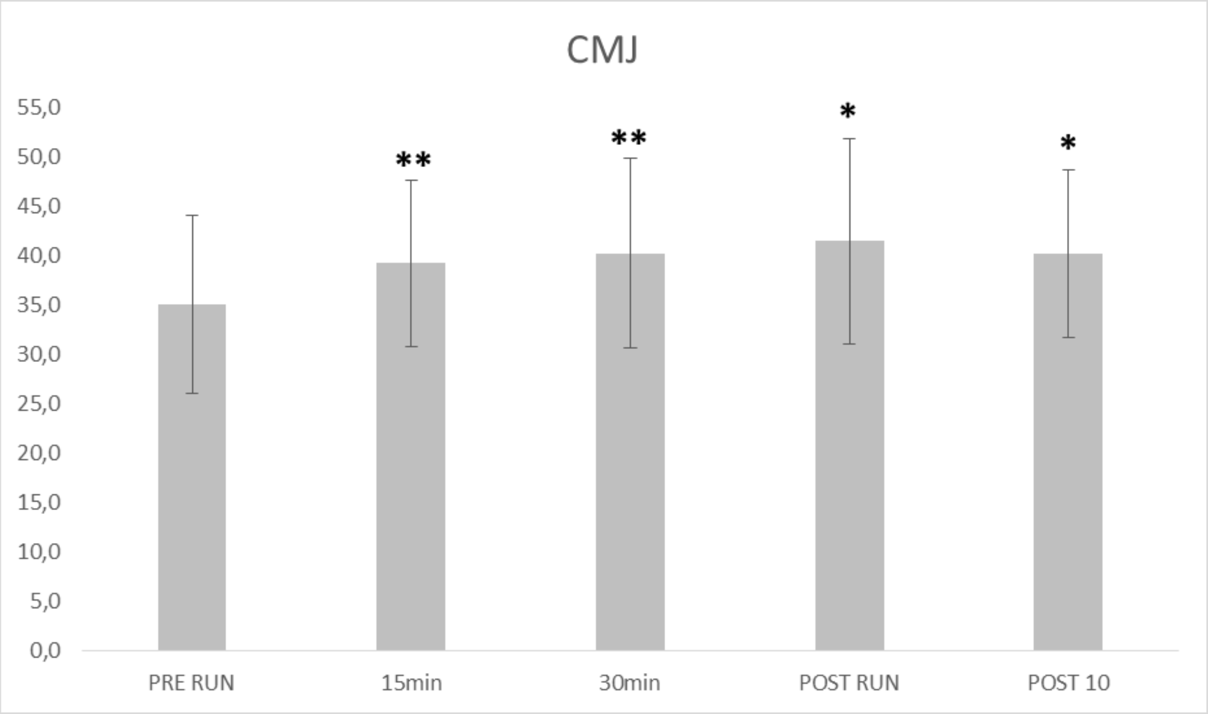
5.4 Statistical analysis

Statistical analyses were executed with the IBM SPSS Statistics Version 20. Data was imported to the SPSS program and then analysed. First normality of data was explored using SPSS's Descriptive Statistics function, and the data was normally distributed. Statistical analysis was conducted using general linear model Bonferroni's test to measure changes in different measurement points in the strength tests, and paired t-test for comparison of control and pre run values in each test. Pearson Correlation was used for measuring CMJ and LA differences because both variables have distance scale.

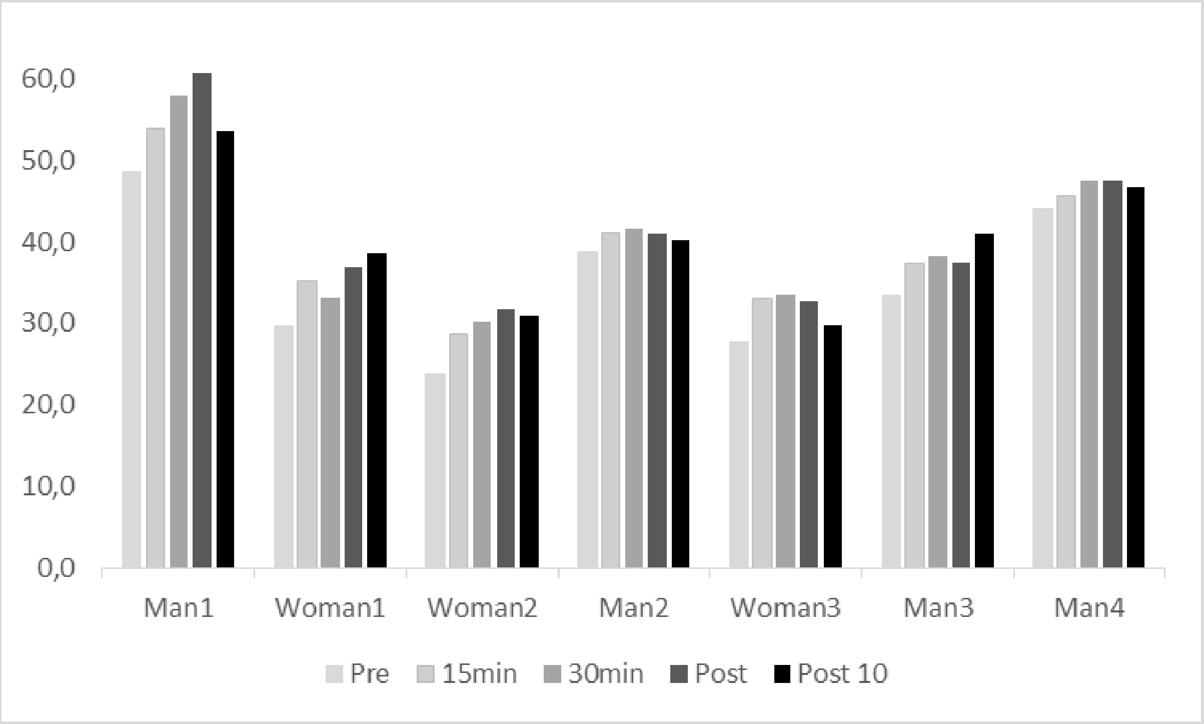
6 RESULTS

Results from the 45-minute point was left out from all the analysis. Only three subjects reached the 45-minute point of running (table 2). Post run values demonstrate results measured straight after subject had stopped running. Running times varied between 36:35 min – 49:15 min (table 2). Those three subjects who ran over 45-minutes executed one strength test pattern more than the other subjects.

The main results from the strength measurements are presented in pictures from 4 to 7. Main finding was the statistical difference found in CMJ between pre run and 15 min ($p = 0.005^{**}$), pre run and 30 min ($p = 0.009^{**}$), pre run and post run ($p = 0.033^{*}$) and pre run and post 10 ($p = 0.049^{*}$) (picture 4). During running the CMJ results increased in all measurement points between pre run and post run (35.1 ± 9.0 cm; 39.2 ± 8.4 cm; 40.3 ± 9.7 cm and 41.5 ± 10.4 cm respectively) values. CMJ post 10 values decreased little from the post run values (41.5 ± 10.4 cm and 40.2 ± 8.5 cm). Individual changes in CMJ are presented in picture 5 and percent changes in appendix 5.

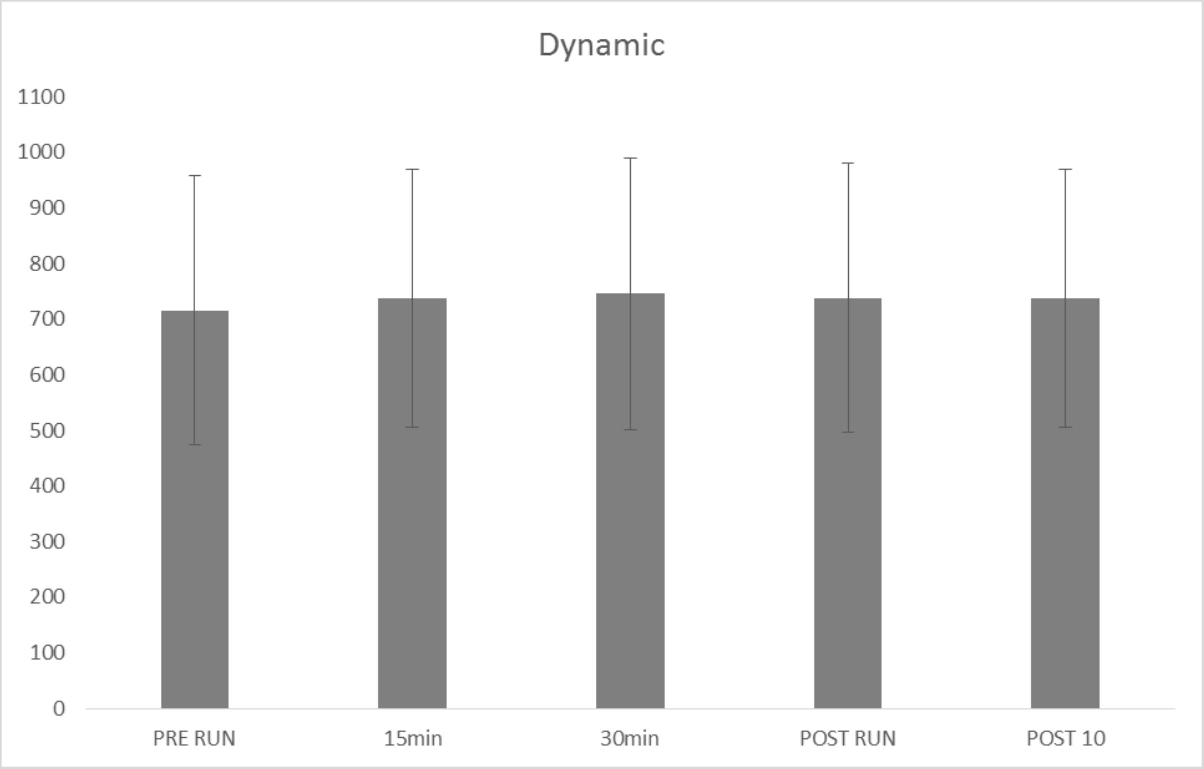


PICTURE 4. Changes in CMJ during the running protocol. Vertical axel is jump height in centimetres (± SD). Statistical difference between pre run and 15 min (p = 0.005**), pre run and 30 min (p = 0.09**), pre run and post run (p = 0.033*) and pre run and post 10 (p = 0.049*).

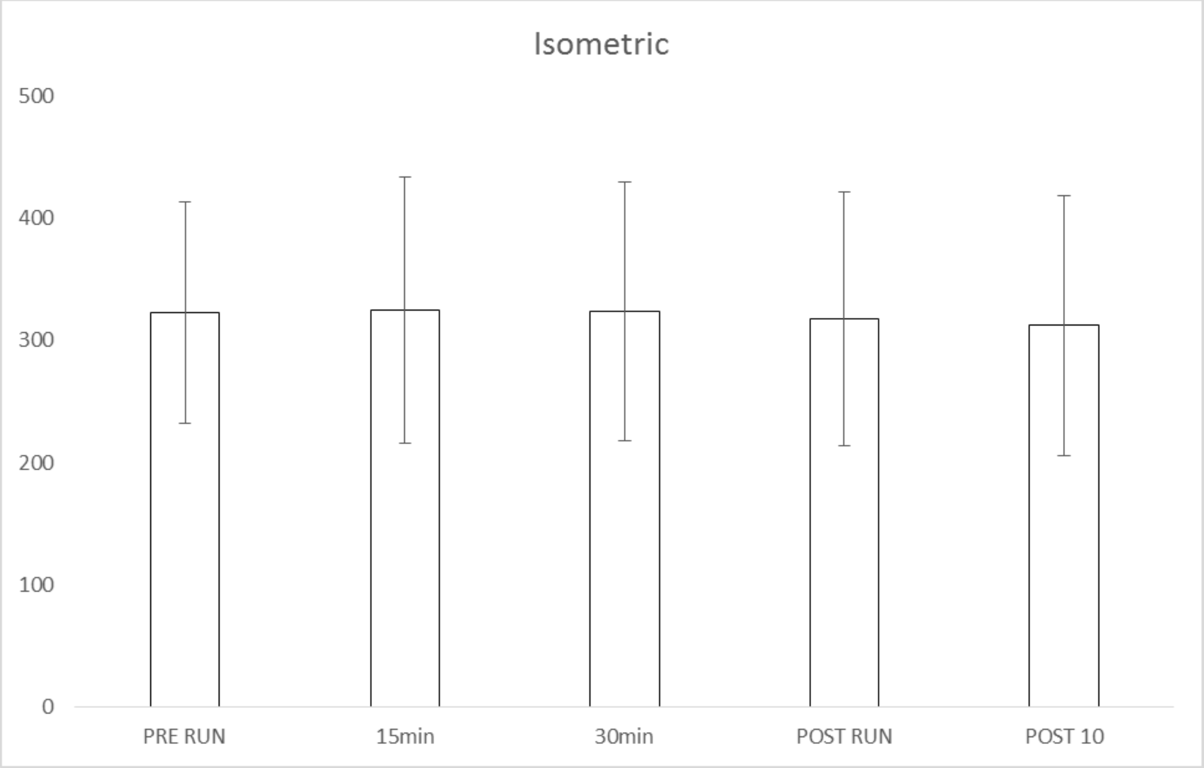


PICTURE 5. Individual changes in CMJ during the running protocol. Vertical axel jump height in centimetres (cm).

No correlation was found between LA pre and CMJ pre run (0.189, p = 0.685), LA 15 min and CMJ 15 min (-0.205, p = 0.659), LA 30 min and CMJ 30 min (-0.388, p = 0.389), LA post run and CMJ post run (-0.61, p = 0.897) and LA post 10 and CMJ post 10 (-0.60, p = 0.910). Also, no statistical changes were measured both in dynamic leg press power or isometric leg press force between pre run and post 10 values in any measurement point (pictures 6 and 7).

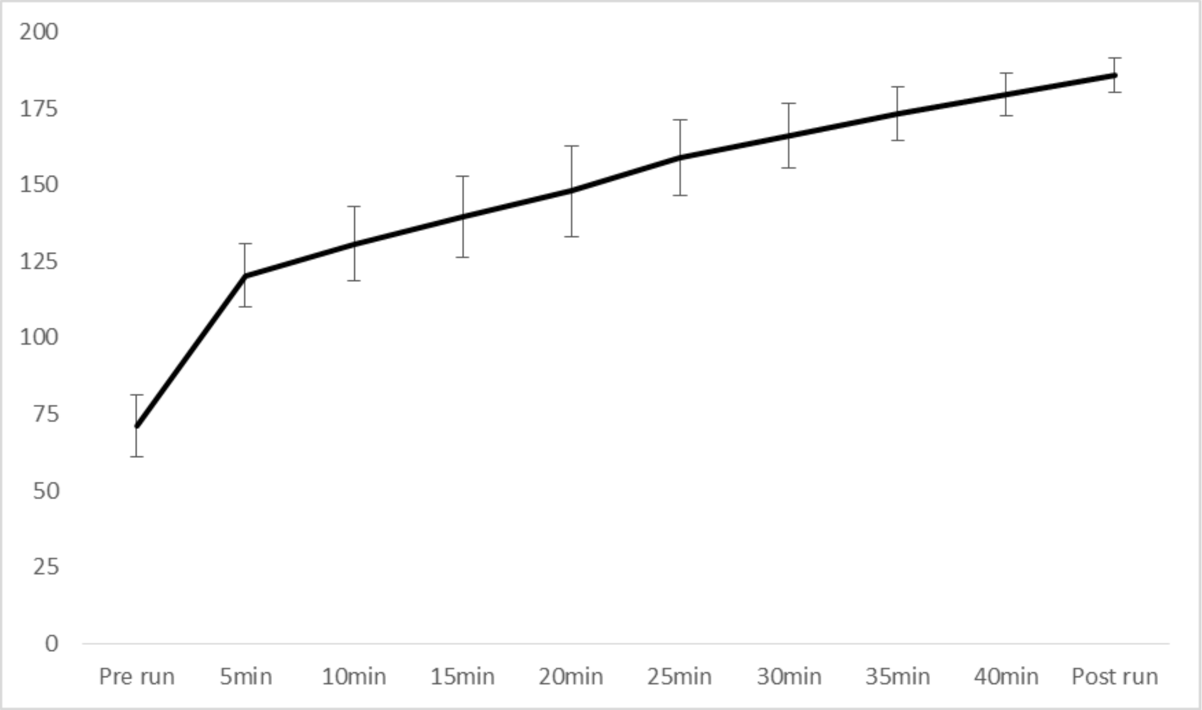


PICTURE 6. Changes in dynamic leg press power during running protocol. Vertical axel in Watts (W) ± SD.

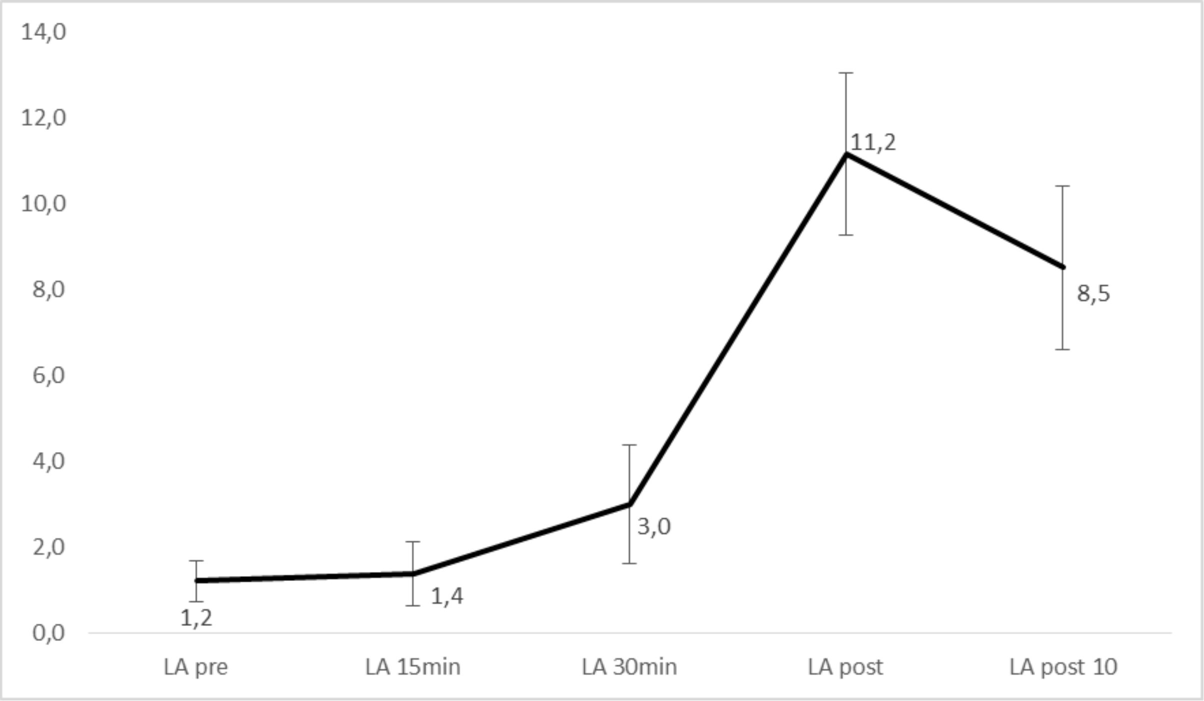


PICTURE 7. Changes in isometric leg press force during running protocol. Vertical axel kilograms (kg) ± SD.

Picture 8 shows heart rate (HR) measured during running. HR rises linearly during running. Post run HR was 186 (± 5.6) which demonstrate maximal effort. Lactate (LA) rose notably after 30 minutes of running (picture 9). Post run LA was 11.2 (± 1.9) and decreased post 10 minutes to 8.5 (± 1.9).



PICTURE 8. Heart rate (HR) during running protocol ± SD.



PICTURE 9. Lactate (LA) measured every 15 minutes during running protocol ± SD.

In the first session strength test values were measured for control. No correlation was found between control and pre run values in CMJ (p = 0.466), dynamic leg press (p = 0.563) or isometric leg press (p = 0.193), respectively. Subject's individual changes in each measurement points are described in appendices 2 to 4. Changes among subjects nor between sexes were not analysed because of the limited number of the subjects in the study.

7 DISCUSSION

The objective of this study was to investigate how fatiguing running test affects the three different strength and power measurements. Main findings in this research were that CMJ increased during fatiguing running (picture 4). CMJ increase was statistically significant between pre run and 15 min (p = 0.005**), pre run and 30 min (p = 0.09**), pre run and post run (p = 0.033*) and pre run and post 10 (p = 0.049*). No correlation between CMJ and LA was found compared in the same measurement points, which indicate that LA did not have effect to the CMJ. LA rose during the running protocol which indicate build-up of fatigue, and yet it did not decrease CMJ results on its part.

King et al. (2013) found little correlation between lower extremity fatigue and decreased jumping performance which supports our CMJ results. They noted however that different levels of fatigue may effect differently to neuromuscular function and jumping performance (King et al. 2013). Boullosa et al. (2011) concluded in their study that PAP increased CMJ performance (3.6 %) after maximum running speed test. In this study CMJ height increased 18.2 % after fatiguing running test. Boullosa et al. (2011) measured concurrent decrease in maximum force and increased peak power during changes in CMJ, whereas in this study neither of those measurements were made. Therefore conclusion that enhancement of CMJ after running was due to PAP cannot be made certainly.

No statistical changes were measured in dynamic leg press or isometric leg press during running. However in pictures 6 and 7 it is seen that neither of the test results decreased. Mean pre and post run values for dynamic leg press were 716 W and 738 W respectively, and for isometric leg press 323 kg and 318 kg respectively. Post run dynamic leg press increased slightly from the pre run value, and the decrease in isometric leg press was minor. It can be concluded that endurance athletes have delayed fatigue mechanism, or that they can produce high forces in a fatigued state.

Research question 1 made a hypothesis that strength variables do not decrease after exhaustion, and possibly vice versa increase. Based on the results from this study the hypothesis was correct. CMJ results increased during running, and other measured variables stayed more or less in the base level. Same type of results have been measured in marathon runners (Vuorimaa et al. 1996), and with endurance athletes (Garrandes et al. 2007; Boullosa et al. 2011).

For the research question 2, it seems that PAP can enhance performance of endurance athletes in fatigue. Prior to this study other researchers have found out that the fatigue and PAP can happen at the same time (Hodgson et al. 2005). Maximal or near maximal effort was performed by the subjects in the running protocol based on the HR (picture 8) and LA curves (picture 9), and the appearance of the subjects during the test. At the same time, no decrease was detected during strength measurements. This points out that there was a mechanism that could substitute the fatigue from running so that the strength and power was produced at maximal output. Although direct measurements of PAP were not made in this study, previous studies point to the direction that enhancement of strength happens during fatigue and PAP is the possible mechanism for it.

7.1 Limitations in this research

All of the measurements were done by the same person, same as the preparation of all the equipment’s. This eliminates error caused by people’s different habits or skills in measuring. During measurements all the equipment’s worked, and researcher did not detect factors that would cause possible errors in the results. All numeric data was double checked after the measurements, and again before starting the data analysis.

Only speculative results are the countermovement jumps, which were measured from the impulse. All test subjects were advised to use same technique, and the technique was trained if needed, and controlled during performance. No correlation was found between the control CMJ and the pre run CMJ, which indicates that learning did not happen between the two sessions. However, especially one subjects jumps raised the question of whether measuring error had happened. Subjects best jump was 60.6 cm post run (appendix 2, Man1). However two other jumps post run were 54.8 and 56.5 cm, respectively, which are in the same size range. Also that best jump goes linearly with other results (appendix 2). All the other CMJ results appeared to be reliable, and therefore previously mentioned 60.6 cm jump result is included, and leaves no need to question its reliability.

Subject’s fitness level could not be tested before the actual test protocol. This was because of the in-season for subjects (cross-country skiing, indoor running). The fatiguing running protocol and tests were designed for this research. Purpose was that different parts of running would represent approximately different endurance running characteristics. Between 0-15 minutes basic endurance, between 15-30 minutes speed endurance and from 30 minutes forward maximal endurance (picture 8). Based on the HR, LA and the running time, estimated fitness level corresponded well to the real fitness level.

Speculative is the influence of running after 45 minutes with one minute loads. Those three subjects who ran over 45 minutes, performed strength tests one more time than the others. Time between strength tests after 45 minutes and strength tests after exhaustion (post run) was only between 3-4 minutes (table 2). Strength tests after 45 minutes and the extra running probably have influenced the post run strength tests, and thus affected the results. Especially isometric leg press seemed to be the most intense in the later stages of the protocol.

7.2 Conclusions

It seems that endurance trained athletes are fatigue resistant, and that they can produce strength and power after exhaustive running. Resistance is partly adaptation from training, but genetics i.e. muscle fiber composition probably also have an influence. Endurance athletes have bigger percentage of slow twitch muscle fibers (Morana & Perrey 2009). Noteworthy, fatigue resistance existed in this study, but cannot be stated to be universal, mainly because fatigue is highly dependent on task and individual (Barry & Enoka 2007). Trend for the fatigue resistance from the results can be seen, and the results are in comparison with the previous studies of endurance athletes.

Further studies could investigate different fatiguing protocols and their effect to the strength performance in endurance athletes, or compare athletes with different characteristics in this test protocol, or in some other test protocol. Also different protocols that are specific to sport performance, could give information of mechanisms of fatigue in competition. One example is study from Vesterinen et al. (2009) where fatigue during simulated cross-country skiing competition was investigated. The protocol used here was not sport specific but was designed to promote fatigue and to be easily monitored and executed.

7.3 Practical applications

Endurance athletes may benefit from warm-up that includes higher intensities to get their body ready for training or competition. If warm-up is done running it could include faster running paces than just jogging. Based on the results from this study even prolonged running do not affect negatively to strength and power abilities of endurance athletes. Heavier running can in fact improve strength and power abilities, which can give an edge in a competitions final moments. Enough recovery must be ensured between warm-up and competition. Lactate build up or muscle soreness are not pursued with the warm-up.

If endurance athletes do strength or power training, it seems that this kind of training can be done after endurance (running) training, even when the running have been speed or maximal endurance. Or, high intensity running can be used as a warmup for strength and power training, making the warmup sport specific for endurance athletes, especially for runners. This phenomena happened straight after the running, but that how long this enhanced performance lasts was not answered with this study. It is not known for example if the phenomena would happen with intensive endurance training in the morning and strength training in the evening.

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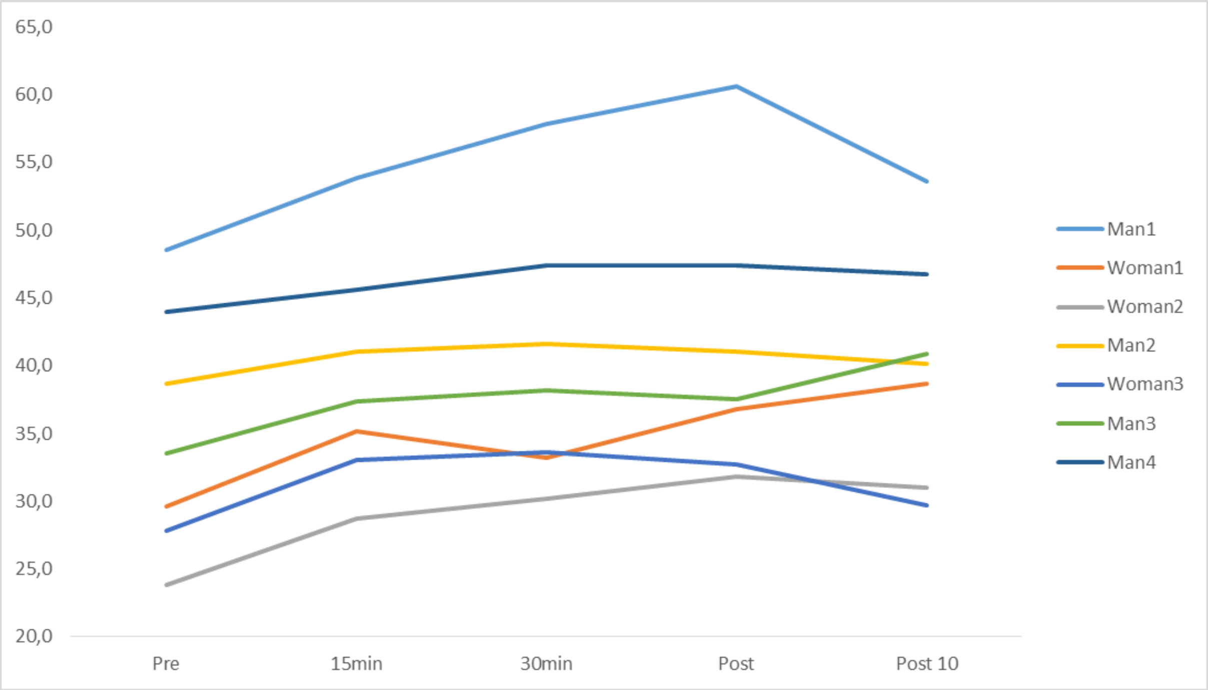
APPENDIXES

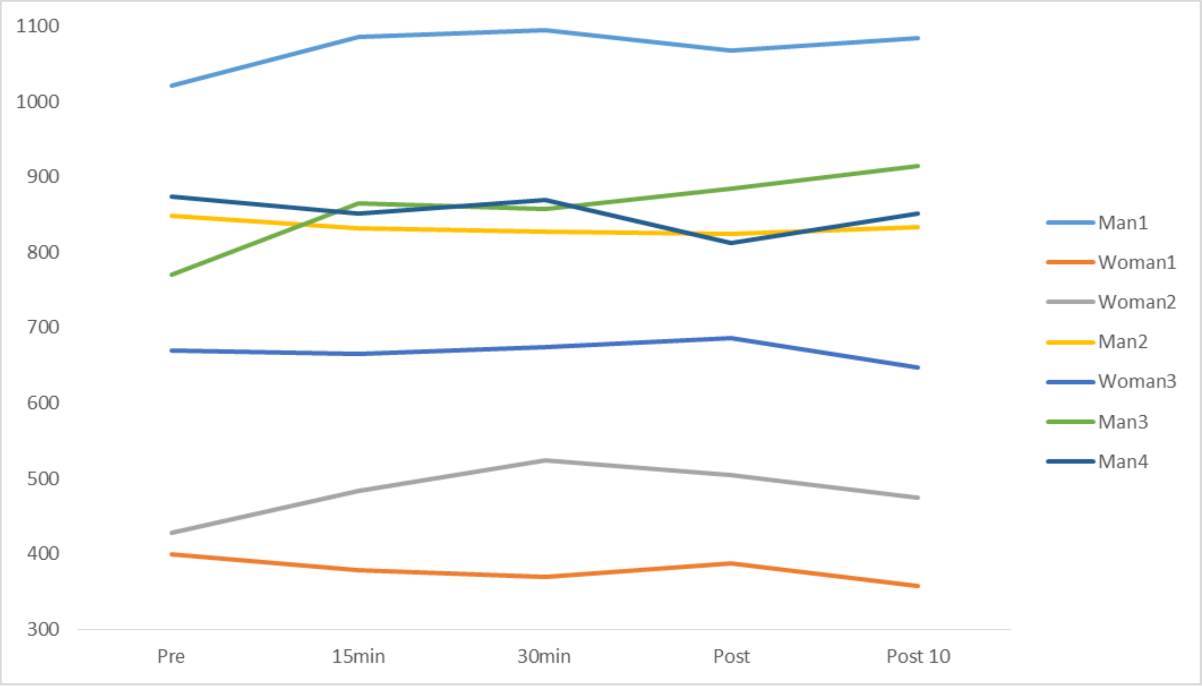
APPENDIX 1. Running protocol and the timing of strength measurements.

				CMJ (cm), every 30s			Leg press (W), every 15s			Isom. leg press (kg), every 30s		
Time (min)	Speed (km/h)	LA	HR	1	2	3	1	2	3	1	2	3
PRE	0											
5	9											
10	10											
15	11											
20	12											
25	13											
30	14											
35	15											
40	16											
45	17											
46	18											
47	19											
48	20											
49	21											
50	22											
POST	(stopping time)											
POST 10												

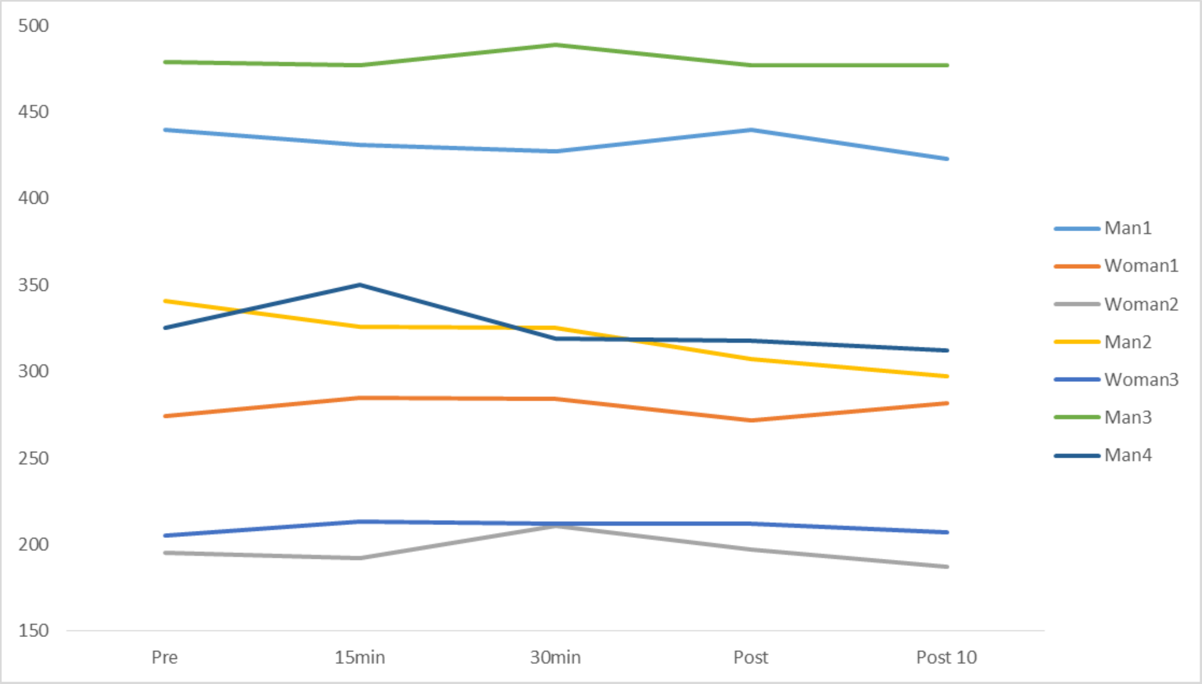
APPENDIX 2. Individual CMJ results for all subjects.



APPENDIX 3. Individual dynamic leg press results for all subjects.



APPENDIX 4. Individual isometric leg press results for all subjects.



APPENDIX 5. Subject's individual percent changes in CMJ, dynamic leg press and isometric leg press. Minus sign expresses negative change to the pre (run) value.

CMJ	**Man1**	**Woman1**	**Woman2**	**Man2**	**Woman3**	**Man3**	**Man4**
Pre	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %
15min	10,9 %	18,9 %	20,6 %	5,9 %	18,7 %	11,6 %	3,6 %
30min	19,2 %	12,2 %	26,9 %	7,5 %	20,9 %	14,0 %	7,7 %
Post	24,9 %	24,3 %	33,6 %	5,9 %	17,6 %	11,9 %	7,7 %
Post 10	10,5 %	30,7 %	30,3 %	3,6 %	6,8 %	22,1 %	6,1 %
Dynamic	**Man1**	**Woman1**	**Woman2**	**Man2**	**Woman3**	**Man3**	**Man4**
Pre	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %
15min	6,4 %	-5,0 %	12,9 %	-1,9 %	-0,7 %	12,3 %	-2,6 %
30min	7,2 %	-7,3 %	22,4 %	-2,4 %	0,7 %	11,4 %	-0,6 %
Post	4,5 %	-3,0 %	18,0 %	-2,7 %	2,5 %	14,8 %	-7,1 %
Post 10	6,2 %	-10,3 %	11,0 %	-1,7 %	-3,3 %	18,8 %	-2,6 %
Isometric	**Man1**	**Woman1**	**Woman2**	**Man2**	**Woman3**	**Man3**	**Man4**
Pre	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %
15min	-2,0 %	4,0 %	-1,5 %	-4,4 %	3,9 %	-0,4 %	7,7 %
30min	-3,0 %	3,6 %	8,2 %	-4,7 %	3,4 %	2,1 %	-1,8 %
Post	0,0 %	-0,7 %	1,0 %	-10,0 %	3,4 %	-0,4 %	-2,2 %
Post 10	-3,9 %	2,9 %	-4,1 %	-12,9 %	1,0 %	-0,4 %	-4,0 %