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Human Kinetics
ORIGINAL INVESTIGATION

The Effects of Sport-Specific Maximal Strength and Conditioning Training on Critical Velocity, Anaerobic Running Distance, and 5-km Race Performance

Bettina Karsten, Liesbeth Stevens, Mark Colpus, Eneko Larumbe-Zabala, and Fernando Naclerio

Purpose: To investigate the effects of a sport-specific maximal 6-wk strength and conditioning program on critical velocity (CV), anaerobic running distance (ARD), and 5-km time-trial performance (TT). ***Methods:*** 16 moderately trained recreational endurance runners were tested for CV, ARD, and TT performances on 3 separate occasions (baseline, midstudy, and poststudy). ***Design:*** Participants were randomly allocated into a strength and conditioning group (S&C; n = 8) and a comparison endurance-training-only group (EO; n = 8). During the first phase of the study (6 wk), the S&C group performed concurrent maximal strength and endurance training, while the EO group performed endurance-only training. After the retest of all variables (midstudy), both groups subsequently, during phase 2, performed another 6 wk of endurance-only training that was followed by poststudy tests. ***Results:*** No significant change for CV was identified in either group. The S&C group demonstrated a significant decrease for ARD values after phases 1 and 2 of the study. TT performances were significantly different in the S&C group after the intervention, with a performance improvement of 3.62%. This performance increase returned close to baseline after the 6-wk endurance-only training. ***Conclusion:*** Combining a 6-wk resistance-training program with endurance training significantly improves 5-km TT performance. Removing strength training results in some loss of those performance improvements.

Keywords: time–distance relationship, exercise testing, endurance capacity, resistance exercises

Exercises that enhance endurance capacities are imperative in improving competitive running performance. Besides neurological and morphological changes,[1,2] anaerobic factors may play an important role in the success of endurance events.[3] A proper integration of a periodized resistance-training (RT) and endurance-training program can cause such positive adaptations,[4] for example, changes in motor-unit recruitment patterns, force-development rates, anaerobic enzyme activity, stretch-shortening cycle, and a shift between specific fiber groups.[1,2,5] In running, the combination of these changes can provide an athlete with enhanced tactical advantages, such as in attacks or final sprints, while potentially also affecting indices of aerobic capacity. The effects of concurrent endurance and strength and conditioning (S&C) training have been shown to be an effective strategy to increase endurance performance (ie, Ferrauti et al[6]). Note that to target optimal training adaptions, Jones and Bampouras[7] recommended using sport-specific resistance training.

Another critical determinant in endurance-running performance is the highest sustainable velocity.[8] The fastest sustainable performance intensity can be described through the power-duration relationship of the critical power (CP) concept. CP reflects a rate of aerobic energy reconstitution that dictates the maximal sustainable power without a progressive loss in metabolic steady state. In running the analogous term *critical velocity* (CV) is traditionally used, which, once exceeded (ie, under nonmetabolic steady-state conditions), results in the use of anaerobic running distance (ARD). The depletion rate of ARD is proportional to the magnitude of velocity requirement and reflects at exhaustion the accumulation of fatigue-related metabolites to a tolerable critical limit. ARD therefore reflects the maximal distance that can be performed above CV; it has, however, been subject to controversy as regards its exact nature and its reliability.[9–11] CV demarcates the boundary between heavy and severe exercise intensity and has been considered a reference marker of endurance performance.[12] Marathon times, for example, correlate with CV. However, CV generally overpredicts a mean marathon velocity, as performance intensities are located in the heavy domain—below the lactate turn point—with CV being located slightly above this marker. Indeed, a stronger correlation between 10-km race performance and CV intensity has been reported.[13]

To date, 2 cycling studies have investigated the effects of a strength-training intervention on CP and the anaerobic work capacity (W′—the analogue of ARD). Bishop and Jenkins[14] used untrained participants who underwent a 6-week RT intervention. They reported a significant increase in W′ with no change in time to exhaustion (TTE) at CP and consequently proposed RT not to alter indices of endurance ability. Similar findings were described by Sawyer et al[8] with recreational athletes who, after an 8-week strength-training intervention, showed significant improvement of W′ with no alteration of CP. In addition, TTE performed at predetermined intensities, which are required to determine CP, were increased but did not affect CP values. While improving exercise tolerance, the researchers concluded that CP is unsuitable to track changes in endurance capacity that are elicited by strength training, while W′ may present a better indicator of such changes. On the contrary, other authors have identified CP/CV to be a valid and reliable marker of endurance capacity,[15,16] which further necessitates the current study.

While research has demonstrated the beneficial effects of S&C on endurance performance, no such evidence to date has been

Karsten, Stevens, Colpus, and Naclerio are with the Centre for Sports Science and Human Performance, University of Greenwich, Kent, UK. Larumbe-Zabala is with the Clinical Research Inst, Texas Tech University Health Science Center, Lubbock, TX. Address author correspondence to Bettina Karsten at B.Karsten@greenwich.ac.uk.

provided for the distance–time relationship of CV and ARD. The purpose of this study was therefore to investigate the effects of an integrated S&C program and regular endurance training in runners on CV, ARD, and 5-km TT performance. As a second objective, we aimed to analyze the effects of removing the S&C training while maintaining the endurance training on CV, ARD, and 5-km TT performance. Based on the findings of previous investigations, we hypothesized that the addition of an S&C program would result in significant changes of all measured variables. Furthermore, we hypothesized that by removing the S&C treatment, results would demonstrate a progressive loss of possible effects on all measured variables.

Methodology

Experimental Approach to the Problem

Participants. Sixteen recreational endurance runners and triathletes with a minimum of 2 years of regular training and with a frequency of 3 to 5 training sessions and a training volume of 180 to 300 min/wk were randomly allocated to the experimental S&C group (n = 8, 5 male and 3 female, 39 ± 5.1 y, height 176.6 ± 8.3 cm, body mass 73.6 ± 10.6 kg, $\dot{V}O_{2max}$ 47.3 ± 4.8 mL · min^{-1} · kg^{-1}) and to an endurance-training-only group (EO; n = 8, 6 male and 2 female, 30 ± 7.7 y, height 174.9 ± 6.3 cm, body mass 68.7 ± 9.2 kg, $\dot{V}O_{2max}$ 47.0 ± 7.4 mL · min^{-1} · kg^{-1}).

Participants agreed to refrain from intense exercise and alcohol consumption on the day preceding any tests and not to consume a major meal or caffeine 3 hours before testing. In addition they were not allowed to perform any other exercises than those required in the current investigation.

All participants were notified about the study procedures, protocols, benefits, and risks. A health-history questionnaire was used to ensure that they were healthy and free of any musculoskeletal injury or cardiovascular disease. The study was carried out in accordance with the guidelines contained in the Declaration of Helsinki and was approved by the institutional review board for human subjects at the university.

Design. This study used a 2-parallel-groups randomized controlled design, where 2 between-participants conditions, S&C and EO, were tested. Participants attended the laboratory for 2 pretraining test sessions, where maximal oxygen uptake ($\dot{V}O_{2max}$) and CV/ARD were tested. Thereafter, they performed a 5-km TT on an outdoor track for which running time was recorded. Before the start of the study all participants performed only low-intensity aerobic training (ie, 70–85% HR_{max}) and were instructed to maintain a similar training throughout the experimental period**.** Participants included in the S&C group started a 12-week experimental period that was divided into 2 phases. Phase 1 involved a 6-week maximal S&C intervention (12 sessions) while the EO group did not perform any type of RT and continued with their normal endurance training. In phase 2, both groups only performed their regular endurance training. CV, ARD, and 5-km TT performance were retested after phase 1 (wk 8) and phase 2 (wk 15). Before the start of the S&C program, participants of the S&C group were familiarized with the S&C exercises and the procedures of 1-repetition-maximum (1-RM) testing. Figure 1 depicts the general structure of study.

Measurements

$\dot{V}O_{2max}$ test. Before testing, resting heart rate (HR) and a blood sample from the fingertip were obtained. Samples were analyzed for blood [lactate] using a Biosen C-line analyzer (EKF Diagnostics,

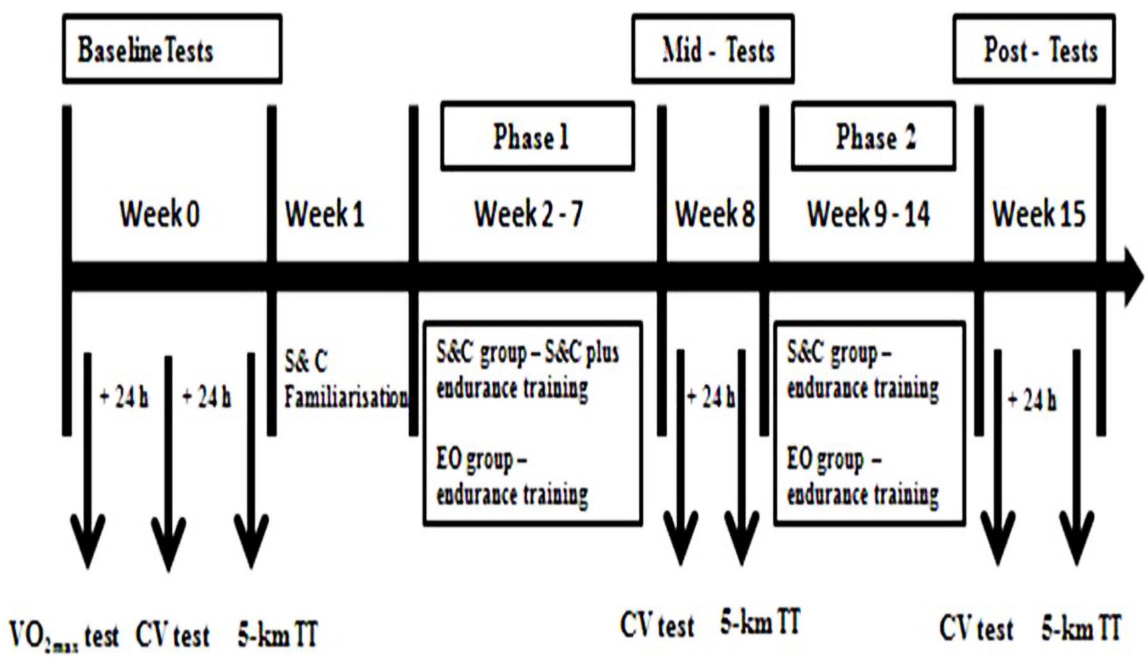

Figure 1 — Testing timeline: testing period at baseline, after phase 1, and after phase 2. Abbreviations: S&C, experimental group (performing strength and conditioning + endurance training from wk 1 to 7 and endurance training only from wk 9 to 14); EO, endurance-only group (endurance training from wk 1 to 14); $\dot{V}O_{2max}$, maximal oxygen uptake; CV, critical velocity; TT, time trial.

Barleben, Germany). The incremental treadmill test (Woodway, Weil am Rhein, Germany) commenced at an initial speed of 3 km/h (1% slope). After 3 minutes, the speed was increased by 1 km/h every minute until participants reached volitional exhaustion. Immediately posttest, another blood sample was obtained and analyzed. Throughout the test, gas was sampled continuously and analyzed using a Metalyzer 3B gas analyzer (Cortex, Magdeburg, Germany). $\dot{V}O_{2max}$ and corresponding velocity ($v\dot{V}O_{2max}$) were calculated using the highest 30-second average values over the last minute of the exercise.

CV Test. Participants had to run at 90%, 100%, and 105% of individual $v\dot{V}O_{2max}$ values, using a 30-minute recovery between trials.[11] After a 5-minute warm-up period at 6 km/h, the speed was rapidly increased to individual 90%, 100%, or 105% $v\dot{V}O_{2max}$ values. Subjects were strongly verbally encouraged throughout each test, and TTE was recorded to the nearest second. They performed a 5-minute cooldown at a self-chosen pace before passively resting for another 25 minutes. Resting HR and fingertip capillary blood samples were obtained before and after each TTE run. Fluid intake was permitted ad libitum. During each TTE trial, participants were cooled using an electric fan. Laboratory conditions were stable in a range of 18°C to 22°C with 45% to 55% humidity. All athletes reached their individual $\dot{V}O_{2max}$ value (± 1.25 mL · min^{-1} · kg^{-1}), a posttest blood (lactate) of ≥8 mmol/L, and an HR within ±5 beats of their maximal HR values established during the $\dot{V}O_{2max}$ test. Linear regression was used to determine CV and ARD (r^2 = .99–1.0, SE range CV = 0.1–0.5 km/h) using the distance–time relationship (d = CV × t) + ARD, where d = distance run and t = total running time.

5-km TT. Testing was only carried out when wind speeds did not exceed 2 m/s (see Jones and Doust[17]) and under dry conditions. To minimize biological variation,[18] participants were tested at the same time of the day (± 2 h). After a 10-minute warm-up at a self-chosen pace, a 5-km run on a 400-m outdoor running track was performed. Participants were instructed to perform their best effort during each 5-km TT. Finishing times were recorded to the nearest second.

S&C Training

During phase 1, the S&C group performed a 6-week RT program involving 4 lower-body resistance exercises: Romanian deadlift, parallel squat, calf raises, and lunges. The program was performed twice a week on nonconsecutive days (12 sessions in total). To determine the training load of each of the selected exercise, participants included in S&C group performed a maximal strength test (1-RM) for all the 4 selected exercises. The 1-RM value was determined according to the methodology proposed by Baechle et al.[19] Each S&C workout included 4 sets of 4 repetitions at 80% 1-RM with 2-minute rests between sets for each exercise. Participants were instructed to perform the exercises as fast as possible using a proper technique.

Statistical Analysis

A descriptive analysis was performed, and subsequently the Kolmogorov-Smirnov and Shapiro-Wilk tests were applied to assess normality. A 2 × 3 (group × time) mixed-ANOVA model was used to assess training effects (control vs intervention) along with 3 repeated measures (pre vs post vs detraining). A 2 × 3 (group × time) mixed-ANOVA model was used to test for significant differences in CV, ARD, and 5- km TT performance between the 2 groups, along with 3 repeated measures (baseline, mid, and post). Bonferroni-corrected post hoc analyses were performed. Generalized eta-squared (η^2_G) and Cohen d values were reported to provide an estimate of standardized effect size (small d = 0.2, η^2_G = 0.01; moderate d = 0.5, η^2_G = 0.06; and large d = 0.8, η^2_G = 0.14). The significance level was set at P < .05. Results are reported as mean ± SD unless stated otherwise.

Results

All data were normally distributed. Table 1 shows the values measured for CV, ARD, and TT for the 2 treatment groups.

CV showed no significant main effect of time ($F_{2,28}$ = 2.14, P = .137, η^2_G = 0.003), treatment intervention ($F_{1,14}$ = 0.55, P = .47, η^2_G = 0.04), or interaction between time and intervention ($F_{2,28}$ = 2.22, P = .127, η^2_G = 0.003). Pairwise comparisons indicated no significant change in CV across the 3 testing periods for the 2 treatment conditions; see Figure 2. However, when comparing baseline values with those after phases 1 and 2, S&C showed medium effect sizes (d = 0.5) and EO showed small effect sizes (<0.2).

A statistically significant main effect of time was found ($F_{2,28}$ = 10.28, P < .001, η^2_G = 0.05) for ARD values. In addition, no group ($F_{1,14}$ = 2.46, P = .139, η^2_G = 0.14) or interaction ($F_{2,28}$ = 1.2, P = .315, η^2_G = 0.01) resulted in statistically significant effects. However, pairwise comparisons revealed significant decreases in ARD, only for the S&C group, from baseline to posttest (t_{14} =3.37, P = .014, d = 0.84) and from midtest to posttest (t_{14} = 3.28, P = .017, d = 0.82); see Figure 3.

No significant main effect per time ($F_{2,28}$ = 1.76, P = .191, η^2_G = 0.002) or treatment group ($F_{1,14}$ = 0.01, P = .931, η^2_G = 0.001) was observed for 5-km TT. However, significant interaction was determined per time and treatment intervention ($F_{2,28}$ = 4.18, P = .026, η^2_G = 0.005). Pairwise comparisons for the S&C group revealed a significant decrease in 5-km TT from baseline to midtest (t_{14} = 4.25, P = .002, d = 1.06), followed by a significant increase from

Table 1 Baseline, Phase 1, and Phase 2 Values for Critical Velocity, Anaerobic Running Distance (ARD), and Time Trial for the Experimental (S&C, n = 8) and Control (EO, n = 8) Groups

	Baseline		Phase 1		Phase 2	
	S&C	EO	S&C	EO	S&C	EO
Critical velocity (km/h)	13.8 ± 2.1	14.7 ± 1.8	14.2 ± 1.7	14.7 ± 1.9	14.2 ± 1.7	14.8 ± 1.8
ARD (m)	117.2 ± 41.1	147.3 ± 44.6	110.5 ± 50.3	138.9 ± 42.7	88.0 ± 46.3	130.9 ± 42.9
Time trial (s)	1288.3 ± 183.4	1264.4 ± 203.7	1242.9 ± 187.0	1270.3 ± 221.8	1285.1 ± 181.5	1255.8 ± 200.3

Abbreviations: S&C, strength and conditioning; EO, endurance training only.

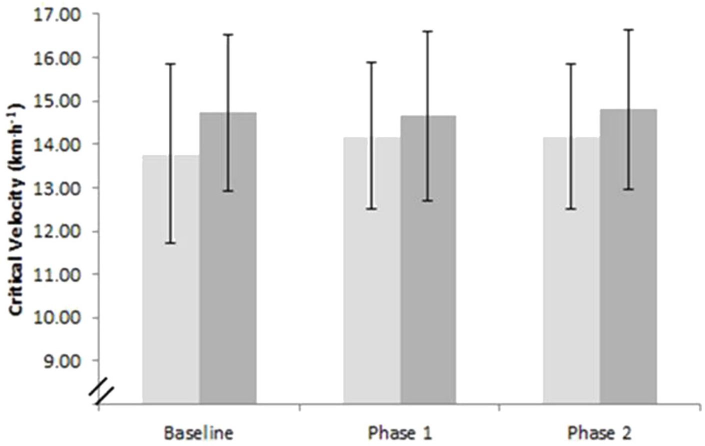

Figure 2 — Values of critical velocity at baseline, after phase 1 (7 wk), and after phase 2 (14 wk) for the strength and conditioning (light gray) and the endurance-training-only (dark gray) group. After phase 1, critical velocity increased by 2.98% and 0.14% in the strength and conditioning group while the endurance-training-only group showed a 0.48% decrease and a 0.54% increase after phases 1 and 2, respectively. **P* < .05.

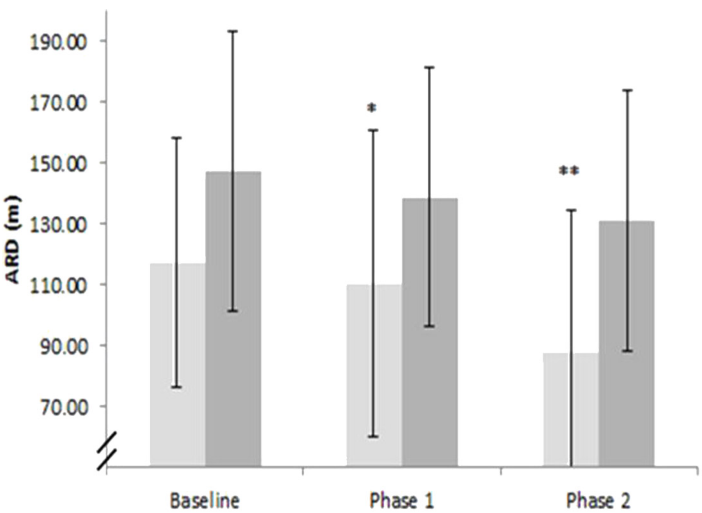

Figure 3 — Values of anaerobic running distance (ARD) at baseline, after phase 1 (7 wk), and after phase 2 (14 wk) for the strength and conditioning (light gray) and the endurance-training-only (dark gray) group. *Significant difference between ARD values for phase 1 and baseline for the strength and conditioning group (*P* < .05). **Significant difference for ARD values between phase 2 and baseline for the strength and conditioning group (*P* < .05).

midtest to posttest ($t_{14} = -2.74$, $P = .048$, $d = 0.68$); see Figure 4. In contrast, the EO group showed no statistically significant changes.

Discussion

The main findings of the study were that a 6-week running-specific S&C training program resulted in increased 5-km TT performance, alongside a decrease in ARD values with nonsignificant changes of CV. However, when CV is expressed as a percentage, a meaningful

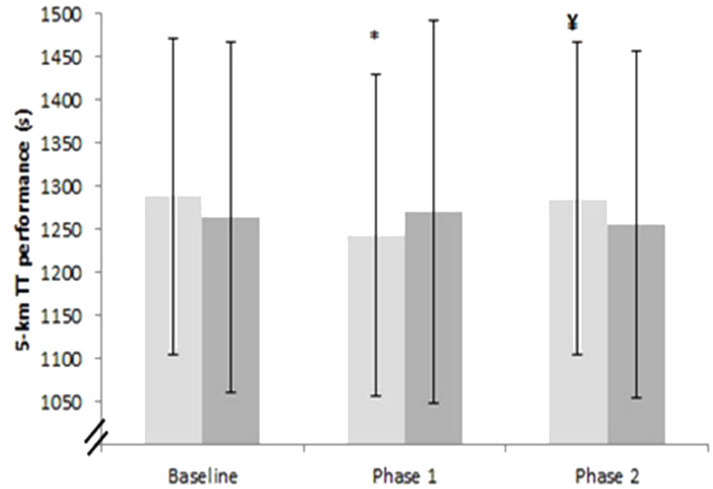

Figure 4 — Illustration of the 5-km (s) time trial (TT) performance at baseline and after phase 1 and phase 2 for the strength and conditioning (light gray) and the endurance-training-only (dark gray) group. *Significantly different from baseline. ¥Significantly different from 7-week testing values.

increase of 2.98% after phase 1 was identified.[20] As a consequence, 5-km TT performance would theoretically decrease by a mean of 38 seconds. However, the 5-km TTs performed by our participants demonstrate a larger mean performance improvement of 45 ± 24 seconds (*P* < .05). These findings are supported by those of Paavolainen et al,[22] who demonstrated significant 5-km TT performance changes when employing an explosive strength-training program in endurance-trained athletes. Such positive effects of an integrated S&C training on endurance performance have also been reported by others (ie, Mikkola et al[23] and Taipale et al[24]). Mikkola et al[23] moreover recommended heavy RT to be most effective when enhancing maximal running speed and performance. In their works, Saunders et al[25] highlighted strength-training properties that can cause an enhanced muscular ability to use more elastic energy, causing a reduction in energy wasted in braking force. Furthermore, to improve endurance performance in well-trained athletes, Aargard and Anderson[26] recommended the integration of heavy RT concurrently with endurance training. They demonstrated these effects by use of a 16-week concurrent strength- and endurance-training program in elite cyclists. Endurance capacity was enhanced by a significant 8%. Our results are furthermore supported by several other studies that also found positive effects of combined strength and endurance training on performance.[21,27,28] Rønnestad et al,[28] for example, highlighted the importance of strength-training integration and maintenance in well-trained endurance cyclists throughout the season. However, even though both groups continued with their regular endurance training, factors other than the implementation of the S&C training may have contributed to the increase in performance in the current study.

Different from our findings, Barnes et al[29] advised male athletes to include any heavy RT during the competitive season, as their results demonstrated a 0.5% 5-km TT performance decrease after a 9-week intervention. Ferrauti et al,[6] despite an increase in leg strength, demonstrated no aerobic performance improvement when applying combined strength and endurance training over 8 weeks. Recently, Sawyer et al[8] demonstrated a nonsignificant change in CP in untrained subjects after an 8-week strength-training intervention, despite an increased exercise tolerance for all TTE trials. Similarly, Bishop and Jenkins[14] demonstrated no changes in CP and significantly enhanced values of W′ after a 6-week RT intervention. The difference in findings might be due to the choice of participants, as both aforementioned studies used less-trained or untrained participants. Moreover, Sawyer et al[8] applied a hypertrophy-oriented RT program involving 3 sets at 8-RM for 7 exercises (both lower and upper body) and 3 sets at 12-RM for 1 other exercise (heel raises), while in our study maximal-strength RT was performed.[19] As identified by Mikkola et al,[23] Taipale et al,[24] and Hickson et al,[30] an RT program focused on maximal strength development appears to be most effective in enhancing indices of aerobic performance.

Rønnestad et al[28] demonstrated attenuated performance-enhancing effects when reducing twice-weekly to once-weekly heavy resistance training during the change from preparatory to competitive season. At present our study is novel, as it also investigates resulting effects when terminating the S&C program while continuing with an EO program. Performance times for the 5-km TT within 6 weeks returned to preintervention values in the S&C group with no changes in the EO group. In short, the applied S&C program caused significant performance improvements (mean difference of –45 s, P = .001; Figure 3), while when terminated it resulted in a significant performance reduction toward baseline levels (mean difference + 42 s, P = .04; Figure 4).

The current study identified significant changes for ARD values between baseline and phase 1 and between baseline and phase 2 values for the S&C but not the EO group (Figure 3). These findings are inconsistent with those of Bishop and Jenkins[14] and Sawyers et al,[8] as both of those studies resulted in a significant improvement in W′. Reasons for the difference in findings are likely to be multifactorial (ie, duration of recovery time between exhaustive trials or reliability of ARD). Researchers such Vanhatalo et al[31] argue a more complex behavior of W′ when adapting to training. Their works suggest that enhanced values of CP result in a decrease in W′ but that the overall consequences of such changes are still beneficial to endurance performance. Dekerle et al[9] advised prudence when interpreting values of W′ and its changes over training. Both W′ and ARD have been demonstrated to be less reliable.[10,11] With an apparent disagreement in the literature about the true constitution and reliability of this parameter, we can only speculate about the exact cause in its decrease. Note, however, the continuous decrease of ARD values, while TT performance returned back to preintervention values after the termination of the S&C training. Whether reliable or valid, values of ARD decreased in the S&C group, demonstrating its independency with indices of aerobic performance.

Practical Application

The current study found a meaningful endurance-enhancing effect of a sport-specific S&C training intervention in recreational runners. Coaches and endurance athletes are therefore advised to integrate twice-weekly heavy-resistance S&C training for a minimum of 6 weeks when preparing for races. To avoid undesirable performance reduction, coaches are furthermore encouraged to maintain lower-volume RT thorough the competitive period. Limitations of the current study were that the volume of training was not equalized (perhaps adding another high-intensity endurance-training session would have produced different results) and the use of recreationally trained athletes who were exercising at a low to moderate intensity. Further research should clarify whether our results could be transferred to runners with different performance levels or with a more controlled and periodized training strategy.

Conclusion

A 6-week concurrent endurance and RT program using heavy load (80% 1-RM) resulted in a significant increase in 5-km TT performances. In addition, a nonsignificant but probably important improvement in the CV values was observed. Future studies are recommended that investigate the optimal duration and hence an optimal performance improvement of such sport-specific S&C training.

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