©Journal of Sports Science and Medicine (2018) **17**, 167-173
http://www.jssm.org

Research article

The Effect of Two Different Concurrent Training Programs on Strength and Power Gains in Highly-Trained Individuals

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Abstract
The effects of concurrent strength and endurance training have been well studied in untrained and moderately-trained individuals. However, studies examining these effects in individuals with a long history of resistance training (RT) are lacking. Additionally, few studies have examined how strength and power are affected when different types of endurance training are added to an RT protocol. The purpose of the present study was to compare the effects of concurrent training incorporating either low-volume, high-intensity interval training (HIIT, 8-24 Tabata intervals at ~150% of VO_{2max}) or high-volume, medium-intensity continuous endurance training (CT, 40-80 min at 70% of VO_{2max}), on the strength and power of highly-trained individuals. Sixteen highly-trained ice-hockey and rugby players were divided into two groups that underwent either CT (n = 8) or HIIT (n = 8) in parallel with RT (2-6 sets of heavy parallel squats, > 80% of 1RM) during a 6-week period (3 sessions/wk). Parallel squat performance improved after both RT + CT and RT + HIIT (12 ± 8% and 14 ± 10% respectively, $p < 0.01$), with no difference between the groups. However, aerobic power (VO_{2max}) only improved after RT + HIIT (4 ± 3%, $p < 0.01$). We conclude that strength gains can be obtained after both RT + CT and RT + HIIT in athletes with a prior history of RT. This indicates that the volume and/or intensity of the endurance training does not influence the magnitude of strength improvements during short periods of concurrent training, at least for highly-trained individuals when the endurance training is performed after RT. However, since VO_{2max} improved only after RT + HIIT and this is a time efficient protocol, we recommend this type of concurrent endurance training.

Key words: Endurance, exercise; HIIT, performance, resistance, squat.

Introduction

Performance in most sports depends on the interplay between several physiological factors. A challenge for coaches and athletes is to find the right combination and work load of exercises during training to promote a long-term optimization of all these factors. This is an important part of the periodization process, which is the division of training into phases with different objectives to promote performance and to avoid excessive fatigue and overtraining (Smith, 2003). Even though the objective during one such phase could be strength improvements via resistance training (RT), most athletes need to simultaneously train other physical capacities to avoid a decline in performance. Combining resistance and endurance exercises is especially challenging because several studies have shown that muscle hypertrophy and gains in strength and power are often blunted when endurance exercises are added to a RT program (Bell et al., 2000; Dudley and Djamil, 1985; Fyfe et al., 2016; Hakkinen et al., 2003; Hickson, 1980; Kraemer et al., 1995; Sale et al., 1990). The mechanisms underpinning this interference effect are not well understood but likely comprise a combination of factors affecting both acute and chronic fatigue as well as the exercise induced anabolic response (Coffey and Hawley, 2017). Examples of such factors may include reduced neural activation; accumulation of metabolites such as inorganic phosphate, H^+ and ammonia; and depletion of ATP, creatine phosphate and muscle glycogen (Leveritt et al., 1999).

Power is the feature most negatively affected by concurrent training, and studies show that just a few relatively short endurance sessions per week are enough to blunt power (Hakkinen et al., 2003; Mikkola et al., 2012). Muscle hypertrophy and strength seem to be less negatively affected, and a low-to-moderate volume endurance training (2–3 sessions/wk, 20–60 min/session) is associated with no or only minor blunting effects (Hakkinen et al., 2003; Lundberg et al., 2013; Shaw et al., 2009; Tsitkanou et al., 2016). However, even minor blunting effects may be detrimental for elite athlete performance, and moreover, if long and/or frequent endurance sessions are added to a RT program there is a large body of evidence showing that muscle hypertrophy and strength will be compromised (Hickson, 1980; Jones et al., 2013; Kraemer et al., 1995). For example, Hickson (1980) observed a strong blunting effect on one-repetition maximum (1RM) squat progression when running exercises (40 min, 6 sessions/wk) were added to a 10-week RT program.

In recent years, high-intensity interval training (HIIT) has become a very popular form of endurance training among both athletes and recreationally-active individuals. The popularity of HIIT can be attributed to the fact that it is time efficient and provides performance and health improvements that are similar to those gained from more traditional low/medium-intensity, long-duration continuous training (Francois and Little, 2015; Gibala et al., 2006; Milanovic et al., 2015). Since it is well established that high-volume endurance training has a negative impact on muscle hypertrophy, strength and power (Hickson, 1980; Jones et al., 2013; Kraemer et al., 1995), HIIT might be a better choice during training periods when these outcomes need to be prioritized. However, a potential problem with the HIIT approach is that even if the duration is short, the high intensity of this training might have a negative impact on strength and power due to its potential peripheral fatiguing effect. This is supported in acute studies where HIIT

Received: 22 November 2017 / Accepted: 25 January 2018 / Published (online): 14 May 2018

performed prior to RT reduced force generating capacity and RT volume (Bentley et al., 2000; de Souza et al., 2007). The mechanisms behind this effect is not well known but altered neuromuscular recruitment patterns, accumulation of metabolites and reduced substrate availability have been suggested (Ratamess et al., 2016). Interestingly, a recent study examining the long term effect of concurrent training did not find a larger attenuating effect of HIIT compared with moderate-intensity continuous training on strength and power gains (Fyfe et al., 2016). Therefore, reducing training volume rather than intensity seems more important for avoiding the potential interfering effects of concurrent training.

Most concurrent training interventions have been studied in untrained or moderately-trained individuals. Individuals with long-term experience in strength and power training might respond differently to the addition of endurance training to their routine. Therefore, the objective of the present study was to examine the effects of two different concurrent training programs on strength and power gains in individuals with a long history of RT. We hypothesized that the addition of high-volume CT to a six-week RT program would have a blunting effect on strength and power compared to the effect of low-volume HIIT.

Methods

Participants

Sixteen male former high-level athletes (ice-hockey and rugby players, 27.3 ± 5.0 years) participated in the study. They were still active athletes who trained regularly but competed sporadically. The participants were considered for inclusion if they were 1) currently undergoing strength training four times or more per week, 2) had more than five years of experience with regular strength training, and 3) included squats in their weekly training routine. The participants were considered to be highly-trained based on their long history of elite-training and excellent performance in the 1RM parallel squat exercise (1.7 ± 0.3 kg / kg body mass), which was in line with that of international rugby players and power athletes (Baker and Newton, 2008; Zourdos et al., 2016). The participants were assigned to groups that performed either squat RT followed by CT (RT + CT; n = 8) or squat RT followed by HIIT (RT + HIIT; n = 8). The exercise order, i.e. performing RT first, was based on previous findings that sequencing strength training prior to endurance training appears to be beneficial for lower body strength gains (Murlasits et al., 2018). The two groups were matched for 1RM squat strength and VO_{2max}. Two subjects, one in the RT + CT group and one in the RT + HIIT group, interrupted their training and were excluded from the study.

The participants were instructed to maintain their normal diet throughout the intervention, to record food intake during the 24 h preceding the pre-tests, and to duplicate the same diet before post-tests. Performance enhancers such as caffeine and creatine, as well as alcohol, were not allowed during the intervention period.

The participants were informed about the possible risks and discomforts involved before giving their written consent to participate in the study. The study was approved by the Regional Ethics Committee of Stockholm, Sweden.

Testing

Pre- and post-tests were performed in a rested state (no training > 48 h before the tests) and at the same time of day for each subject. Four familiarization sessions were performed before the pre-tests, which included both heavy parallel squats and HIIT on a cycle ergometer. The test order was as follows: anthropometric measurements (weight, height and body fat), counter-moment-jump vertical height (CMJ), 1RM parallel squat, maximal lactate steady-state workload (MLSS) and VO_{2max} (Haff and Triplett, 2016). The duration of all the tests performed in one session was ~2 h. Body fat was calculated from skinfold thickness measured with calipers (Harpenden, Baty International CTD, West Sussex, UK) as described by Durnin and Womersley (1974).

CMJ test

The participants performed a general warm-up before testing that consisted of light cycling at 100 W for 8 min. CMJ performance was then assessed using an optical measurement system (Optojump, Microgate, Bolzano-Bozensh, Italy). The system has been demonstrated to have a strong validity and test-retest reliability for the estimation of vertical jump height (Glatthorn et al., 2011). The participants performed three maximal unloaded jumps with 30 s of passive recovery between each effort. If the third jump was higher than the previous two, the subject performed an additional fourth jump. If this effort was higher than the third a fifth jump was added, and so on, until no further improvements were observed. The best jump was used to determine maximal vertical jump height. Jumps were initiated from a standing starting position, with the hands placed on the hips throughout the jump. The jump depth was self-selected, and the participants were instructed to accelerate as quickly as possible from their lowest position to achieve maximal jump height.

1RM parallel squat test

Lower-body strength was assessed via 1RM testing using the parallel-back squat exercise. The participants performed five warm-up sets as follows: 10 repetitions at 20 kg, 5 repetitions at 40% of predicted 1RM, 5 repetitions at 60% of predicted 1RM, 3 repetitions at 80% of predicted 1RM, and 2 repetitions at 90% of predicted 1RM. The rest periods between the sets were 2, 3, 3 and 5 min, respectively. The participants then performed sets of 1 repetition of increasing weight to determine their 1RM. Five minutes of rest were provided between each attempt. The participants were required to reach a parallel thigh/floor position or deeper for the attempt to be considered successful, as determined by two test supervisors (certified strength and conditioning specialists). An attempt was deemed successful only when the two supervisors reached consensus.

MLSS and VO_{2max} tests

MLSS was determined during incremental submaximal exercise (5 min of cycling, 90 RPM, at each step: 100, 150, 200, 250 W, etc. until reaching a Borg scale score ≥ 17). The participants completed 4–6 steps, such that the total duration of the test was ≤ 30 min. Capillary blood samples were collected from the fingertip during the 1-min periods of rest between each step and analyzed for lactate using an automated analyzer (Biosen 5140, EKF Diagnostics, Barleben, Germany). The gas composition of expired air and HR were measured continuously using the Oxycon Pro (Erich Jaeger GmbH, Hoechberg, Germany) and Polar Electro Oy (Kempele, Finland) systems, respectively. MLSS was determined based on the D_{max} method as previously described (Cheng et al., 1992). The submaximal MLSS test was followed by 10 min of pedaling at 100 W before the $VO_{2\,max}$ test was initiated at a workload corresponding to the last completed 5-min step of the MLSS test. Thereafter, the workload was increased by 20 W each minute until fatigue was reached (drop in cadence to < 50 RPM). $VO_{2\,max}$ was calculated as the highest recorded mean oxygen uptake during the last 60 s of the test. The criteria for attaining $VO_{2\,max}$ (RPE ≥ 18, RER ≥ 1.1, and a plateau in VO_2 with increasing workload) were met for all participants. Time to exhaustion during the $VO_{2\,max}$ test (TTE-$VO_{2\,max}$) was defined as the time point when the cadence involuntarily dropped to below 50 RPM. A capillary blood sample was collected immediately after the test to measure peak lactate levels (BL-$VO_{2\,max}$). The Oxycon Pro system used for the gas exchange measurements is known for its high validity and reliability (Foss and Hallen, 2005).

Training

The training interventions lasted 6 weeks and the participants performed 3 concurrent strength and endurance workouts per week, i.e. for a total of 18 training sessions. No additional lower body strength or endurance training was allowed. Three subjects had to perform 1-2 additional training sessions during week 7 to reach a total of 18 sessions, giving a training compliance of 100%. All exercise sessions were supervised by members of the investigative team who were certified strength and conditioning specialists. Each strength training session was initiated with 10-min cycling at 100 W, followed by 4 sets of parallel squats with a light to medium loading (40–80% of 1RM). Thereafter the participants performed 5x2 reps, ≥ 90% 1RM (Mondays and Fridays) or 2x5 reps, ≥ 80% 1RM (Wednesdays) of parallel squats. The loading was self-selected (above 90% respectively 80% of 1RM) and all sets were performed to failure or close to failure. If the first set/sets were not close to failure the loading was increased. Three minutes of rest was allowed between light to medium loading sets and 5 min between heavy loading sets. Approximately 15 min after the strength training session, the RT + CT group performed 40–80 min of continuous cycling (Monark 828 E, Monark Exercise, Varberg, Sweden), and the RT + HIIT group performed 4–20 min of high-intensity interval cycling (Monark Ergometic, Peak Bike 894 E, Monark Exercise, Varberg, Sweden). The duration of the CT sessions was increased from 40 min during weeks 1–2 to 60 min during weeks 3–4 and 80 min during weeks 5–6. The intensity was set to 70% of $VO_{2\,max}$ and was kept constant throughout the intervention. The HIIT protocol was increased from one block of eight Tabata intervals (8 × 20 s separated by 10 s rest) during weeks 1-2 to two blocks during weeks 3-4 (2 × 8 × 20 s) and three blocks during weeks 5–6 (3 × 8 × 20 s). The intensity was set to 150% of $VO_{2\,max}$ during the first training session; if a participant was able to complete all intervals, a 10-W increase was added during the following session. The RT + HIIT group, therefore, experienced a progression in both duration and intensity, whereas the RT + CT group experienced a progression in duration only.

Statistical analyses

Data are presented as the mean ± SD. Repeated-measures analysis of variance (2 × 2 mixed ANOVA) was used to test the interaction between time (pre- and post-training) and intervention (RT + CT and RT + HIIT group). Within-group differences were assessed using paired t-tests. The effect size (ES) was calculated as the mean difference between the pre-training and the post-training values divided by the standard deviation of the pre-training values. The following scale was used to categorize the magnitude of effect as proposed by (Rhea, 2004) for highly-trained individuals: < 0.25 = trivial; 0.25-0.5 = small; 0.5-1.0 = moderate; > 1.0 = large. Statistical significance was determined at $p < 0.05$. All statistical analyses were performed using STATISTICA (StatSoft, Inc, Tulsa, Oklahoma, USA).

Results

Body composition

Body mass and lean body mass increased slightly in the RT + HIIT group (1.3 ± 1.4%, p = 0.035 and 1.2 ± 1.3%, p = 0.032 respectively) whereas only lean body mass increased in the RT + CT group (1.2 ± 1.5%, p = 0.044) (Table 1). The percent body fat remained unchanged in both groups.

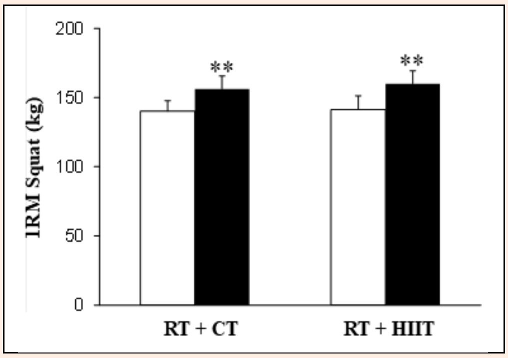

Figure 1. Effect of 6 weeks of training on leg strength (1RM in parallel squats). Values are reported as the mean ± SD. RT + CT: resistance training followed by continuous endurance training (n = 8); RT + HIIT: resistance training followed by high-intensity interval training (n = 8). **p < 0.01 vs. pre-training.

Strength and CMJ performance

Maximal strength, measured as 1RM for parallel squats, increased in both the RT + CT group (11.5 ± 7.8%, p = 0.006) and the RT + HIIT group (14.4 ± 10.1%, p = 0.001) (Figure 1). The effect size was moderate for both groups (0.75 and 0.66 respectively). CMJ vertical height was unaffected by training in both groups (RT + CT: 41.4 ± 4.5 cm pre-training and 40.1 ± 4.1 cm post-training, p = 0.15; RT + HIIT: 40.6 ± 6.2 cm pre-training and 40.7 ± 4.8 cm post-training, p = 0.89).

Endurance-related parameters

Both the absolute and relative $VO_{2\,max}$ increased in the RT + HIIT group (4.4 ± 2.8%, p = 0.001 and 3.1 ± 1.6%, p = 0.003 respectively) but not in the RT + CT group. Time to exhaustion during the $VO_{2\,max}$ test increased in both groups (RT + CT: 12.5 ± 15.8%, p = 0.045; RT + HIIT: 19.7 ± 12.4%, p = 0.002) (Table 2). Maximal lactate steady-state workload also increased in both groups (RT + CT: 12.5 ± 8.7%, p = 0.005; RT + HIIT: 5.5 ± 5.2%, p = 0.022). Blood lactate levels after the $VO_{2\,max}$ test remained unchanged in the RT + CT group but increased in the RT + HIIT group (11.5 ± 9.8%, p = 0.015). No between-group differences were observed for any of the endurance-related measures.

Table 1. Effect of training on body composition. Values are reported as the mean (± SD).

	Group	Pre	Post	ES (rating)
Body mass (kg)	RT+CT	79.3 (10.4)	80.1 (9.3)	.07 (trivial)
	RT+HIIT	83.1 (10.9)	84.2 (11.2)*	.10 (trivial)
Lean body mass (kg)	RT+CT	68.6 (7.4)	69.3 (6.9)*	.11 (trivial)
	RT+HIIT	71.5 (7.6)	72.4 (8.1)*	.12 (trivial)
Fat (%)	RT+CT	13.3 (3.5)	13.3 (2.6)	.00 (trivial)
	RT+HIIT	13.7 (3.4)	13.7 (3.2)	.02 (trivial)

RT + CT, resistance training followed by continuous endurance training (n = 8); RT + HIIT, resistance training followed by high-intensity interval training (n = 8); ES, effect size. *, p < 0.05 vs. pre-training.

Table 2. Effects of training on endurance-related variables. Values are reported as the mean (± SD).

	Group	Pre	Post	ES (rating)
VO_2max (L/min)	RT+CT	4.1 (.6)	4.3 (.5)	.25 (small)
	RT+HIIT	4.4 (.3)	4.6 (.4)**	.58 (moderate)
VO_2max (mL/min/kg)	RT+CT	52.3 (5.5)	53.5 (3.9)	.22 (trivial)
	RT+HIIT	53.4 (3.8)	55.1 (4.0)**	.43 (small)
TTE-VO_2max (s)	RT+CT	323 (45)	361 (50)*	.84 (moderate)
	RT+HIIT	344 (52)	410 (59)**	1.27 (large)
BL-VO_2max (mmol/L)	RT+CT	15.3 (1.7)	15.6 (1.4)	.19 (trivial)
	RT+HIIT	14.7 (1.6)	16.3 (1.4)*	1.04 (large)
MLSS (W)	RT+CT	204 (37)	229 (33)**	.65 (moderate)
	RT+HIIT	230 (24)	243 (26)*	.52 (moderate)

RT + CT, resistance training followed by continuous endurance training (n = 8); RT + HIIT, resistance training followed by high-intensity interval training (n = 8). TTE-VO2max, time to exhaustion during the VO_2max test; BL-VO_2max, blood lactate level after the VO_2max test; MLSS, maximal lactate steady-state workload; ES, effect size. *, p < 0.05 vs. pre-training; **, p < 0.01 vs. pre-training.

Discussion

The results of the present study suggest that highly strength-trained individuals can improve their maximal strength by concurrently undergoing resistance and endurance training. Furthermore, the volume and/or intensity of the endurance training does not appear to influence the magnitude of this improvement because similar gains were observed for the RT + CT and RT + HIIT groups.

Our findings did not support our hypothesis. We hypothesized that high-volume CT would have a blunting effect on strength gains compared to the effect of low-volume HIIT. This hypothesis was informed by a meta-analysis by Wilson and colleagues that demonstrated a negative relationship between endurance training volume and gains in muscle hypertrophy, strength, and power (Wilson et al., 2012). The weekly length of the endurance training sessions in the RT + CT group was ~3 hr, on average. This is a relatively high volume compared with that used in other concurrent training studies (Fyfe et al., 2016; Hakkinen et al., 2003; Kuusmaa et al., 2016; Lundberg et al., 2013; Shaw et al., 2009; Tsitkanou et al., 2016), and indicates that individuals with a long history of RT can improve strength even when high-volume endurance training is combined with RT.

It is important to point out that a variety of concurrent training protocols have been tested in the literature. Endurance and RT can be performed on different days or on the same day, in different training sessions or within the same training session. Also, RT can be performed before or after endurance training. In the present study, RT was followed by endurance training within the same training session. This exercise sequence could in part explain why a relatively large strength improvement was observed in both the RT + CT and RT + HIIT groups. Most studies showing negative effects on strength have used the opposite exercise sequence, i.e., endurance training before RT (Bell et al., 1988; Bell et al., 2000; Dudley and Djamil, 1985; Fyfe et al., 2016; Hickson, 1980; Kraemer et al., 1995; Sale et al., 1990), and it has been suggested that performing endurance training before RT might interfere with force production and reduce the amount of load that can be lifted during RT (Bruce W. Craig, 1991; Leveritt et al., 1999). A recent study confirmed this 'acute fatigue hypothesis' by showing that strength performance is negatively affected by previous endurance exercise (Ratamess et al., 2016). Therefore, the recommendation that followed was that the intra-session exercise sequence should consist of RT followed by endurance training.

The results of the present study show that athletes can combine RT with different modes of endurance training and still show substantial progression in lower body strength. However, this observation does not seem to apply to power, because we did not observe any improvement in CMJ performance in the RT + CT or RT + HIIT group. Heavy-load squat training alone is associated with increased CMJ performance (Hartmann et al., 2012; Helgerud et al., 2011), and our results therefore suggest that power gains were compromised when endurance training was added to the RT program. This finding is consistent with those of previous studies on less-trained individuals (Chtara et al., 2008; Fyfe et al., 2016). However, it should be pointed out that the RT program used in the present study was performed to failure or close to failure. This is an effective program for improving strength and to some degree power (Davies et al., 2016; Hartmann et al., 2012; Helgerud et al., 2011; Hoffman et al., 2009). However, "non-failure" protocols have been shown to be more efficient for power improvements (Pareja-Blanco et al., 2017) and it can therefore not be ruled out that the absence of CMJ performance increments was a consequence of how the RT program was designed.

Aerobic power ($VO_{2\ max}$) only improved in the RT + HIIT group, even though the average time spent on the HIIT cycling sessions was substantially lower than the time spent on the CT sessions (12 vs. 60 min). This finding confirms the results of previous studies showing that recreationally active individuals obtain similar or larger improvements in $VO_{2\ max}$ and muscle oxidative capacity after low-volume HIIT than after high-volume CT (Burgomaster et al., 2008; Tabata et al., 1996). HIIT therefore also seems to be a more efficient training strategy for highly-trained individuals.

The present study was a relatively short training intervention (only 6 weeks), and it is possible that a longer training period is needed to observe differences between the RT + CT and RT + HIIT groups. For example, in the classic study by Hickson and colleagues, there was no negative effect of endurance training on strength gains during the first five weeks of concurrent training, but a large negative effect was found from weeks six to ten (Hickson, 1980). In particular, experienced athletes may be able to continue to improve their strength during short periods of concurrent training due to their high level of stress tolerance. However, in the long term even this group might be negatively affected by the opposing mechanisms of adaptation and/or difficulties in fatigue management (Coffey and Hawley, 2017). Another limitation of the present study was that it did not include a control group that performed only strength training. It is therefore possible that both the RT + CT and RT + HIIT protocols would have blunted strength gains compared to a resistance-only protocol. However, any potential blunting effect was probably small considering that the 1RM squat improvements in the present study (12–14%) are comparable to the improvements observed in other studies of highly-trained individuals performing RT alone. For example, experienced resistance-trained American football players demonstrated a 10–14% increase in 1RM parallel squats after a seven-week training period (Hoffman et al., 2009), and power lifters increased their 1RM parallel squats by 8–11% after a six-week supervised training period (Zourdos et al., 2016).

Conclusion

In conclusion, the present findings suggest that individuals with a long history of RT can improve their lower body maximal strength after a short period of concurrent resistance and endurance training and that the type of endurance training does not seem to influence this improvement. However, since HIIT is very time efficient, and VO_2max improved only in the RT + HIIT group, we recommend that HIIT be incorporated when concurrently training for strength and endurance.

Acknowledgements

We thank all the participants for their time and effort. No conflicts of interest, financial or otherwise, are declared by the authors. The experiments comply with the current laws of the country in which they were performed.

References

Baker, D.G. and Newton, R.U. (2008) Comparison of lower body strength, power, acceleration, speed, agility, and sprint momentum to describe and compare playing rank among professional rugby league players. *Journal of Strength and Conditioning Research* **22,** 153-158.

Bell, G.J., Petersen, S.R., Quinney, H.A. and Wenger, H.A. (1988) Sequencing of endurance and high-velocity strength training. *Canadian Journal of Sport Sciences* **13,** 214-219.

Bell, G.J., Syrotuik, D., Martin, T.P., Burnham, R. and Quinney, H.A. (2000) Effect of concurrent strength and endurance training on skeletal muscle properties and hormone concentrations in humans. *European Journal of Applied Physiology* **81,** 418-427.

Bentley, D.J., Smith, P.A., Davie, A.J. and Zhou, S. (2000) Muscle activation of the knee extensors following high intensity endurance exercise in cyclists. *European Journal of Applied Physiology* **81,** 297-302.

Bruce W. Craig, J.L., Robert Pohlman and Herbert Stelling. (1991) The effect of running, weightlifting and a combination of both on growth hormone release. *Journal of Applied Sport Science Research* **5,** 198-203.

Burgomaster, K.A., Howarth, K.R., Phillips, S.M., Rakobowchuk, M., Macdonald, M.J., McGee, S.L. and Gibala, M.J. (2008) Similar metabolic adaptations during exercise after low volume sprint interval and traditional endurance training in humans. *Journal of Physiol* **586,** 151-60.

Cheng, B., Kuipers, H., Snyder, A.C., Keizer, H.A., Jeukendrup, A. and Hesselink, M. (1992) A new approach for the determination of ventilatory and lactate thresholds. *International Journal of Sports Medicine* **13,** 518-522.

Chtara, M., Chaouachi, A., Levin, G.T., Chaouachi, M., Chamari, K., Amri, M. and Laursen, P.B. (2008) Effect of concurrent endurance and circuit resistance training sequence on muscular strength and power development. *Journal of Strength and Conditioning Research* **22,** 1037-1045.

Coffey, V.G. and Hawley, J.A. (2017) Concurrent exercise training: do opposites distract? *Journal of Physiol* **595,** 2883-2896.

Davies, T., Orr, R., Halaki, M. and Hackett, D. (2016) Effect of Training Leading to Repetition Failure on Muscular Strength: A Systematic Review and Meta-Analysis. *Sports Medicine* **46,** 487-502.

de Souza, E.O., Tricoli, V., Franchini, E., Paulo, A.C., Regazzini, M. and Ugrinowitsch, C. (2007) Acute effect of two aerobic exercise modes on maximum strength and strength endurance. *Journal of Strength and Conditioning Research* **21,** 1286-1290.

Dudley, G.A. and Djamil, R. (1985) Incompatibility of endurance- and strength-training modes of exercise. *Journal of Applied Physiology (1985)* **59,** 1446-1451.

Durnin, J.V. and Womersley, J. (1974) Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years.

British Journal of Nutrition **32,** 77-97.
Foss, O. and Hallen, J. (2005) Validity and stability of a computerized metabolic system with mixing chamber. *International Journal of Sports Medicine* **26,** 569-575.
Francois, M.E. and Little, J.P. (2015) Effectiveness and safety of high-intensity interval training in patients with type 2 diabetes. *Diabetes Spectrum* **28,** 39-44.
Fyfe, J.J., Bartlett, J.D., Hanson, E.D., Stepto, N.K. and Bishop, D.J. (2016) Endurance Training Intensity Does Not Mediate Interference to Maximal Lower-Body Strength Gain during Short-Term Concurrent Training. *Frontiers in Physiology* **7,** 487.
Gibala, M.J., Little, J.P., van Essen, M., Wilkin, G.P., Burgomaster, K.A., Safdar, A., Raha, S. and Tarnopolsky, M.A. (2006) Short-term sprint interval versus traditional endurance training: similar initial adaptations in human skeletal muscle and exercise performance. *Journal of Physiol* **575,** 901-911.
Glatthorn, J.F., Gouge, S., Nussbaumer, S., Stauffacher, S., Impellizzeri, F.M. and Maffiuletti, N.A. (2011) Validity and reliability of Optojump photoelectric cells for estimating vertical jump height. *Journal of Strength and Conditioning Research* **25,** 556-560.
Haff, G. and Triplett, N.T. (2016) *Essentials of strength training and conditioning.* Fourth edition. Champaign, IL: Human Kinetics. 254-257.
Hakkinen, K., Alen, M., Kraemer, W.J., Gorostiaga, E., Izquierdo, M., Rusko, H., Mikkola, J., Hakkinen, A., Valkeinen, H., Kaarakainen, E., Romu, S., Erola, V., Ahtiainen, J. and Paavolainen, L. (2003) Neuromuscular adaptations during concurrent strength and endurance training versus strength training. *European Journal of Applied Physiology* **89,** 42-52.
Hartmann, H., Wirth, K., Klusemann, M., Dalic, J., Matuschek, C. and Schmidtbleicher, D. (2012) Influence of squatting depth on jumping performance. *Journal of Strength and Conditioning Research* **26,** 3243-3261.
Helgerud, J., Rodas, G., Kemi, O.J. and Hoff, J. (2011) Strength and endurance in elite football players. *International Journal of Sports Medicine* **32,** 677-682.
Hickson, R.C. (1980) Interference of strength development by simultaneously training for strength and endurance. *European Journal of Applied Physiology and Occupational Physiology* **45,** 255-263.
Hoffman, J.R., Ratamess, N.A., Klatt, M., Faigenbaum, A.D., Ross, R.E., Tranchina, N.M., McCurley, R.C., Kang, J. and Kraemer, W.J. (2009) Comparison between different off-season resistance training programs in Division III American college football players. *Journal of Strength and Conditioning Research* **23,** 11-19.
Jones, T.W., Howatson, G., Russell, M. and French, D.N. (2013) Performance and neuromuscular adaptations following differing ratios of concurrent strength and endurance training. *Journal of Strength and Conditioning Research* **27,** 3342-3351.
Kraemer, W.J., Patton, J.F., Gordon, S.E., Harman, E.A., Deschenes, M.R., Reynolds, K., Newton, R.U., Triplett, N.T. and Dziados, J.E. (1995) Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. *Journal of Applied Physiology (1985)* **78,** 976-989.
Kuusmaa, M., Schumann, M., Sedliak, M., Kraemer, W.J., Newton, R.U., Malinen, J.P., Nyman, K., Hakkinen, A. and Hakkinen, K. (2016) Effects of morning versus evening combined strength and endurance training on physical performance, muscle hypertrophy, and serum hormone concentrations. *Applied Physiology, Nutrition, and Metabolism* **41,** 1285-1294.
Leveritt, M., Abernethy, P.J., Barry, B.K. and Logan, P.A. (1999) Concurrent strength and endurance training. A review. *Sports Medicine* **28,** 413-427.
Lundberg, T.R., Fernandez-Gonzalo, R., Gustafsson, T. and Tesch, P.A. (2013) Aerobic exercise does not compromise muscle hypertrophy response to short-term resistance training. *Journal of Applied Physiology (1985)* **114,** 81-89.
Mikkola, J., Rusko, H., Izquierdo, M., Gorostiaga, E.M. and Hakkinen, K. (2012) Neuromuscular and cardiovascular adaptations during concurrent strength and endurance training in untrained men. *International Journal of Sports Medicine* **33,** 702-710.
Milanovic, Z., Sporis, G. and Weston, M. (2015) Effectiveness of High-Intensity Interval Training (HIT) and Continuous Endurance Training for VO2max Improvements: A Systematic Review and Meta-Analysis of Controlled Trials. *Sports Medicine* **45,** 1469-1481.
Murlasits, Z., Kneffel, Z. and Thalib, L. (2018) The physiological effects of concurrent strength and endurance training sequence: A systematic review and meta-analysis. *Journal of Sports Sciences* **36(11),** 1212-1219.
Pareja-Blanco, F., Rodriguez-Rosell, D., Sanchez-Medina, L., Sanchis-Moysi, J., Dorado, C., Mora-Custodio, R., Yanez-Garcia, J.M., Morales-Alamo, D., Perez-Suarez, I., Calbet, J.A.L. and Gonzalez-Badillo, J.J. (2017) Effects of velocity loss during resistance training on athletic performance, strength gains and muscle adaptations. *Scandinavian Journal of Medicine & Science in Sports* **27,** 724-735.
Ratamess, N.A., Kang, J., Porfido, T.M., Ismaili, C.P., Selamie, S.N., Williams, B.D., Kuper, J.D., Bush, J.A. and Faigenbaum, A.D. (2016) Acute Resistance Exercise Performance Is Negatively Impacted by Prior Aerobic Endurance Exercise. *J Strength Cond Res* **30,** 2667-2681.
Rhea, M.R. (2004) Determining the magnitude of treatment effects in strength training research through the use of the effect size. *Journal of Strength and Conditioning Research* **18,** 918-920.
Sale, D.G., Jacobs, I., MacDougall, J.D. and Garner, S. (1990) Comparison of two regimens of concurrent strength and endurance training. *Medicine and Science in Sports and Exercise* **22,** 348-356.
Shaw, B.S., Shaw, I. and Brown, G.A. (2009) Comparison of resistance and concurrent resistance and endurance training regimes in the development of strength. *Journal of Strength and Conditioning Research* **23,** 2507-2514.
Smith, D.J. (2003) A framework for understanding the training process leading to elite performance. *Sports Medicine* **33,** 1103-1126.
Tabata, I., Nishimura, K., Kouzaki, M., Hirai, Y., Ogita, F., Miyachi, M. and Yamamoto, K. (1996) Effects of moderate-intensity endurance and high-intensity intermittent training on anaerobic capacity and VO_2max. *Medicine and Science in Sports and Exercise* **28,** 1327-1330.
Tsitkanou, S., Spengos, K., Stasinaki, A.N., Zaras, N., Bogdanis, G., Papadimas, G. and Terzis, G. (2016) Effects of high-intensity interval cycling performed after resistance training on muscle strength and hypertrophy. *Scandinavian Journal of Medicine & Science in Sports* **27,** 1317-1327.
Wilson, J.M., Marin, P.J., Rhea, M.R., Wilson, S.M., Loenneke, J.P. and Anderson, J.C. (2012) Concurrent training: a meta-analysis examining interference of aerobic and resistance exercises. *Journal of Strength and Conditioning Research* **26,** 2293-2307.
Zourdos, M.C., Jo, E., Khamoui, A.V., Lee, S.R., Park, B.S., Ormsbee, M.J., Panton, L.B., Contreras, R.J. and Kim, J.S. (2016) Modified Daily Undulating Periodization Model Produces Greater Performance Than a Traditional Configuration in Powerlifters. *Journal of Strength and Conditioning Research* **30,** 784-791.

Key points

- Lower body maximal strength is improved after concurrent strength and endurance training in highly trained individuals.
- The magnitude of this strength improvement is not influenced by the type of endurance training, i.e. HIIT or CT.
- HIIT improves VO_{2max} and is more time efficient than CT.
- HIIT is recommended to athletes when concurrently training for strength and endurance.

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