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Effects of endurance training only versus same-session combined endurance and strength training on physical performance and serum hormone concentrations in recreational endurance runners

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30 ABSTRACT

31 This study investigated the effects of endurance training only (E, n=14) and same-session
32 combined training, when strength training is repeatedly preceded by endurance loading (E+S,
33 n=13) on endurance (1000 m running time during incremental field test) and strength
34 performance (1RM in dynamic leg press), basal serum hormone concentrations, and
35 endurance loading-induced force and hormone responses in recreationally endurance trained
36 men. E was identical in the two groups and consisted of steady-state and interval running, 4-6
37 x wk⁻¹ for 24 weeks. E+S performed additional maximal and explosive strength training (2 x
38 week⁻¹) immediately following an incremental running session (35-45min, 65-85% HR_{max}). E
39 and E+S decreased running time at week 12 (-8±5%, p=0.001 and -7±3%, p<0.001) and 24 (-
40 13±5%, p<0.001 and -9±5%, p=0.001). Strength performance decreased in E at week 24 (-
41 5±5%, p=0.014) but was maintained in E+S (btw-groups at week 12 and 24, p=0.014 and
42 0.011). Basal serum testosterone and cortisol concentrations remained unaltered in E and E+S
43 but testosterone/SHBG-ratio decreased in E+S at week 12 (-19±26%, p=0.006). At week 0
44 and 24, endurance loading-induced acute force (-5 to -9 %, p=0.032 - 0.001) and testosterone
45 and cortisol responses (18-47%, p=0.013 - p<0.001) were similar between E and E+S. This
46 study showed no endurance performance benefits when strength training was performed
47 repeatedly after endurance training compared to endurance training only. This was supported
48 by similar acute responses in force and hormonal measures immediately post endurance
49 loading after the training with sustained 1RM strength in E+S.

50

51 **Key words: concurrent training, acute interference, testosterone, cortisol, endurance**
52 **running, endocrine adaptations,**

53

54 INTRODUCTION

55 High frequency and volume combined endurance and strength training has previously been
56 shown to impair maximal strength development in untrained subjects (Hickson 1980). While
57 detrimental effects on endurance performance are typically not observed in these subjects,
58 heavy and explosive strength training added to endurance training of moderately and highly
59 trained endurance runners may lead to beneficial adaptations in running economy, running
60 speed at $\text{VO}_{2\text{max}}$ and time to exhaustion, when adequate recovery between each training mode
61 is provided (Beattie et al. 2014).

62 The superior effects of combined training on maximal and sub-maximal endurance running
63 performance in endurance athletes are often attributed to improved neuromuscular efficiency,
64 increased force generating capacity, and delayed recruitment of type II fibres as well as a
65 conversion of fast-twitch type Iix fibres into more fatigue resistant type Iia fibers (Rønnestad
66 and Mujika 2014). Although neuromuscular adaptations induced by combined training
67 typically occur in conjunction with changes in endocrine function, only little is known
68 regarding the contribution of the endocrine system when combining strength and endurance
69 training (Kraemer et al. 1995; Taipale et al. 2010).

70 Previous studies have indicated that both endurance and strength exercises can transiently
71 increase hormone concentrations (Kraemer et al. 1990; Häkkinen and Pakarinen 1993;
72 Hackney et al. 2012), such as testosterone (T), growth hormone (GH) and cortisol (C).
73 Among other physiological functions, it is likely that these acute alterations in anabolic and
74 catabolic hormone concentrations directly affect the rates of protein synthesis, red blood cell
75 production and energy restoration (Shahani et al. 2009; Vingren et al. 2010), facilitating
76 biological adaptations to exercise training. As part of the adaptation process during prolonged
77 endurance and/or strength training, exercise induced acute hormone responses (Keizer et al.

78 1987; Kraemer et al. 1995; Häkkinen et al. 2000) and basal hormone concentrations (Kraemer
79 et al. 1995; Häkkinen et al. 2000; Ahtiainen et al. 2003; Hackney et al. 2003; Taipale et al.
80 2010) may be observed.

81 Although the hormonal responses to short term endurance and strength exercises are rather
82 similar (Stokes et al. 2013), their physiological functions may differ due to the catabolic vs.
83 anabolic nature of both types of exercises, possibly contributing to the beneficial effects of
84 strength training on endurance performance. In previous studies, endurance and strength
85 training have typically been performed on separate days allowing for prolonged recovery
86 between subsequent training sessions (Rønnestad and Mujika 2014; Beattie et al. 2014).
87 However, several studies have shown that heavy strength training sessions caused acute
88 detrimental effects on subsequent running performance for 6-24 hours (Doma and Deakin
89 2013; Palmer & Sleivert 2003) owing to the possibility that strength training may in fact
90 compromise endurance development for running performance. On the other hand, previous
91 studies have also shown acute reductions in strength performance following endurance
92 running (de Souza et al. 2007), possibly reducing the beneficial long-term effects of strength
93 training on endurance performance. As decrements in endurance running performance may
94 still be observed 24h following a strenuous strength loading (Doma and Deakin 2013) while
95 recovery following endurance loadings of moderate duration and intensity is much shorter
96 (Bentley et al. 2000, Millet & Lepers 2004), performing endurance training immediately prior
97 to strength training may minimize acute interference and optimize strength training-induced
98 endurance development.

99 The purpose of the present study was to investigate 1) the adaptations in endurance and
100 strength performance as well as basal serum hormone concentrations and 2) the adaptations in
101 acute force and hormone responses to endurance loading, following prolonged endurance
102 training only versus same-session combined training when strength training is repeatedly

103 preceded by endurance loading. A secondary purpose of this study was to investigate whether
104 acute endurance loading-induced changes in force production and serum hormone
105 concentrations are associated with endurance and strength performance development.

106 MATERIALS AND METHODS

107 *Subjects*

108 Twenty-seven recreationally endurance-trained males participated in this study. The subjects
109 had performed endurance running for a minimum of 1 year with 2-6 sessions (at both
110 moderate and high intensity) per week prior to the start of the study. Before giving informed
111 consent, all subjects received information about possible risks of all study procedures. A
112 completed health questionnaire and resting ECG were reviewed by a cardiologist prior to the
113 first exercise testing. All subjects were free of acute and chronic illness, disease and injury
114 and did not report use of medications that would contraindicate the performance of intense
115 physical activity or would interfere with endocrine function. Demographic characteristics of
116 all subjects were as follows (mean±SD): age 33±7years, body height 179±6 cm and body
117 weight 78±7 kg. The study was conducted according to the Declaration of Helsinki and
118 ethical approval was granted by the Ethics Committee at the local University.

119 *Study design*

120 Following health-screening, subjects were assigned to an endurance only (E, n=14) or same-
121 session combined endurance and strength training (E+S, n=13) group. All subjects performed
122 identical endurance training for 24 weeks but additional strength training was added to the
123 E+S training program and was performed always immediately after a standardized endurance
124 running protocol.

125 Prior to the commencement of E and E+S training, baseline testing of endurance (incremental
126 field test) and strength performance (dynamic leg press and counter movement jump [CMJ])
127 was conducted and concentrations of serum hormones (T, GH, and C) and sex hormone
128 binding globulin (SHBG) were assessed. Acute force and hormone responses were
129 determined by measuring maximal force (bilateral isometric leg press) and serum hormone
130 concentrations before and after an incremental treadmill protocol (Fig 1). To ensure sufficient
131 recovery, all tests were separated by at least 48 h of rest. The measurements of loading
132 responses were repeated after 24 weeks, while the baseline measurements of endurance and
133 strength performances as well as serum hormone concentrations were also conducted after 12
134 weeks. All post-training measurements (at week 12 or 24, respectively) were performed at the
135 same time of day within ± 1 h of the testing time at week 0. To control the experimental
136 conditions, subjects received both verbal and written instructions about the measurement
137 preparation in order to minimize physical and mental stress and to allow for at least 7-8 h of
138 sleep on the day before each testing. Basal concentrations of serum hormones were assessed
139 in the morning (between 7:00 a.m. and 9 a.m.) after 12 h of fasting.

140 +++Figure 1 somewhere near here+++

141 *Testing procedures*

142 *Strength and power performance*

143 One repetition maximum (1RM) using the dynamic horizontal leg press device (David 210,
144 David Health Solutions, Helsinki, Finland) was determined at week 0, 12 and 24,
145 respectively. Following a warm up (1 set of 5 repetitions at 70% of estimated 1RM, 1 set of 2
146 repetitions at 80-85% of estimated 1RM, 1 set of 1 repetition at 90-95% of estimated 1RM), a
147 maximum of 5 trials were allowed to obtain a true 1RM. The device was set up so that the
148 knee angle in the initial flexed position was approximately 60 degrees (as measured by a

149 manual goniometer) and a successful trial was accepted when the knees were fully extended
150 (~180 degrees). The greatest load that the subject could lift to full knee extension was
151 accepted as 1RM.

152 Maximal power was determined by a counter movement jump (CMJ) on a force plate
153 (Department of Biology of Physical Activity, Jyväskylä, Finland) at week 0, 12 and 24,
154 respectively. Subjects were asked to keep their hands in contact with their hips throughout the
155 movement and were instructed to jump as high as possible on command. Force data was
156 collected and analyzed by Signal software (Signal 4.04, Cambridge Electronic Design Ltd.,
157 Cambridge, UK). Jumping height was calculated from the take-off velocity using the formula
158 $h=v^2/2g$, in which h refers to jumping height and v refers to take-off velocity (Komi and
159 Bosco 1978). The best trial in terms of jumping height measured in cm was used for
160 statistical analysis.

161 To assess acute endurance loading-induced force responses at week 0 and 24, maximal
162 isometric bilateral leg press force (MVC_{max}) was assessed by a horizontal leg press
163 dynamometer (Department of Biology of Physical Activity, University of Jyväskylä, Finland).
164 Subjects were seated with a hip and knee angle of 110 and 107 degrees, respectively and were
165 instructed to produce maximal force as rapidly as possible on verbal command and to
166 maintain the force plateaued for 3-4 seconds. Before the treadmill protocol three trials
167 separated by 1 minute of rest were conducted, while after the exercise only two trials
168 separated by 15 seconds were performed. The trial with the highest maximal force measured
169 before or after the loading, respectively was used for statistical analysis. The force signal was
170 low-pass filtered (20Hz) and analyzed (Signal software, version 4.04, Cambridge Electronic
171 Design Ltd., Cambridge, UK).

172 *Endurance performance measures and endurance loading*

173 Running performance was determined by an incremental field test of 6x1000m (1 minute
174 inter-set rest) performed on a 200 m indoor running track at week 0, 12 and 24, respectively.
175 The initial speed for all subjects was 6 min·km⁻¹ and the speed was increased by 30 seconds
176 every 1000 m. The test was performed in small groups and velocity was controlled every 100
177 m. The final 1000 m were performed at individual maximal running speed and the time of this
178 trial was used for statistical analysis.

179 At week 0 and 24, a graded protocol on a motorized treadmill was used to measure endurance
180 loading-induced acute force and hormone responses. The initial velocity for all subjects was 9
181 Km·h⁻¹ and increased by 1 Km·h⁻¹ every 3 minutes, while the incline was kept constant at
182 0.5°. The treadmill was stopped every 3 minutes for 20 seconds in order to collect capillary
183 blood samples from the fingertip for the determination of blood lactate concentrations.
184 Twenty µl of blood were collected by small capillaries, inserted into reaction capsules
185 containing a hemolyzing and anticoagulant agent and lactate concentrations were analyzed
186 using a Biosen analyzer (C_line Clinic, EKF, Magdeburg, Germany). Time to exhaustion was
187 used for statistical analysis and was defined as the maximal testing time until voluntary
188 exhaustion. Furthermore, the velocity at a blood lactate concentration of 4 mmol·l⁻¹ (V₄) was
189 used as an indicator of running economy (Heck et al. 1985). Following voluntary exhaustion,
190 a 5 minute cool down at the initial speed (9 Km·h⁻¹) was performed. In order to determine
191 acute force and hormone responses, MVC_{max} and serum hormone concentrations were
192 assessed before the start of the treadmill protocol and after the cool down (Fig 1).

193 *Venous blood sampling*

194 Venous blood samples (10 ml) for the determination of serum hormone concentrations (basal
195 concentrations at week 0, 12 and 24; endurance loading-induced acute responses at week 0
196 and 24) were collected by a qualified lab technician. Whole blood was centrifuged at 3,500

197 rpm (Megafuge 1.0 R, Heraeus, Germany) for 10 minutes after which serum was removed
198 and stored at -80°C until analysis (approximately 4-8 weeks). Analysis of total serum
199 testosterone, GH (22-kDa), sex hormone binding globuline (SHBG) and cortisol were
200 performed using chemical luminescence techniques (Immunlite 1000, Simens, New York,
201 USA) and hormone specific immunoassay kits (Siemens, New York, USA). The sensitivity
202 for serum hormones were: T $0.5\text{ nmol}\cdot\text{l}^{-1}$, GH $0.03\text{ mIU}\cdot\text{l}^{-1}$, SHBG $0.2\text{ nmol}\cdot\text{l}^{-1}$ and C 5.5
203 $\text{nmol}\cdot\text{l}^{-1}$. The intra-assay coefficients of variation for T, GH, SHBG, and C were $8.7\pm 2.7\%$,
204 $7.1\pm 4.6\%$, $6.4\pm 1.7\%$, $6.0\pm 0.5\%$ and $7.1\pm 1.1\%$, respectively. The inter-assay coefficients of
205 variation for T, GH, SHBG and C were $10.6\pm 3.2\%$, $11.1\pm 4.3\%$, $5.8\pm 0.3\%$, 7.6 ± 1.4 and
206 $7.9\pm 1.2\%$, respectively. Basal T/C- and T/SHBG-ratios were also calculated. Plasma volume
207 changes were estimated from changes in hematocrit and hemoglobin (Dill and Costill 1974)
208 but were not used to correct obtained serum hormone concentrations (Kraemer and Ratamess
209 2005).

210 *Endurance training*

211 The subjects were required to maintain habitual physical activity throughout the study period.
212 The prescribed endurance training program was identical in the two groups and consisted of
213 both continuous and interval training sessions 4-6x per week (Table 1), based on the polarized
214 training approach (Muñoz et al. 2014). The endurance exercises focused on running but
215 alternative endurance types such as cycling and cross country skiing were occasionally
216 permitted for specific exercises in order to minimize the risk of injuries (Table 1). While two
217 training sessions per week were supervised, the remaining endurance training sessions were
218 performed individually. In case of sickness, subjects were required to catch up missing
219 training sessions to standardize training volume between subjects. The training intensity was
220 based on heart rate zones calculated from maximal heart rate determined during the
221 incremental treadmill protocol (except for short intervals for which intensities were calculated

222 based on the determined best 1000 m time, Table 1). Training intensity, duration and distance
223 were consistently controlled and recorded by heart rate monitors (RS800cx, Polar Electro Oy,
224 Kempele, Finland), using manually pre-programmed exercise files. The endurance training
225 intensity and volume increased throughout the two 12-week periods (Table 1).

226 +++Table 1 somewhere near here+++

227 *Strength training*

228 In the E+S group, additional strength training was performed twice a week (once a week at
229 week 12 and 24, respectively) and was conducted always after the incremental endurance run
230 (35-45 min by progressively increasing intensity from 65-85%, Table 1), with at least 48 h in
231 between two combined training sessions. Subjects were instructed to rest or perform a light
232 run (35-40 min, 60-65%, Table 1) on the day before the combined E+S session. A maximum
233 of 10 minutes was allowed between transitions from the running session to the strength
234 training session.

235 The strength training consisted of mixed maximal and explosive (~20% of strength training
236 volume) strength training sessions and was focused on the lower limbs, while additional
237 exercises for the upper body were included. The loads of each exercise were determined by
238 the number of repetitions and execution velocity which was progressively increased
239 throughout the two 12-week periods. Exercises for the lower body included bilateral leg press,
240 bilateral and unilateral knee flexion and calf raises. During weeks 1-12 and 13-20 jumping
241 exercises commonly used to improve explosive force production were performed (loaded and
242 unloaded squat jumps, drop jumps, leaps, step-ups). During weeks 21-24 hurdle jumps and
243 resisted knee lifts were also incorporated into the strength training program. Exercises for the
244 upper body included dynamic seated vertical press, biceps curls as well as exercises
245 commonly used to improve core stability (crunches, torso rotation, and lower back extension).

246 As the subjects were not accustomed to strength training, low loads (15-20x 40-50% of 1RM,
247 1-2min inter-set rest) were utilized during weeks 1-4. Thereafter, strength training intensity
248 progressed to heavier loads and a lower number of sets (5-12x 60-85% of 1RM, 1-3min inter-
249 set rest). During the second 12-week period the major strength program structure was
250 maintained, while both training volume and loads used were increased to maximize maximal
251 and explosive strength improvements.

252 *Statistical analyses*

253 Data are presented as mean \pm SD and shown as relative changes from the pre-loading values
254 unless otherwise indicated. The normality of distribution was assessed using the Shapiro-Wilk
255 test and log transformation was performed when necessary. Within and between-group
256 differences of basal measures were assessed by a mixed ANOVA design with repeated
257 measures. Within and between-group differences of acute loading responses were assessed by
258 a mixed ANCOVA design, using the pre-loading values as covariates. Bivariate correlations
259 were computed using the Pearson product-moment correlation coefficient. The statistical
260 significance for all tests was set at 0.05. Statistical analysis was conducted using IBM SPSS
261 20.0 (SPSS, Inc., Chicago, IL, USA).

262 RESULTS

263 The weekly average training time was 4.9 \pm 0.2 h and 4.7 \pm 0.5 h in E and E+S, leading to a total
264 training time of 116.5 \pm 4.5 h and 111.8 \pm 10.8 h, respectively. The weekly average running
265 distance was 36.6 \pm 5.6 km and 33.5 \pm 7.9 km in E and E+S leading to a total mileage of
266 879.5 \pm 133.3 km and 804 \pm 189.3 km, respectively.

267 *Endurance and strength performance adaptations*

268 1000 m running time (Fig 2) significantly decreased in E at week 12 (from $3.8\pm 0.3 \text{ min}\cdot\text{km}^{-1}$
269 to $3.5\pm 0.3 \text{ min}\cdot\text{km}^{-1}$, $p=0.001$) and week 24 (to $3.3\pm 0.2 \text{ min}\cdot\text{km}^{-1}$, $p<0.001$). Similarly,
270 significant reductions in 1000 m time were also observed in E+S at week 12 (from 3.6 ± 0.4
271 $\text{min}\cdot\text{km}^{-1}$ to $3.4\pm 0.4 \text{ min}\cdot\text{km}^{-1}$, $p<0.001$) and week 24 (to $3.3\pm 0.2 \text{ min}\cdot\text{km}^{-1}$, $p=0.001$) and no
272 significant between-group differences in the changes of 1000 m time were found.

273 Time to exhaustion determined during the incremental treadmill test significantly increased at
274 week 24 in E (from $24.9\pm 3\pm 4 \text{ min}$ to $27.2\pm 3.1 \text{ min}$, $10\pm 7\%$, $p<0.001$) and E+S (from 27.3 ± 2.8
275 min to $29.1\pm 2.5 \text{ min}$, $7\pm 7\%$, $p=0.011$), while no significant between-group differences in the
276 changes of time to exhaustion were observed.

277 Similarly, V_4 significantly increased in E at week 24 (from $3.7\pm 0.5 \text{ m}\cdot\text{s}^{-1}$ to $3.9\pm 0.3 \text{ m}\cdot\text{s}^{-1}$,
278 $8\pm 9\%$, $p=0.013$) and E+S (from $3.9\pm 0.4 \text{ m}\cdot\text{s}^{-1}$ to $4.1\pm 0.4 \text{ m}\cdot\text{s}^{-1}$, $6\pm 6\%$, $p=0.003$), while no
279 significant between-group differences in the changes of V_4 were observed.

280 +++Figure 2 somewhere near here+++

281 Dynamic leg press 1RM strength (Fig 3a) remained statistically unaltered in E at week 12 but
282 significantly decreased at week 24 (from $148\pm 25 \text{ kg}$ to $141\pm 23 \text{ kg}$, $p=0.014$). In E+S 1RM
283 strength remained significantly unaltered at both week 12 and 24 and the between-group
284 difference in the changes of 1RM strength was significant at week 12 ($p=0.014$) and 24
285 ($p=0.011$). Baseline 1RM strength performance significantly correlated with the
286 corresponding change in 1RM strength during the first 12-week period ($r=-0.622$, $p=0.023$) in
287 E+S but not E.

288 CMJ height (Fig 3b) remained statistically unaltered in both E and E+S at week 12 and 24,
289 while the change in CMJ height at week 12 was significantly greater in E+S than E ($3\pm 8 \%$ vs.
290 $-4\pm 7 \%$, $P=0.025$).

291 +++Figure 3a and 3b somewhere near here+++

292 *Basal hormone concentrations*

293 No significant changes in basal serum concentrations (Table 2) of T, GH, cortisol, SHBG and
294 the T/C-ratio were observed in either group at week 12 or 24. The T/SHBG-ratio (Fig 4)
295 significantly decreased in E+S at week 12 ($-19\pm 26\%$, $p=0.006$) but was no longer
296 significantly altered at week 24. The change in T/SHBG-ratio from week 12 to 24 was
297 significantly larger in E+S compared to E ($42\pm 47\%$ vs. $-5\pm 33\%$, $p=0.006$).

298 +++Table 2 somewhere near here+++

299 *Acute force responses*

300 In MVC_{max} (Fig 5) significant acute decreases occurred during the endurance loading in E and
301 E+S at week 0 ($-8\pm 8\%$, $p=0.001$ and $-9\pm 9\%$, $p=0.005$, respectively) and 24 ($-5\pm 9\%$, $p=0.03$
302 and $-6\pm 10\%$, $p=0.032$, respectively). No significant training-induced changes in acute force
303 responses to endurance loading at week 24 were observed.

304 +++Figure 4 somewhere near here+++

305 *Acute hormone responses*

306 Serum T (Fig 6a) significantly increased during the endurance loading in E and E+S at week 0
307 ($18\pm 22\%$, $p=0.01$ and $26\pm 27\%$, $p=0.012$, respectively) and week 24 ($32\pm 46\%$, $p=0.006$ and
308 $27\pm 35\%$, $p=0.013$, respectively). No significant training-induced changes in acute serum T
309 responses at week 24 were observed.

310 Serum C (Fig 6b) significantly increased during the endurance loading in E and E+S at week
311 0 ($47\pm 40\%$, $p<0.001$ and $37\pm 28\%$, $p<0.001$, respectively) and week 24 ($42\pm 31\%$, $p<0.001$

312 and 35±29%, p<0.001, respectively) but no significant training-induced changes in acute
313 serum C responses at week 24 were observed.

314 +++Figure 5a and 5b somewhere near here+++

315 Serum GH significantly increased during the endurance loading in E and E+S at week 0 (227
316 fold, p<0.001 and 208 fold, p<0.001, respectively) and week 24 (341 fold, p<0.001 and 210
317 fold, p<0.001, respectively). No significant training-induced changes in acute serum GH
318 responses at week 24 were observed.

319 *Plasma volume*

320 No between-group differences in basal plasma volume changes at week 12 and 24 were
321 observed. Basal plasma volume shifts in the two groups ranged from -1 to +4%. Similarly, no
322 between-group differences in acute endurance loading-induced plasma volume shifts were
323 observed at either measurement time. Loading-induced plasma volume shifts at week 0 and
324 24 ranged from -6 to -7% in the two groups.

325 DISCUSSION

326 The main findings of this study were: 1) both groups improved maximal and sub-maximal
327 endurance performance to a similar extent; 2) 1RM strength was significantly decreased in E
328 after the training period but was maintained in E+S, leading to the between-group difference
329 at week 12 and 24; 3) the T/SHBG-ratio significantly decreased in E+S at week 12 and the
330 change from week 12 to 24 was significantly larger in E+S than in E; 4) the endurance
331 loading-induced acute force and hormone responses were similar in the two groups before and
332 after the training period and no training-induced changes in acute loading responses were
333 observed.

334 Previous studies have shown that maximal and explosive strength training added to endurance
335 training improved running economy (Millet et al. 2002; Paavolainen et al. 2003; Storen et al.
336 2008), velocity at the lactate threshold (Mikkola et al. 2007; Guglielmo et al. 2009), maximal
337 running speed (Millet et al. 2002) and running time over a given distance (Paavolainen et al.
338 2003; Spurrs et al. 2003), while only small or no effects on maximal oxygen consumption
339 ($\text{VO}_{2\text{max}}$) were reported (Paavolainen et al. 2003; Spurrs et al. 2003; Storen et al. 2008;
340 Taipale et al. 2010). Although added strength training may further induce endurance
341 development due to greater training volume compared to endurance training alone,
342 improvements in running performance have also been shown with reduced endurance training
343 volume compensated by added strength training (Paavolainen et al. 2003). In general,
344 however, beneficial adaptations in cardiorespiratory function and endurance performance
345 following concurrent training have typically occurred with concomitant increases in maximal
346 and/or explosive strength development, indicating that strength training-induced endurance
347 development may occur as a result of enhanced neuromuscular performance (Paavolainen et
348 al. 2003; Mikkola et al. 2007; Taipale et al. 2010).

349 In contrast to these studies, the present investigation found similar improvements in maximal
350 and sub-maximal endurance performance for both training groups with no additional effects
351 of the supplemented strength training in the E+S group. However, while the present E group
352 significantly decreased 1RM strength after 24 weeks, maximal leg strength was maintained
353 but not increased in the E+S group and a similar tendency was observed for CMJ height.

354 The present research design purposefully differed from previous studies since the strength
355 loading was always performed immediately after an exhausting endurance running session,
356 and therefore, every strength training session may have been affected by residual fatigue.
357 While several cross-sectional studies have shown acute detrimental effects on strength
358 performance (Leveritt and Abernethy 1999; de Souza et al. 2007) and anabolic hormone

359 responses (Goto et al. 2005) when strength loading was immediately preceded by endurance
360 cycling or running, this has, to the best of our knowledge, only been supported by few
361 longitudinal training studies. Craig et al. (1991) failed to observe lower body strength gains
362 when strength training was repeatedly preceded by endurance running and, in line with our
363 results, endurance performance increased to a similar magnitude in their combined and E
364 training group. However, compared to the study of Craig et al. (1991), our E group
365 significantly reduced maximal strength performance after 24 weeks of training, while our E+S
366 group was able to maintain their basal strength performance which may in turn provide
367 benefits over long-term.

368 Strength training-induced increases in maximal endurance running performance may in part
369 be attributed to increased fatigue resistance allowing sustaining repeated cycles of stretch-
370 shortening contractions over a prolonged period of time (Paavolainen et al. 1999). This
371 greater level of resistance against neuromuscular fatigue in response to endurance loading
372 would be expected after a prolonged period of combined endurance and strength training
373 compared to endurance training only. However, the endurance loading-induced acute
374 reductions in MVC_{max} were similar between E and E+S groups in the present study when
375 compared before and after the 24-week training period, supporting the finding that both
376 groups experienced similar improvements in endurance adaptations. However, caution should
377 be taken since the endurance loading was performed with relative maximal loads (i.e. time to
378 exhaustion based on current training status at weeks 0 and 24) and both training groups
379 significantly increased time to exhaustion after 24 weeks of training. In light of the resulting
380 increases in loading volume, the observed acute reductions in maximal force at week 24 may
381 actually indicate a training adaptation. However, as the magnitude of reductions was similar
382 in E and E+S, our findings indicate these positive adaptations to be induced by the prolonged
383 endurance training rather than the added strength training.

384 Interestingly, in the E+S group a significant correlation was observed between the basal levels
385 of 1RM strength and the corresponding changes in maximal strength performance during the
386 first 12 but not 24 weeks. Although not statistically significant, after 12 weeks of training the
387 E+S group had improved strength performance by $5\pm 7\%$ which was diminished at week 24,
388 despite a progressive increase in training load. While the observed correlation indicates the
389 importance of strength training especially for the weaker endurance runners, our results
390 suggest a biphasic response to the performed strength training which may indicate the
391 strength loading stimulus to be less effective during the second 12 weeks of training. As both
392 the strength and endurance training volume and intensity progressively increased during the
393 latter half of the training, it may be possible that the unfavorable effects of preceding
394 endurance loading on the quality of the subsequent strength training session were intensified
395 during the second 12-week period and, thus, resulting in further impairment of strength
396 development.

397 However, this finding was not accompanied by significant changes in basal hormone
398 concentrations. Typically, the training induced endocrine adaptations differ between the types
399 of training performed (Kraemer et al. 1995). Prolonged strength training may lead to increases
400 in basal levels of anabolic hormone concentrations at least in previously untrained subjects
401 (Häkkinen et al. 2000; Ahtiainen et al. 2003), while the basal concentrations of these
402 hormones may actually be decreased following endurance training only (Hackney et al. 2003).
403 Combined endurance and strength training studies in which endurance and strength were
404 performed on separate days, on the other hand, have shown small increases in basal serum
405 testosterone concentrations in untrained (Kraemer et al. 1995) and significant increases in
406 endurance trained subjects (Taipale et al. 2010). These previous findings indicate that the
407 strength training-induced changes in basal hormone concentrations may counteract an
408 endurance training-induced catabolic state, possibly contributing to the beneficial effects of

409 strength training for endurance athletes. In the present study, however, only small fluctuations
410 in basal hormone concentrations were observed, supporting the lack of effects of strength
411 training on endurance performance, when performed immediately after endurance running
412 sessions.

413 Interestingly, in our E+S group a significant reduction in the T/SHBG-ratio was observed
414 after 12 weeks of training and this initial decrease was followed by a large increase thereafter,
415 leading to a significant between-group difference in the magnitude of changes in the
416 T/SHBG-ratio from week 12 to 24. As the T/SHBG-ratio correlates with free available
417 testosterone concentrations (Selby 1990) and may therefore reflect an anabolic state, the
418 observed reductions in the E+S group during the first 12 weeks may indicate increased uptake
419 of testosterone by the target cells (Vingren et al. 2010). Although receptor content was not
420 assessed in this study, the observed reduction in the T/SHBG-ratio during the first 12 weeks
421 of training may reflect a positive response to a new training stimulus since the subjects were
422 recreationally endurance trained but not accustomed to strength training. Similar
423 improvements in endurance performance between the E+S and E groups in conjunction with
424 small increases in maximal strength for the E+S group at the 12-week time point suggests that
425 the present strength training method may be effective in inducing strength development for at
426 least 12 weeks. In a previous study (Taipale et al. 2010) the beneficial effects of strength
427 training on running economy were apparent not during the actual combined endurance and
428 strength training intervention but after a reduction in strength training volume. It may also be
429 possible that a reduction in strength training volume after the present 12 weeks of training
430 would have been necessary in order to induce improvements in maximal and sub-maximal
431 endurance performance.

432 Similar to the maintained serum hormone concentrations during the 24 weeks of training, no
433 training-induced changes in endurance loading responses of testosterone, growth hormone

434 and cortisol were observed. Both groups significantly increased endurance loading-induced
435 acute anabolic and catabolic hormone concentrations before and after the training to a similar
436 extent. While these findings are in contrast to a study by Kraemer et al. (1995) who found
437 significantly larger testosterone responses to endurance loading after combined training in
438 physically active subjects, our findings are in line with results of Craig et al. (1991). In their
439 study, endurance running-induced growth hormone responses were examined between an
440 endurance training only group and a combined strength and endurance training group, where
441 endurance training always preceded strength training in the same session. In line with our
442 results, they found no differences in growth hormone responses. However, similar to our
443 observed acute force responses, the improvements in treadmill running time to exhaustion
444 found in the present study may have blunted any potential changes in acute endurance
445 loading-induced serum hormone concentrations. Furthermore, due to the length of the study
446 where pre-training measurements were conducted in the Fall and post-training measurements
447 carried out in the Spring, possible seasonal variations in serum hormone concentrations
448 should be considered when interpreting the present findings (Svartberg et al. 2003).

449 Although training- or loading-induced alterations in serum hormone concentrations may be
450 associated with chronic increases in strength performance, the possible role of neural
451 interference in respect to the present findings should not be neglected. While a thorough
452 investigation of neuromuscular mechanisms was beyond the scope of this study, it is possible
453 that residual fatigue from the preceding endurance session affected neural activation of the
454 exercised muscles during the subsequent strength training sessions, as shown in our previous
455 study in untrained men (Eklund et al. 2014). Due to the high volume of endurance training
456 performed in the present study, it is possible that such a neural inhibition may have
457 contributed to the lack of expected increases in strength performance in the present E+S
458 group.

459 In conclusion, the present study showed that same-session combined training where strength
460 training was repeatedly preceded by endurance loading did not lead to superior endurance
461 performance benefits in recreational endurance runners, when compared to endurance running
462 only. It is likely that this was attributed to the impaired strength development, despite
463 consistent progressive strength training in the E+S group. In support of this assumption, no
464 between-group differences in training-induced changes in acute force and hormone responses
465 to endurance loading were observed and basal hormone concentrations were maintained in the
466 two groups. Although in the present design no group utilizing other combined endurance and
467 strength training modes were included, these results suggest that endurance athletes should
468 separate their endurance and strength training sessions in order to maximize benefits of the
469 added strength training.

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573 TABLES

574 **Table 1.** Prescribed endurance training program for the two groups.

	Weeks 1-12	Weeks 13-24
Incremental run	2x/week, running only 35-45min/65-85%	2x/week, running only 40-45min/65-85%
Long run	1x/week, running, cycling or skiing 70-120min/60-65%	1x/week, running, cycling or skiing 85-125min/60-65%
Long intervals	1x/week, running only 4-5x5min/80-85%, rest 3min <65%	1x/week, running only 4-6x5min/85%, rest 3min <65%
Short intervals		1x/week, running only (on the track) 3-6x400m + 3-6x 800m/85%, rest 2min <65%
Light run	1x/week, running only 35-40min/60-65%	1x/week, running, cycling or skiing 40min/60-65%
Optional run	Optional 1x/week, running, cycling or skiing 35-40min/ 70-75%	

575 Intensity zones are % of HRmax except for short intervals (% of 1000m time).

576 In the E+S group, strength training was performed twice a week after the incremental

577 endurance run.

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583 **Table 2.** Basal concentrations of serum hormones throughout the 24 weeks of training.

	E			E+S		
	Week 0	Week 12	Week 24	Week 0	Week 12	Week 24
Testosterone (nmol·l⁻¹)	16.9±6.4	15.3±4.1	15.6±5.2	19.7±7.9	15.9±5.3	19.1±5.9
GH (22-kDa) (mIU·l⁻¹)	0.5±0.6	0.6±1.3	0.6±0.7	1.0±1.7	2.6±7.5	1.2±2.1
SHBG (nmol·l⁻¹)	29.6±11.3	29.1±10.5	32.2±11.8	33.6±9.8	36.4±13.0	33.0±9.9
Cortisol (nmol·l⁻¹)	499.9±85.2	469.2±92.8	514.0±44.2	504.4±130.9	466.4±104.7	498.2±93.2
T/SHBG-ratio (nmol·l⁻¹)	0.6±0.2	0.6±0.2	0.5±0.1	0.6±0.3	0.5±0.2**	0.6±0.2
T/C-ratio (nmol·l⁻¹)	0.034±0.012	0.033±0.010	0.030±0.010	0.040±0.013	0.034±0.008	0.040±0.016

584 GH=growth hormone; SHBG=sex hormone binding globulin; T/SHBG-ratio=testosterone/SHBG-

585 ratio; T/C-ratio=testosterone/cortisol-ratio; **p<0.01 compared to week 0.

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596 FIGURE CAPTIONS

597 **Figure 1.** Study design. Baseline tests included the determination of endurance (incremental
598 field test) and strength performance (1RM during dynamic leg press and CMJ height) as well
599 as the determination of basal hormone concentrations.

600 **Figure 2.** Changes in maximal 1000 m running time determined during an incremental field
601 test of 6x1000m. *** $p < 0.001$ compared to values obtained at week 0.

602 **Figure 3.** Changes in 1RM strength (A) and CMJ height (B). * $p < 0.05$, within bar compared
603 to values obtained at week 0; outside the bar as indicated.

604 **Figure 4.** Changes in T/SHBG ratio. ** $p < 0.01$, inside the bar compared to values obtained at
605 week 0; outside the bar as indicated.

606 **Figure 5.** Endurance loading-induced acute reductions in isometric maximal force (MVC_{max})
607 at week 0 and week 24. * $p < 0.05$, ** $p < 0.01$ compared to obtained pre-loading values at week
608 0 and 24, respectively.

609 **Figure 6.** Endurance loading-induced acute changes in serum testosterone (A) and cortisol
610 (B) concentrations. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ compared to obtained pre-loading values
611 at week 0 and 24, respectively.

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Fig. 1

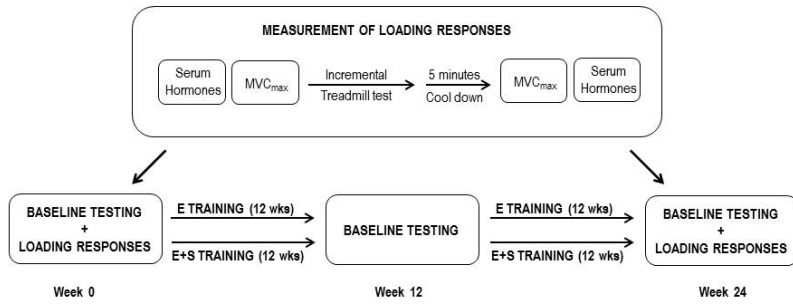
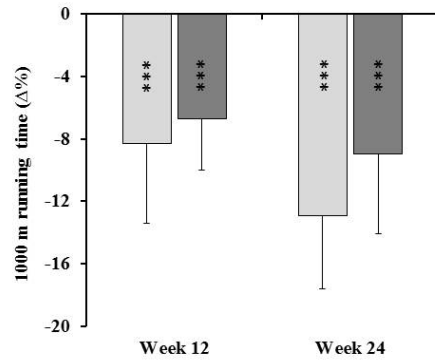


Fig. 2



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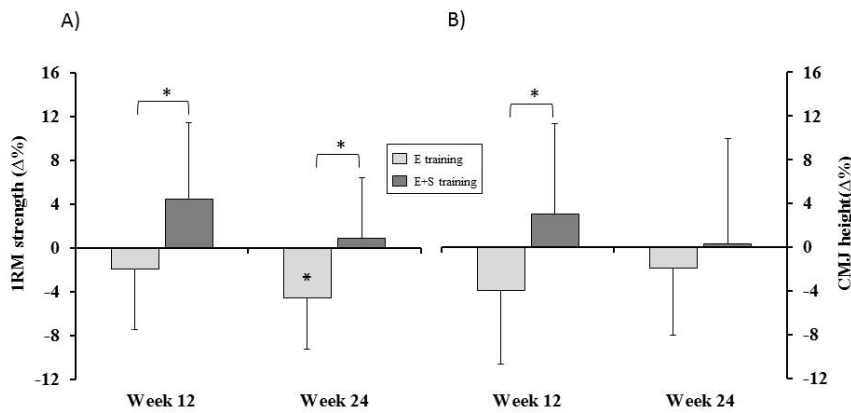
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Fig. 3



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Fig. 4

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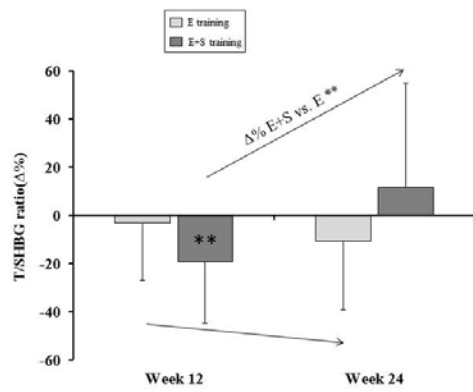
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Figure 5

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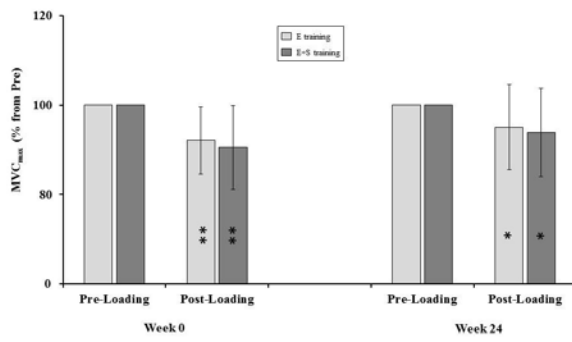
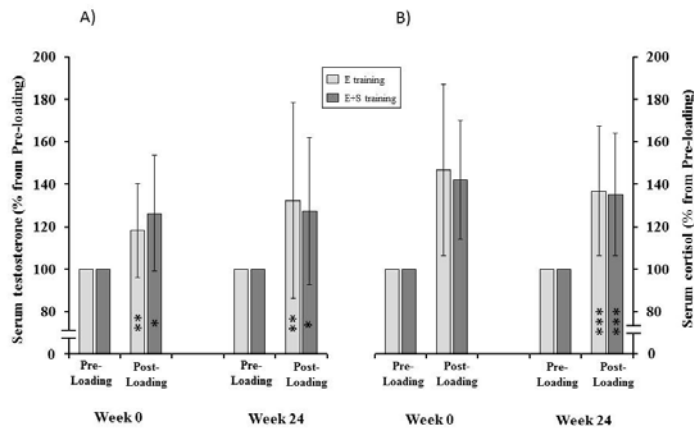


Figure 6



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