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ORIGINAL ARTICLE

High volume of endurance training impairs adaptations to 12 weeks of strength training in well-trained endurance athletes

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Abstract The purpose of the present study was to compare the effect of 12 weeks of strength training combined with a large volume of endurance training with the effect of strength training alone on the strength training adaptations. Well-trained cyclists with no strength training experience performed heavy strength training twice a week in addition to a high volume of endurance training during a 12-week preparatory period ($S + E$; $n = 11$). A group of non-strength trained individuals performed the same strength training as $S + E$, but without added endurance training (S; $n = 7$). Thigh muscle cross-sectional area, 1 repetition maximum (1RM) in leg exercises, squat jump performance, and peak rate of force development (RFD) were measured. Following the intervention period, both $S + E$ and S increased 1RM strength, thigh muscle cross-sectional area, and squat jump performance ($p < 0.05$), and the relative improvements in S were greater than in $S + E$ ($p < 0.05$). S increased peak RFD while $S + E$ did not, and this improvement was greater than in $S + E$ ($p < 0.05$). To the best of our knowledge, this is the first controlled study to demonstrate that the strength training response on muscle hypertrophy, 1RM strength, squat jump performance, and peak RFD is attenuated in well-trained endurance athletes during a period of concurrent endurance training.

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Introduction

In accordance with the principle of training specificity, strength training and endurance training induce quite different muscular adaptations. Consequently, endurance athletes have historically been reluctant to include heavy strength training as a part of their normal training. However, during the last decade, endurance athletes have been encouraged to add strength training to their normal endurance training to further improve endurance performance (e.g. Hoff et al. 1999; Millet et al. 2002; Rønnestad et al. 2010, 2011; Sunde et al. 2010; Turner et al. 2003). These recommendations are based on the studies in which some endurance athletes performed strength training in addition to their normal endurance training, while others formed a control group that simply continued the normal endurance training. In most of these studies, increased strength and endurance performance together with no change in body mass were reported (e.g. Hoff et al. 1999; Millet et al. 2002; Storen et al. 2008; Sunde et al. 2010). Several authors suggested that the normal muscle hypertrophy response to strength training was absent in these studies (e.g. Hoff et al. 1999; Storen et al. 2008; Sunde et al. 2010), although no measurements of cross-sectional area (CSA) of the strength-trained muscles were included. Lack of hypertrophic response to strength training indicates attenuated strength training adaptations. However, without a control group performing the identical strength training program as the endurance athletes, but without performing the endurance training, it is difficult to conclude whether a high volume of endurance training in fact inhibits strength training adaptations.

The pioneering work of Hickson (1980) revealed that concurrent strength and endurance training attenuated the increase in maximal muscle strength when compared with a group performing strength training only. A number of subsequent investigations have either confirmed (e.g. Bell et al. 2000; Dudley and Djamil 1985; Kraemer et al. 1995) or contradicted (e.g. Häkkinen et al. 2003; Leveritt et al. 2003; McCarthy et al. 1995, 2002) this finding. A closer look at studies finding of attenuated strength gains from concurrent strength and endurance training reveals that the examined muscles were exposed to at least six training days per week, and this was observed in both untrained and moderately trained muscles (e.g. Bell et al. 2000; Dudley and Djamil 1985; Hickson 1980; Kraemer et al. 1995). In the studies finding no strength gain attenuation, fewer training days were performed, suggesting that strength gains may be attenuated when endurance training frequency and/or volume is too high. In line with this, no muscle fibre hypertrophy was reported in the few studies on endurance athletes in whom biopsies were performed (Aagaard et al. 2011; Bishop et al. 1999; Hickson et al. 1988). Unfortunately, neither of these studies included a group performing strength training only. Furthermore, it should be noted that the fibre area of both muscle fibre type I and type II has been found to vary significantly within the m. vastus lateralis, meaning that fibres in the deep parts of the muscle are larger than those located superficially (Lexell and Taylor 1989). In addition, the size relationship between type I and II fibres varies within the muscle (Lexell and Taylor 1989). This means that analyses of muscle fibre area should preferably be accompanied by multiple-site measures at the whole muscle level (e.g. using MRI, CT, or DEXA). Nutrition is another factor that can potentially influence the adaptations to strength training. Energy deficit is known to have a negative effect on muscle hypertrophy (Houston 1999; Lambert et al. 2004), and may partly explain the attenuated strength training adaptations observed in untrained subjects when concurrent training is performed at a high training frequency. However, determining dietary intake is challenging and is consequently rarely performed in longitudinal studies. In the present study dietary intake was determined by a weighted food intake method.

It has been suggested that training-induced changes in the ability to develop force during high shortening velocities and rate of force development (RFD) are more attenuated than changes in the ability to produce high force during low shortening velocities, when strength training is combined with endurance training (Dudley and Fleck 1987; Rhea et al. 2008). Vertical jump power can be assessed in a reliable way during vertical jumping (Samozino et al. 2008). It is important to note that this assessment is not based solely on the recording of maximal jumping height, and thus maximal jumping height must not be considered as a surrogate measure per se of maximal leg extension power. In trained rugby players as well as in untrained subjects there has been observed superior improvement in vertical jump performance after strength training alone when compared to concurrent strength and endurance training (Hennessy and Watson 1994; Hunter et al. 1987). In the present study we further explored these observations and investigated the effect of combining strength training with a high endurance training volume on changes in vertical jump ability, and isometric RFD characteristics of the muscle.

To the best of our knowledge, no studies investigating the effect of supplementing the endurance training with strength training, in non-strength trained but well-trained endurance athletes, have compared the strength training adaptations with a non-strength trained control group performing strength training only. Consequently, the purpose of the present study was to investigate the effects of 12 weeks of strength training combined with a high volume of endurance training in previously non-strength trained endurance athletes with the effects of strength training alone on muscle CSA, 1RM, RFD, and vertical jump performance. We hypothesized that combining strength training with a high volume of endurance training would reduce strength training adaptations in all parameters investigated in the present study.

Methods

Participants

Twelve well-trained cyclists [classified according to the criteria suggested by Jeukendrup et al. (2000)] and nine recreationally active individuals volunteered for the study, which was approved by the Southern Norway regional division of the National Committees for Research Ethics. All participants signed an informed consent form prior to participation. None of the participants had performed any strength training during the preceding 6 months. One of the cyclists and two of the recreationally active individuals did not complete the study due to illness. Their data are not included.

Experimental design

The cyclists ($S + E$; $n = 11$ [all men], age 27 ± 2 years, height 183 ± 2 cm, body mass 76.1 ± 2.8 kg) performed heavy strength training in addition to their usual endurance training. The recreationally active individuals (S; $n = 7$ [all men], age 26 ± 2 years, height 180 ± 3 cm, body mass 75.7 ± 3.4 kg) performed the same strength training regimen as $S + E$, but performed at most one endurance training session per week in addition to the strength training. The

Table 1 Strength training program for both groups during the 12–week intervention period

	Intervention period					
	Week 1–3		Week 4–6		Week 7–12	
	1. Bout	2. Bout	1. Bout	2. Bout	1. Bout	2. Bout
Half squat	3 × 10RM	3 × 6RM	3 × 8RM	3 × 5RM	3 × 6RM	3 × 4RM
One-legged leg press	3 × 10RM	3 × 6RM	3 × 8RM	3 × 5RM	3 × 6RM	3 × 4RM
One-legged hip flexion	3 × 10RM	3 × 6RM	3 × 8RM	3 × 5RM	3 × 6RM	3 × 4RM
Ankle plantar flexion	3 × 10RM	3 × 6RM	3 × 8RM	3 × 5RM	3 × 6RM	3 × 4RM

intervention was completed during the cyclists' preparation phase prior to the competition season. Tests were conducted before (pre-intervention) and after the 12-week intervention (post-intervention). Prior to the pre-intervention test, two familiarization sessions were conducted with the purpose of instructing the participants in proper technique and testing procedure.

Training

Endurance training for $S + E$ consisted primarily of cycling. Endurance training duration was calculated based on recordings from heart rate monitors (Polar, Kempele, Finland). During the 12-week intervention period $S + E$ performed a total of 119 ± 13 h of endurance training, corresponding to 9.9 ± 1.1 h per week.

Heavy strength training performed by $S + E$ and S targeted leg strength and was performed twice a week. On days where both strength and endurance training were scheduled for $S + E$, the cyclists were encouraged to perform strength training in the first training session of the day and endurance training in the second session. A review of the cyclists' training diaries confirmed that the cyclists largely complied with this guideline. Based on the assumption that it is the intended rather than actual velocity that determines the velocity-specific training response (Behm and Sale 1993), the heavy strength training was conducted with the emphasis on maximal mobilization in the concentric phase (lasting around 1 s), while the eccentric phase was performed more slowly (lasting around 2–3 s).

At the start of each strength training session, participants performed a ~10–min warm-up at self-selected intensity on a cycle ergometer, followed by two to three warm-up sets of half squat with gradually increasing load. The performed exercises were: half squat, leg press with one leg at a time, standing one-legged hip flexion, and ankle plantar flexion. Both intervention groups were supervised by an investigator at all sessions during the first 2 weeks and thereafter at least once every 2nd week for the remainder of the intervention period. During the first 3 weeks, participants trained with 10RM sets in the first session in the week and 6RM sets in the second session. During the next 3 weeks, sets were adjusted to 8RM and 5RM for the first and second weekly sessions, respectively. During the final 6 weeks, sets were adjusted to 6RM and 4RM, respectively (Table 1). Participants were encouraged to increase their RM loads as their strength evolved throughout the intervention period and assistance was permitted during the last repetition. The number of sets in each exercise was always three, with 1.5–2 min rest between sets. Adherence to the strength training program was high, with $S + E$ and S completing 97 ± 1 and 92 ± 2% of the prescribed strength training sessions, respectively.

Testing

Testing was completed as follows: day 1, measurement of thigh muscle CSA; day 2, measurement of squat jump height, RFD, and 1RM. The participants were instructed to refrain from intense exercise the day preceding testing, and to consume the same type of meal before each test. They were not allowed to eat during the hour preceding the test or to consume coffee or other products containing caffeine during the preceding 3 h. Testing at pre- and post-intervention was overseen by the same investigator and conducted on the same equipment with identical subject/equipment positioning and performed at the same time of the day to avoid influence of circadian rhythm. The post-intervention strength test was conducted 3–5 days after the last strength training session.

Thigh muscle CSA

Magnetic resonance tomography (MR) (Magnetom Avanto 1.5 Tesla, Siemens AG, Munich, Germany) was used to measure thigh muscle CSA. Participants were scanned in supine position. The feet were fixed and elevated by a pad placed on the back of the knees to prevent the muscles on the back of the thighs from compressing against the bench. The machine was centred 2/3 distally on the femur and nine cross-sectional images were sampled starting at the proximal edge of the patella and moving towards the iliac crest, with 35 mm interslice gaps. Each image represented a 5-mm thick slice. The images were subsequently uploaded to a computer for further analysis. The images of the thigh muscles were divided into knee extensor and knee flexor/adductor compartments using a tracer function in the software. The CSA of the thigh muscles was measured from the five most proximal images and the average CSA of these five images was used for statistical analysis.

Squat jump height

On the second test day, the participants performed a 10-min warm-up on a cycle ergometer. Squat jump performance was tested on a force plate (SG-9, Advanced Mechanical Technologies, Newton, Mass., USA, sampling frequency of 2 kHz). The hands were kept on the hips throughout the jump, knees were flexed to 90°, and the participants were instructed to execute a maximal vertical jump from a standing static flexed position (held in 3 s before take-off). No downward movement was allowed prior to the maximal vertical jump, and the force curves were inspected to verify this. Vertical jumping height was calculated from the impulse from the ground reaction force. Each participant performed four attempts, with 1 min rest between each jump. The participants were blinded to the results. The best jump from each participant was used in data analysis (CV < 3%).

Peak rate of force development

After 5 min of rest, peak RFD was measured during isometric half squat in a custom-built rack that was bolted to the floor located over a force plate (SG-9, Advanced Mechanical Technologies, Newton, Mass., USA, sampling frequency of 2 kHz). The knee angle during the half squat was 90°. To ensure similar position during all tests, each participant's squat depth and placement of the feet was carefully monitored and marked on the rack and on the force plate, respectively. Verbal encouragement was given throughout the test and each action was sustained for approximately 3 s. The participants were instructed to perform the muscle activation as quickly and forcefully as possible. The participants were blinded to the results. Four attempts were performed with 2 min recovery between each attempt. Custom made software was used for the subsequent analysis of peak RFD (N s^{-1}), which was defined as the peak slope of the force–time curve (MATLAB R2007a, version 7.4, MathWorks, Nitick, MA, USA). Peak RFD was determined as the peak average slope in moving 2.5 ms time intervals (in the range from 20% to 80% of maximal voluntary force). A 2nd order lowpass digital Butterworth filter was used with a cut off frequency of 50 Hz. The average of the three highest values of peak RFD was used in the statistical analysis.

1RM

After 5 min of rest, maximal strength of the leg extensors was measured as 1RM. 1RM was first measured in half squat and thereafter in leg press. 1RM in half squat was measured using a Smith machine. The average of the 1RM in the two exercises was used in statistical analysis. To ensure similar knee angles during all tests, the participant's knee flexion depth (to 90°) was carefully monitored and marked on a scale on both the leg press machine and the Smith machine. Thus, each participant had to reach his individual depth marked on the scale for the lift to be accepted. In both exercises participants performed a standardized warm-up protocol consisting of three sets with gradually increasing load (40, 75, and 85% of predicted 1RM) and decreasing number of repetitions (10, 7, and 3, respectively). Similarly, the placement of the feet was monitored for each participant to ensure identical test positions during both tests. The first 1RM attempt was performed with a load approximately 5% below the predicted 1RM load. Both 1RM exercises included a preceding eccentric phase. After each successful attempt, the load was increased by 2–5% until the participant failed to lift the same load after 2–3 consecutive attempts. The rest period between each attempt was 3 min.

Dietary intake

In the 6th training week, the participants recorded their daily dietary intake for a 4-day period (Wednesday to Saturday) using a weighted food intake method, which is recognized as a valid method (Bingham 1987) when participants are not supervised 24 h a day. The participants were given food record journals and digital food weighing scales (Vera 67002; Soehnle-Waagen GmbH & Co, Murrhardt, Germany; precision 1 g). They were also given detailed verbal and written guidelines about how to carry out this method. Dietary assessment data were analyzed using a nutrient analysis program (Mat på data 5.1; LKH, Oslo, Norway).

Statistics

All data in the text, figures, and tables are presented as mean ± SE. To test for differences between groups at pre-intervention, unpaired Student's *t* tests were used. Pre- and post-intervention measurements for each group were compared using paired Student's *t* test. To test for differences in relative changes (from pre- to post-intervention) between the groups, unpaired Student's *t* tests were performed. The Student's *t* tests were performed in Excel 2003 (Microsoft Corporation, Redmond, WA, USA). Correlation analyses (Pearson product-moment correlation coefficient) was performed using GraphPad InStat (GraphPad Software, Inc. CA, USA). All analyses resulting in $p \leq 0.05$ were considered statistically significant.

Results

Comparison of groups at baseline

There were no significant differences between *S* + *E* and *S* at baseline with respect to body mass, BMI, thigh muscle CSA (Fig. 2), 1RM (Fig. 3), squat jump height (Fig. 4), or peak RFD (Fig. 5).

Training load, strength, thigh muscle cross-sectional area, and body mass

The *S* group increased their average weekly training load in the strength exercises from the first training week to the last training week to a greater extent than the *S* + *E* group in both absolute and relative terms (from 108 ± 3 to 159 ± 3 kg for *S* vs. from 109 ± 5 to 147 ± 6 kg for *S* + *E*, $p < 0.05$; Fig. 1). The mean 1RM in half squat and leg press increased by 35 ± 4% in *S* and 25 ± 2% in *S* + *E* ($p < 0.01$; Fig. 2). The relative increase in 1RM was larger in *S* than in *S* + *E* ($p < 0.05$; Fig. 2). Thigh muscle CSA (sum of flexors and extensors) increased in both groups, but more in *S* than in *S* + *E* (8.0 ± 0.8 vs. 4.3 ± 0.7%, respectively, $p < 0.05$; Fig. 3). Body mass increased from pre- to post-intervention in *S* by 1.6% (from 75.7 ± 3.4 to 76.9 ± 3.3 kg, $p < 0.05$), while there was no change in body mass in *S* + *E*.

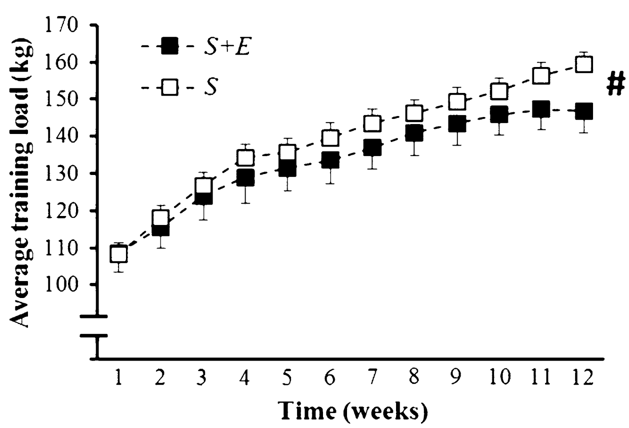

Fig. 1 Average weekly training load (kg) in the leg exercises during the 12-week training intervention. *S* + *E* = strength training in addition to a large volume of endurance training, *S* = the same strength training program as *S* + *E* without a large volume of endurance training. #Significantly greater increase from the 1st to the 12th training week in *S* compared with *S* + *E* in both absolute and relative terms ($p \leq 0.05$)

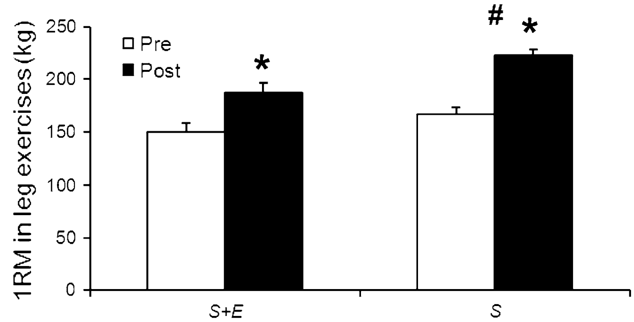

Fig. 2 Average 1RM load in half squat and leg press before (pre) and after the 12 week intervention period (post). For explanation of *S* + *E* and *S*, the reader is referred to Fig. 1. *Greater than at Pre ($p < 0.05$). #The relative change from Pre is greater than in *S* + *E* ($p < 0.05$)

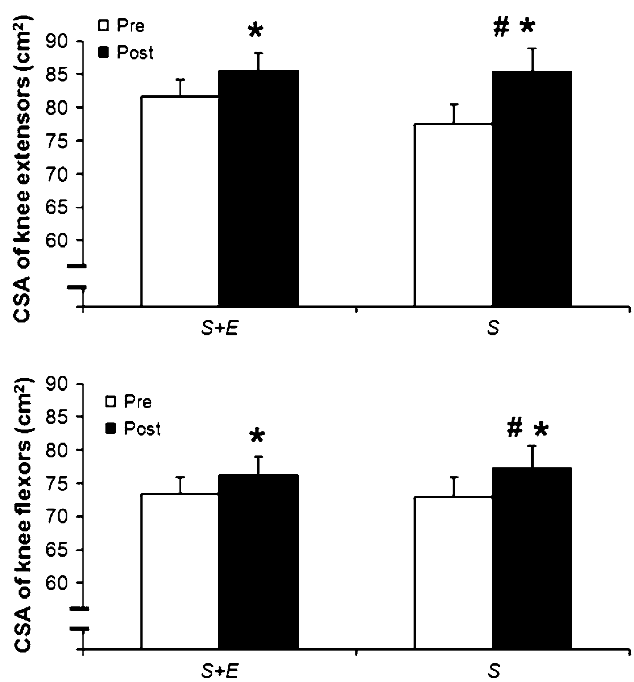

Fig. 3 Thigh muscle cross-sectional area (CSA) separated into area of knee extensors (*upper panels*) and knee flexors (*lower panels*) before (pre) and after the 12-week intervention period (post). For explanation of *S* + *E* and *S*, the reader is referred to Fig. 1. *Greater than at pre ($p < 0.05$). #The relative change from pre is greater than in *S* + *E* ($p < 0.05$)

Squat jump performance and RFD

Both *S* and *S* + *E* increased squat jump performance, but the increase in squat jump performance was larger in *S* than in *S* + *E* (13.0 ± 2.0 vs. 6.2 ± 1.6%, respectively $p < 0.05$; Fig. 4). There was no change in peak RFD in *S* + *E*, while *S* increased peak RFD by 15 ± 5% during isometric half squat ($p < 0.05$; Fig. 5). The relative increase in peak RFD was larger in *S* than in *S* + *E* ($p < 0.05$).

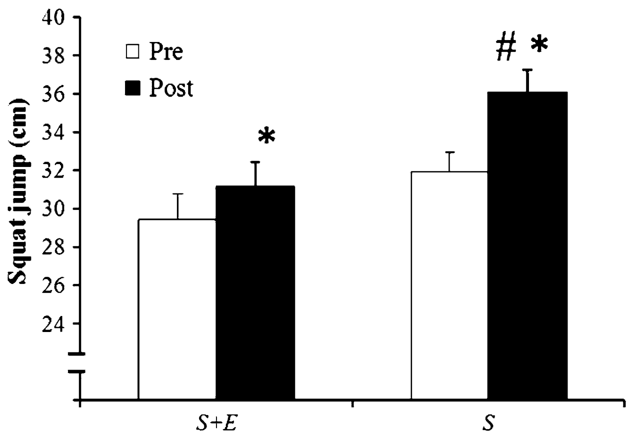

Fig. 4 Squat jump height before (pre) and after the 12-week intervention period (post). For explanation of $S + E$ and S, the reader is referred to Fig. 1. *Greater than at pre ($p < 0.05$). #The relative change from pre is greater than in $S + E$ ($p < 0.05$)

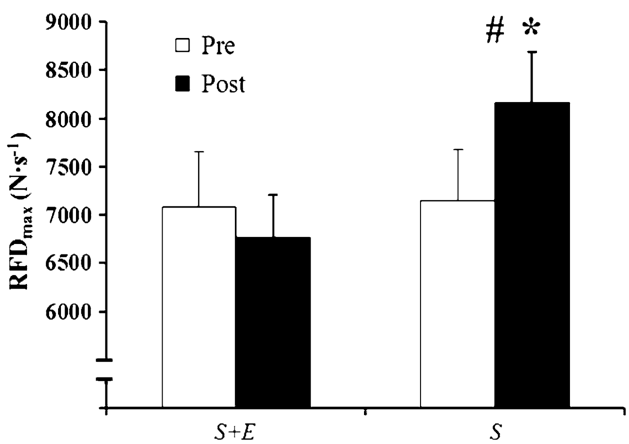

Fig. 5 Peak rate of force development (RFD) in isometric half squat before (Pre) and after the 12-week intervention period (post). For explanation of $S + E$ and S, the reader is referred to Fig. 1. *Greater than at Pre ($p < 0.05$). #The relative change from Pre is greater than in $S + E$ ($p < 0.05$)

Dietary intake

No difference in intake of total energy, protein, carbohydrate, or fat was observed between groups (Table 2).

Discussion

The primary finding in this study was that endurance athletes who combined strength training with a high volume of endurance training experienced attenuated strength training adaptations, measured as changes in 1RM, thigh muscle cross-sectional area, jump performance, and rapid force generation compared with a group of recreationally active

Table 2 Energy, protein, carbohydrate, and fat intake in the 6th training week in the strength and endurance training group ($S + E$) and the group that performed same strength training program as $S + E$ without a large volume of endurance training (S)

Nutrient	$S + E$	S
Energy intake (kJ day^{-1})	11845 ± 1163	10683 ± 807
Energy intake (kJ kg^{-1} day^{-1})	152 ± 12	140 ± 13
Protein (g day^{-1})	118 ± 8	108 ± 8
Protein (g kg^{-1} day^{-1})	1.5 ± 0.1	1.4 ± 0.1
Carbohydrate (g day^{-1})	370 ± 47	315 ± 27
Carbohydrate (g kg^{-1} day^{-1})	4.7 ± 0.5	4.2 ± 0.5
Fat (g day^{-1})	85 ± 10	83 ± 9
Fat (g kg^{-1} day^{-1})	1.1 ± 0.1	1.1 ± 0.1

No differences were observed between groups

individuals performing a similar amount and type of strength training only.

1RM and thigh muscle CSA

During the 12-week intervention period, leg strength in $S + E$ increased by ~25%. This result is in accordance with other studies reporting 16–35% increase in 1RM muscle strength after 10 to 14 weeks of heavy strength training in endurance athletes (runners, cross-country skiers, and cyclists) (Bishop et al. 1999; Hickson et al. 1988; Johnston et al. 1997; Losnegard et al. 2011; Millet et al. 2002). The observed improvement in 1RM in $S + E$ is in the lower range of the expected strength improvement when individuals with no prior strength training experience perform 10–12 weeks of strength training (Kraemer et al. 2002). In the previous studies, the strength training adaptations of endurance athletes has not been directly compared with adaptations in individuals performing the exact same strength training without any endurance training. Consequently, it has been difficult in those studies to conclude whether strength training adaptations was attenuated when endurance athletes combined a high volume of endurance training with strength training. In the present study, strength training without concurrent endurance training resulted in a superior increase in 1RM compared with concurrent strength and endurance training. The present finding of attenuated adaptation in 1RM strength in the endurance athletes agrees with findings for active individuals, although not endurance athletes, who added a high frequency of endurance training (≥3 sessions per week) to strength training (Bell et al. 2000; Hennessy and Watson 1994; Hickson 1980; Kraemer et al. 1995). Importantly, it seems that a smaller endurance training volume (≤2 sessions a week) does not attenuate the 1RM adaptations to strength training (Glowacki et al. 2004; Häkkinen et al. 2003; McCarthy et al. 2002). The order of training sessions on days, where both strength training and endurance training were performed, may potentially influence the attenuated response to strength training in $S + E$. In the present study, the strength training was performed as the first training session of the day and endurance training as the second session. It has been observed that, in untrained subjects, improvement in endurance performance was greater when, in the same session, the endurance training preceded the strength training (Chtara et al. 2005). However, similar interactions are not reported for the adaptation in muscle strength and power (Chtara et al. 2008; Gravelle and Blessing 2000). Importantly, strength- and endurance training was not performed during the same session in the present study, but separated by 4 to 6 h.

The observed attenuated strength gain in the endurance athletes may largely be explained by impaired muscle hypertrophy. It has frequently been observed that endurance athletes who add heavy strength training to their endurance training do not gain body mass (e.g. Aagaard et al. 2011; Hoff et al. 2002; Millet et al. 2002; Storen et al. 2008; Sunde et al. 2010). In the absence of size measurements of the strength-trained muscles, no changes in body weight has often been interpreted as no change in muscle size. This relationship has been demonstrated in studies that have included analyses of muscle fibre area (Bishop et al. 1999; Hickson et al. 1988). However, it should be noted that muscle fibre area is found to vary significantly within the m. vastus lateralis (Lexell and Taylor 1989). This variability suggests that analysis of muscle fibre area should preferably be accompanied by multiple-site measurements at the whole muscle level (e.g. using MRI or CT) in order to obtain more reliable measures of changes in muscle size. It must, however, be mentioned that changes in whole muscle CSA are influenced by changes in muscle architecture (e.g. Aagaard et al. 2001; Blazevich et al. 2007) and therefore, changes in muscle CSA may not per se reflect the corresponding changes in physiological CSA and hence in maximal force generating capacity. However, the importance of measuring adaptations at the whole muscle level is underlined by the findings of Aagaard et al. (2011), who added a lower body strength training program, similar to the program used in the present study, to the normal endurance training in elite cyclists. No change in muscle fibre area from m. vastus lateralis was found despite an increase in lean body mass (Aagaard et al. 2011). In that study, total body mass did not change even though total lean body mass increased. Because only lower body strength training was performed, it is likely that the observed changes in lean body mass occurred in the muscles engaged in the strength training exercises. Similarly, a recent study conducted with cross-country skiers found increased muscle CSA in m. triceps brachii with no change in total body mass after 12 weeks of concurrent strength and endurance training (Losnegard et al. 2011). Interestingly, in the latter study a muscle hypertrophy of 5% was observed (Losnegard et al. 2011) and after 16 weeks of concurrent strength and endurance training in elite cyclists lean body mass increased with 3% (Aagaard et al. 2011). These results suggest an impaired hypertrophic response to the performed strength training when compared to expected changes in normal active subjects (e.g. Wernbom et al. 2007). However, because those studies did not include a control group performing the same strength training program as the endurance athletes, the exact impact of endurance training on the strength training adaptations could not be assessed. Participants in the present study performed a strength training program that was quite similar to what was performed on m. triceps brachii in the Losnegard et al. (2011) study, and the increase in muscle CSA was quite similar (~4% for present study; ~5% for Losnegard et al.). The results from the present study demonstrate that muscle CSA can increase without a change in body mass. However, since the S group achieved a significantly greater increase in muscle CSA (~8%) than the $S + E$ group, our results support the hypothesis that a high volume of endurance training attenuates the hypertrophic adaptations to strength training.

Due to practical challenges with regard to recruiting well-trained endurance athletes for muscle biopsies, the intracellular mechanisms responsible for the present observation of attenuated hypertrophic adaptation to strength training was not addressed in the present study. However, the nutritional data allow some speculations. When assessed halfway in the time course of training there was no difference between groups in intake of protein, carbohydrate, and fat. The daily protein intake for both groups was within ACSM's recommendations for endurance- and strength-trained athletes (ACSM 2009). However, protein synthesis is an ATP-dependent process; thus, muscle protein synthesis may be increased during periods of positive energy balance and attenuated during periods of negative energy balance (Lambert et al. 2004). In young healthy males it has been observed that energy intake above what is needed for weight maintenance increases muscle hypertrophy (Rozenek et al. 2002). When we examined the total energy intake for the two groups, we observed that there was no difference between the groups even though the $S + E$ group performed ~10 h of endurance training per week in addition to the strength training. It is then likely that the lower activity related energy expenditure in S resulted in a positive energy balance and thus a more optimal environment for muscle hypertrophy. The fact that body mass increased for S but not for $S + E$ during the intervention period supports such a scenario. Furthermore, it has been shown that a small positive energy balance ensures a positive anabolic hormonal milieu (Houston 1999).

The carbohydrate intake in $S + E$ during the nutritional registration was lower than recommended by the ACSM (2009). Whether this was an underestimate or not remains unclear, but no change in total body weight during the 12-week intervention period suggests at least that the total energy intake was adequate for weight maintenance. However, low muscle glycogen may impair the intracellular signalling pathways responsible for hypertrophy, and may thus potentially contribute to the observed attenuation of strength training adaptations in $S + E$ (Hawley 2009). Because gains in body mass may compromise performance in the majority of endurance sports, we suggest that the above observations of energy intake in the present study are likely to be generalizable to other populations of endurance athletes. We, therefore, suggest that the often observed attenuated hypertrophic response when a high volume of endurance training is added to strength training might partly be due to a lack of positive energy balance.

Recent discoveries within molecular sports science suggest that endurance training may negatively affect intracellular pathways important for myofibrillar protein synthesis (reviewed in Hawley 2009). Activation of adenosine monophosphate-activated protein kinase (AMPK) by endurance exercise may inhibit mammalian target of rapamycin (mTOR) signalling and suppress strength exercise-induced myofibrillar protein synthesis (Hawley 2009; Nader 2006). Consequently, it may be suggested that the acute intracellular signalling response to concurrent strength and endurance training, does not promote ideal activation of pathways responsible for muscle hypertrophy (Coffey et al. 2009). Observations of disparate mRNA response to concurrent strength and endurance training underline the importance of local factors in explaining compromised strength training adaptations to a large volume of concurrent training (Coffey et al. 2009). Furthermore, high volume endurance training appears to compromise strength training adaptations only when both modes of training engage the same muscle groups (Bell et al. 1991; Hennessy and Watson 1994; Kraemer et al. 1995).

Squat jump and peak RFD

The finding of improved jump performance in the $S + E$ group is in agreement with previous studies involving distance runners and soccer players adding strength training to their normal training (Rønnestad et al. 2008; Spurrs et al. 2003; Turner et al. 2003). Increased jumping ability is an expected adaptation when individuals with no prior strength training experience complete a period of strength training (e.g. Cormie et al. 2010). However, since none of the cited studies included a control group performing the same strength training program without concurrent endurance training, it is difficult to determine whether or not adaptations were impaired by the concurrent endurance training. An impaired adaptation with concurrent endurance training was found in the present study: the S group achieved a significantly greater increase in vertical jump performance than the $S + E$ group. This finding has been corroborated by other studies, in which no improvement in vertical jump performance was observed after adding strength training to a high volume of endurance training (Losnegard et al. 2011; Millet et al. 2002). Vertical jump performance has been shown to accurately evaluate power development in the lower limbs extensor muscles (Samozino et al. 2008). It has been suggested that the ability to develop high power output and RFD is more inhibited by combining strength training with high volume endurance training than the ability to produce high force during low muscle shortening velocities; such as for example during a 1RM lift (Dudley and Djamil 1985; Dudley and Fleck 1987; Häkkinen et al. 2003; Kraemer et al. 1995; Rhea et al. 2008). Indeed, Häkkinen et al. (2003) did not find any improvement in RFD in the group performing concurrent training despite increased muscle size and 1RM strength, while the group performing only strength training improved peak RFD. However, others have observed increased RFD in response to concurrent strength and endurance training in endurance trained athletes (Aagaard et al. 2011). In the present study, $S + E$ did not improve peak RFD, while S increased peak RFD by 15%. The lack of improvement in peak RFD as well as less increase in 1RM, likely explains the inferior improvement in vertical jump ability in $S + E$ compared to S. This notion is partly supported by the findings of a correlation between relative changes in 1RM and relative changes in vertical jump ability in the present study ($r = 0.46$, $p = 0.05$). Unfortunately, the present study did not include measurement of muscle activation, so it is difficult to speculate on the influence of neural adaptations. Häkkinen et al. (2003) suggested that lack of improvement in RFD after concurrent strength and endurance training was due to lack of improvement in rapid voluntary neural activation. On the other hand, endurance training by itself may induce fibre atrophy (Kraemer et al. 1995; Widrick et al. 1996) and reduce the maximum shortening velocity of the type II fibres and is known to reduce peak tension development in all fibre types (Fitts et al. 1989). Consequently, both neural and muscular adaptations may explain the impaired ability to rapid force generation when combining a large volume of endurance training with strength training.

A limitation of the present study is that there may be differences in genes between endurance athletes and recreationally active individuals which might affect strength training adaptations. The fibre type distribution in the two intervention groups was not measured. If there were a greater percentage of type I fibres in the endurance trained cyclists than in the recreational active participants, this could affect the outcome of the study possibly due to a lower hypertrophic response in type I fibres (e.g. Hather et al. 1991). No measurement of fibre type distribution was performed in the present study, which must be kept in mind when the present results are interpreted.

In conclusion, the present data expands on previous findings of attenuated strength training adaptations when a relatively high volume of endurance training is combined with strength training. To the best of our knowledge, this is the first controlled study to suggest that the effect of strength training on muscle hypertrophy, 1RM strength, squat jump performance, and peak RFD is attenuated in well-trained endurance athletes during a period of concurrent endurance training.

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