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

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ABSTRACT

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

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 VO_{2max} 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 (Ronnestad

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 (Ronnestad 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 ±1h 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 0.5º. 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} (V_4) 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 nmol·l^{-1}, GH 0.03 mlU·l^{-1}, SHBG 0.2 nmol·l^{-1} and C 5.5

203   nmol·l^{-1}. The intra-assay coefficients of variation for T, GH, SHBG, and C were 8.7±2.7%,

204   7.1±4.6 %, 6.4±1.7%, 6.0±0.5% and 7.1±1.1%, respectively. The inter-assay coefficients of

205   variation for T, GH, SHBG and C were 10.6±3.2%, 11.1±4.3%, 5.8±0.3%, 7.6±1.4 and

206   7.9±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±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±0.2 h and 4.7±0.5 h in E and E+S, leading to a total

264   training time of 116.5±4.5 h and 111.8±10.8 h, respectively. The weekly average running

265   distance was 36.6±5.6 km and 33.5±7.9 km in E and E+S leading to a total mileage of

266   879.5±133.3 km and 804±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 ± 0.3 min·km^{-1}

269   to 3.5 ± 0.3 min·km^{-1}, p=0.001) and week 24 (to 3.3 ± 0.2 min·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   min·km^{-1} to 3.4 ± 0.4 min·km^{-1}, p<0.001) and week 24 (to 3.3 ± 0.2 min·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 $24.9\pm3\pm4$ min to 27.2 ± 3.1min, $10\pm7\%$, p<0.001) and E+S (from 27.3 ± 2.8

275   min to 29.1 ± 2.5 min, $7\pm7\%$, 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 ± 0.5 m·s^{-1} to 3.9 ± 0.3 m·s^{-1},

278     $8\pm9\%$, p=0.013) and E+S (from 3.9 ± 0.4 m·s^{-1} to 4.1 ± 0.4 m·s^{-1}, $6\pm6\%$, 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 ± 25 kg to 141 ± 23 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 ± 8 % vs.

290   -4 ± 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 ($-19\pm26\%$, $p=0.006$) 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 ($42\pm47\%$ vs. $-5\pm33\%$, $p=0.006$).

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 ($-8\pm8\%$, $p=0.001$ and $-9\pm9\%$, $p=0.005$, respectively) and 24 ($-5\pm9\%$, $p=0.03$

302   and $-6\pm10\%$, $p=0.032$, 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   ($18\pm22\%$, $p=0.01$ and $26\pm27\%$, $p=0.012$, respectively) and week 24 ($32\pm46\%$, $p=0.006$ and

308    $27\pm35\%$, $p=0.013$, 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 ($47\pm40\%$, $p<0.001$ and $37\pm28\%$, $p<0.001$, respectively) and week 24 ($42\pm31\%$, $p<0.001$

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   (VO_{2max}) 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 $5\pm7\%$ 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.

470 ACKNOWLEDGEMENTS

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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) (mlU·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. **<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

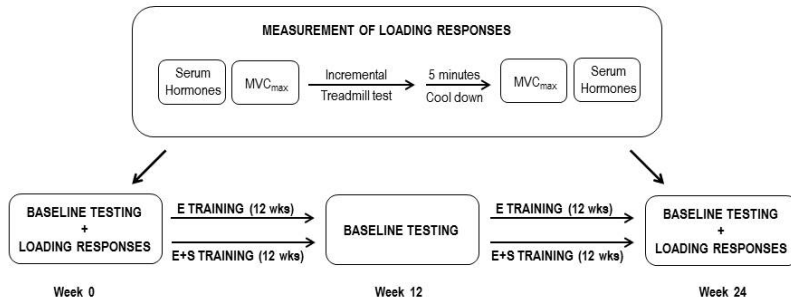611 at week 0 and 24, respectively.

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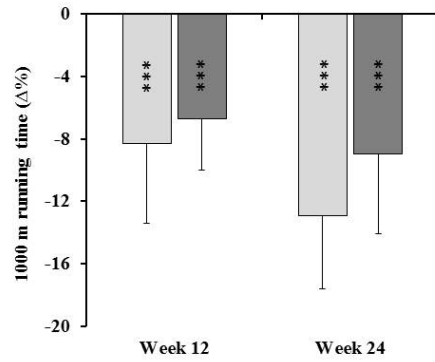617 Fig. 1

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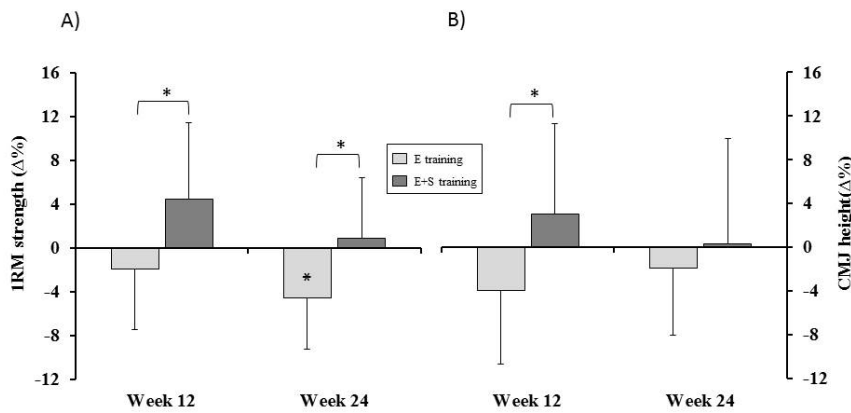622

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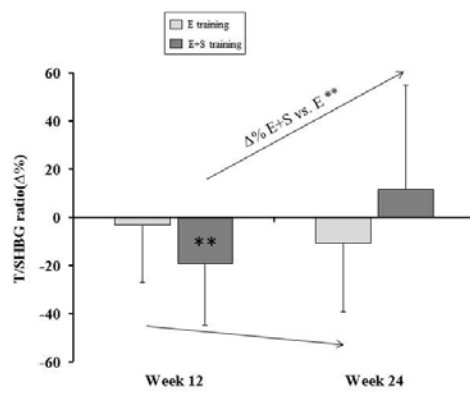

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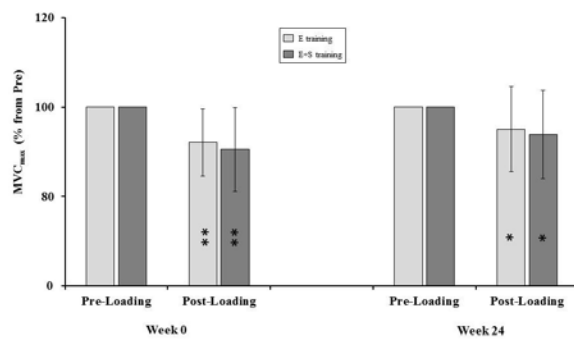
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Figure 5

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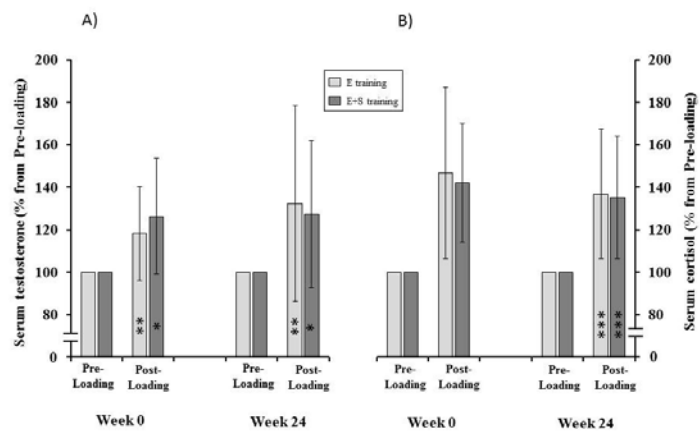
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Figure 6

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