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Abstract

Purpose Heavy-resistance training and plyometric training offer distinct physiological and neuromuscular adaptations that could enhance running economy and consequently distance-running performance. To date no studies have examined the effect of combining the two modes of training on running economy or performance. **Methods** Fifty collegiate male and female cross-country runners performed a 5-km time-trial and a series of laboratory-based tests to determine aerobic, anthropometric, biomechanical and neuromuscular characteristics. Thereafter, each athlete participated in a season of 6-8 collegiate cross-country races over 13 weeks. After the first four weeks, athletes were randomly assigned to either heavy-resistance or plyometric plus heavy-resistance training. Five days after completing their final competition, runners repeated the same set of laboratory tests. We also estimated effects of the intervention on competition performance throughout the season using athletes of other teams as controls. **Results** Heavy-resistance training produced small-moderate improvements in peak speed, running economy and neuromuscular characteristics relative to plyometric resistance training, whereas changes in biomechanical measures favored plyometric resistance training. Males made less gains than females in most tests. Both treatments had possibly harmful effects on competition times in males (mean 0.5%; 90% confidence limits ±1.2%), but there may have been benefit for some individuals. Both treatments were likely beneficial for all females (-1.2%; ±1.3%), but heavy-resistance was possibly better than plyometric resistance training. **Conclusion** The changes in laboratory-based parameters related to distance-running performance were consistent with the changes in competition times for females but only partly for males. Our data indicate that females should include heavy-resistance training in their programs, but males should be cautious about using it in season until more research establishes whether certain males are positive or negative responders.

Key Words Running economy, resistance training, plyometric training, running performance, neuromuscular characteristics, mixed modeling

Introduction

Trained runners have superior running economy compared to lesser-trained or untrained runners (13,14,26,31,32,40), indicating positive adaptations in response to training programs. Recent research has shown running economy to improve in runners using traditional strength training or explosive, plyometric training (25,36,42). It is well documented that initial performance gains following traditional heavy resistance training are a result of predominantly neuromuscular rather than within muscle adaptations (i.e. hypertrophy) (28). These adaptations may include increases in strength, increased motor unit recruitment, improved mechanical efficiency and muscle coordination (28,29,39). A key component to running economy is the ability to store and recover elastic energy from the eccentric contraction (8). Plyometric training is a form of strength training that aims to enhance the ability of the muscles to generate power through the stretch shortening cycle by use of explosive activities such as jumping, hopping and bounding (48). Several studies have indicated improvement in running economy from concomitant plyometric and endurance training (36,43,48). Proposed explanations for the improvement include increased lower body muscle-tendon stiffness, degree of neural input to the muscle, enhanced muscle power development and elastic return, and improved motor unit synchronization (36,37,43). Conversely or in concert improvements from either form of resistance training may enhance running mechanics. Improved biomechanical efficiency and improved leg muscle co-activation and coordination may allow for a reduction in relative workload (18,25,29). The combination of improved running mechanics, neuromuscular efficiency, and strength may result in a decrease in oxygen consumption, thereby improving running economy and ultimately performance. Indeed the combination of heavy-resistance training and plyometric training may facilitate additional improvements in running economy via accumulation of adaptations previously observed when either type of training is performed alone.

There is a strong association between running economy and distance running performance (3,9,12,14). Accordingly, it is likely that any improvement in running economy as a result of training will be associated with improved distance running performance. A review of the literature, however, produced no studies examining the effects of a resistance-training intervention on running economy or performance during the competition phase of a running season, likely because coaches are often unwilling to do time trials or other performance tests that would interfere with preparations for actual competitions. Fittingly, Vandenbogaerde, Hopkins and Pyne (49) recently reported a novel design for investigating the effects of an intervention on competition performance, in which changes in performance between competitions before and after an intervention with a squad of athletes were compared with changes in performance in other squads over the same time frame. To enhance the ecological validity of the present study and as the primary purpose of the investigation, we adopted this research design in an attempt to compare the effects of heavy resistance training versus the combination of heavy resistance- and plyometric-training on performance during the competitive phase of a men's and women's collegiate cross-country running season.

Methods

Prior to the competitive season, an entire collegiate cross-country team performed a 5-km time trial and a series of laboratory tests including an incremental treadmill test to determine aerobic and biomechanical characteristics and a series of maximal jumps to determine muscle power characteristics. Thereafter, each athlete participated in a series of competitive collegiate cross-country races over a 13-week period (Figure 1). Approximately one-third of the way through the competitive season, each athlete was prescribed one of two resistance training programs; either Group 1: traditional heavy resistance training (HRT) or Group 2: plyometric and heavy resistance training (PRT). We then estimated the effects of the intervention on performance in a design equivalent to a parallel-groups controlled trial with athletes of other teams being the control group. Five days after completing the final competition of the season, each runner repeated the same set of laboratory tests. The study was approved by the Auckland University of Technology Ethics Committee; Auckland, New Zealand, and the Hope College Human Subjects Review Board; Holland, Michigan, USA. All participants provided informed written consent to participate.

Subjects. Fifty collegiate cross-country runners (men = 28, women = 22) participated in the study (Table 1). Subjects all competed at the Division 3 National Collegiate Athletics Association (NCAA) level with both teams being ranked nationally. Eight runners failed to complete the prescribed training program and were eliminated from the study. The main reasons were; inability to complete intervention or testing procedures (n = 3), dropout (n = 1) and injury (n = 4). The final sample size for analysis was 42 (Men: n = 23, HRT = 13, PRT = 10; Women: n = 19, HRT = 9, PRT = 10). All athletes trained and competed together 6 days·wk^{-1} under the guidance of the same coach and performed similar workouts to their teammates over the duration of the season. Training logs for all subjects were collected prior to and after the competitive season, and the primary author observed each training session and competition. During week 1 each subject completed a 5-km time trial on a flat 1250-m grass loop (Figure 1). All subjects were instructed to run the distance "as fast as possible" to get a baseline measure of fitness and prescribe subsequent training intensities under the guidance of their coach (Table 2). Gender and

5-km time was used to sequentially allocate subjects to either HRT or PRT (19). Participants had not previously undertaken any structured resistance or plyometric training in the previous ten weeks prior to the competitive season.

Testing Procedures

Body Composition. On arrival to the laboratory, subjects were weighed (BOD POD CosMed USA, Inc., Chicago, USA) in their running shorts to the nearest 0.1kg and their body composition was determined using air-displacement plethysmography (BOD POD GS).

Treadmill Testing. All running tests were performed in a temperature-controlled laboratory (19-21DegC; 65%rH) on a motorized treadmill (TrackMaster TMX425 Full Vision Inc., Newton, USA) set at a 1.0% gradient (11). Before each test, subjects warmed up at a self-selected exercise intensity for five minutes. The amount of work performed during the warm-up was recorded and repeated during subsequent exercise tests. After the warm-up, the subjects completed an incremental treadmill test to determine running economy involving repeated, progressively faster (increments of 1.0 $km{\cdot}h^{-1}$) 4 min stages at fixed running speeds (12 to 18 $km{\cdot}h^{-1}$ for men and 11 to 17 $km{\cdot}h^{-1}$ for women) until subjects were clearly no longer able to sustain a steady-state VO_2 (i.e. a slow component was evident), as determined visually from real-time plots of VO_2. From further post-test inspections of VO_2 data, the maximum velocity at which steady-state oxygen consumption was achieved across the range of subjects was determined (14 $km{\cdot}h^{-1}$) and used thereafter as our primary measure of running economy. A 90 s recovery period occurred between each stage. Expired gases were measured continuously using a metabolic cart (ParvoMedics TrueOne 2400, Salt Lake City, USA) for determination of VO_2, carbon dioxide production, minute ventilation and respiratory exchange ratio. Running economy was defined as the mean VO_2 determined during the last minute of each running stage. In our laboratory, the typical error of measurement (20) of submaximal VO_2 was 1.8%. Approximately 90 s after completion of the final submaximal running stage, VO_2max was determined during an incremental test to volitional exhaustion. Subjects commenced running at 1.0 $km \cdot h^{-1}$ (1.0% gradient) below the final submaximal speed for 1 min. Thereafter, treadmill gradient was increased by 1% each minute until volitional exhaustion. The highest VO_2 over a 30 s period during the test was considered VO_2max. Changes in endurance performance were indicated by the peak running speed reached at the end of the incremental treadmill test. Because we used increases in gradient (rather than speed) in the latter part of the treadmill test, we calculated equivalent speed on the flat as $S = S_T + (S_T \times 0.045) \times i$; where S = peak speed in $km \cdot h^{-1}$, S_T = treadmill speed in $km \cdot h^{-1}$, and i = treadmill inclination in percent (5). Heart rate was determined every 1 s throughout the incremental test using short-range telemetry (Polar RS800sd, Polar Electro, Finland).

Force Plate Measures. Following the incremental test, after a 30 min passive recovery period, subjects performed a 5-jump plyometric test involving five continuous straight-leg jumps on an AccuPower force plate (Advanced Mechanical Technology Inc., Watertown, MA) to determine neuromuscular characteristics. Subjects were instructed to aim for maximal height with contact times as fast as possible, keeping legs straight throughout the jumping sequence. All tests were performed twice and care was taken to ensure subjects maintained erect posture and landed toes first, in the same spot as takeoff. The following parameters were determined: peak force, time to peak force, peak power, maximum rate of force development (RFD), and displacement. Leg stiffness was estimated by dividing the peak force by the vertical displacement measured during the 5-jump test (6).

Resistance-Training Interventions. The resistance training interventions were implemented during week 4 of the competitive season. While maintaining their normal endurance running training, each athlete performed two resistance-training sessions per week over a 7 to 10-wk period, with the exception of weeks 10, 12 and 13 prior to championship competitions where athletes performed only one session (Table 2, Session 1). Specific details of each resistance training session are presented in Table 2. Briefly, a familiarization session occurred during week 3 and involved a measure of each athletes 3 to 6 repetition max (RM) for the leg press exercise followed by a familiarization with each of the prescribed exercises. Each subjects 3 to 6 RM was converted to a 1 RM by the 1RM prediction equation of Lander (1985) (30). Both HRT and PRT programs were periodized throughout the competitive season and matched for volume load throughout the study based on the methods of Stone et al. (1999, 2007) (45). Volume load for HRT and PRT was estimated for each training session using the number of sets, reps, load and body mass of subjects (44,45). Each resistance training session included 4 lower body lifts or 4 complex set lifts which included the identical lifts of the HRT group immediately followed by a plyometric exercise of a similar movement pattern. Additionally all athletes performed the same upper body lifts during each session. Resistance training sessions occurred approximately 30 min after endurance training sessions and athletes were provided with details of the session (sets, repetitions, and weight) upon arrival to the gym. Weights for each athlete were uncontrolled, but recommendations were given based on the previous sessions performance and subjects were encouraged to improve each week. All sessions were monitored and careful attention was given to each athlete to ensure good technique. Athletes were required to record details of all training sessions (resistance and endurance) undertaken during the course of the study. For each resistance training session, the weight (kg) and completed repetitions for each set was recorded, and for each endurance-training session, the training distance (km), and duration (min) were recorded.

Performance during the Competitive Season. The competitive season occurred over a 10 to 13 week duration (Figure 1). Season length was dependent upon both the individual and team achievement at championship competitions (weeks 10, 12 and 13). Only the top (fastest) seven athletes from a team competed in the regional (week 12) and national (week 13) competitions. Athletes competed in various cross-country competitions throughout the competitive season ranging from 5- to 8-km for men and 5- to 6-km for women. NCAA cross-country competition data were downloaded from selected team websites for the entire cross-country season. Each performance time was rounded to the nearest 0.1 s. To focus on the training team (DXC) where the resistance training interventions were implemented, we selected data only from teams that directly competed against our intervention squad at least one time throughout the competitive season. Individuals that did not compete in at least 4 competitions during the season including their teams' inaugural and championship events were not included in the analysis. This selection process resulted in a total of 1741 individual performances in 37 competitions on 16 dates by 325 male athletes from 23 teams and 1652 individual performances in 37 competitions on 16 dates by 285 female athletes from 22 teams.

Analyses. Spreadsheets (22) were used to analyze effects of training on laboratory-test measures. Analyses of changes within each group were made using the post-only crossover spreadsheet. Comparisons of the changes between groups were made with the pre-post parallel-groups spreadsheet. The pre-test value of the dependent variable was included as a covariate to improve precision of the estimate of the effects. The parallel-groups spreadsheet also allowed assessment of the magnitude of the differences between the two training groups arising from randomization at baseline.

Several analyses of the competition data were performed, all with mixed linear models similar to that of Vandenbogaerde et al. (49) using Proc Mixed in the Statistical Analysis System (Version 9.2, SAS Institute, Cary, NC). Mean performances of each of the three training groups (PRT, HRT, control) at each competition were estimated by inclusion of the identity of each competition as a fixed effect interacted with the group effect. Random effects in the model included the identity of the athlete (to account for differences in their ability), the interaction of the identity of the team with the identity of the competition (to account for the interdependence of athletes clustered within each team), and the residual error (representing within-athlete variability in performance between competitions). Effects for female and male runners were estimated in separate analyses. From these analyses, it was apparent that the mean performance times of the control athletes were substantially slower than those of the training team (DXC). The solution for the random effect for athlete was therefore used to filter out slower control runners. Mean performances in the three groups across all competitions were similar when control female athletes with values of their random effect >3 (i.e., more than 3% slower than the average athlete) were excluded; for males, the exclusion criterion was a value >5. The analyses with the filtered athletes provided the means for the competitions shown in Figure 2.

The effects of the treatment on competition time were then estimated via dummy variables having values of 1 for the intervention team (DXC) and 0 for the other (control) teams. Each competition in the intervention period was assigned a different dummy variable. The fixed effect for the interaction of training group and competition in the previous model was replaced with a fixed effect for competition only. The mean effects of each of the two types of resistance training at each competition in the intervention period were estimated with additional fixed effects consisting of the interaction of each dummy variable with the identity of the training group (PRT, HRT, control). The overall means for each treatment and for both treatments combined were obtained by averaging the effects at the three competitions during Weeks 8-12. (The effects at the National Championship in Week 13 for the seven top women were not included in the women's overall mean.) Random effects for the athlete and for the interaction of team and competition were the same as in the previous model. Individual responses to the training at the first competition during the intervention period (Week 6) and averaged over the subsequent competitions (Weeks 8-12 for men; Weeks 8-13 for women) were estimated by including random effects consisting of the interaction of appropriate dummy variables with the identity of the athlete. To allow for the possibility that the runners became more consistent in their performance later in the season, a novel approach was taken by interacting a term representing within-athlete variability between competitions (the interaction of athlete and competition identities) with a dummy variable declining linearly from 1 to 0 between the first and last competitions of the season. One value for this random effect was estimated for the training team and one for the control teams; similarly a different residual error was specified for the training and control teams, to allow for any difference in consistency of performance of these two groups of athletes.

Effects on dependent variables were estimated in percent units via log transformation. Uncertainty in the estimates of effects on performance (peak speed and competition time) was expressed as 90% confidence limits and as probabilities that the true value of the effect was beneficial, trivial or harmful in relation to threshold values for benefit and harm. These probabilities are not presented quantitatively but were used to make a qualitative probabilistic clinical inference about the effect (24). Briefly, the effect was deemed unclear when the chance of benefit was sufficiently high to warrant use of the treatment but the risk of harm was unacceptable. Such unclear effects were identified as those with an odds ratio of benefit to harm of <66. All other effects were deemed clinically clear and assessed by estimating the probability that the true magnitude of the effect was at least as large as the observed magnitude. The threshold values for assessing the magnitude for small, moderate and large beneficial or harmful effects on performance were ±0.5%, ±1.5%, ±2.7% and ±4.2%, which are approximately 0.3, 0.9, 1.6 and 2.5 of the within-subject standard deviation a top athlete would show between competitions (24). For top cross-country runners this standard deviation was 1.5-1.7% in a previous study (23) and 1.3-1.5% by the end of the season in the current study (see Results). The probabilities were reported qualitatively using the following scale: 25-75%, possibly; 75-95%, likely; 95-99.5%, very likely; >99.5%, most likely (21). For the comparison of the effects in the two training groups, the probabilities of benefit and harm of plyometric resistance training were assessed relative to heavy resistance training, which was regarded as the reference or best-practice approach. Magnitudes of effects on measures other than performance were evaluated non-clinically (mechanistically) (24): if the confidence interval overlapped thresholds for substantial positive and negative values (±0.20 standardized units, i.e., 0.20 of the between-subject SD of the dependent in the pre-test), the effect was deemed unclear; all other effects were reported as the magnitude of the observed value and were evaluated probabilistically as described above, except that threshold values for assessing magnitudes of standardized effects were 0.20, 0.60 and 1.2 for small, moderate and large respectively (24).

Results

The proportion of training session's athletes attended during the competition season was 97 ± 3 % (mean ± SD). Before the competition season PRT and HRT groups were similar for men and for women in 5-km time-trial performance, training volume, and body fat, but there were small to moderate differences between groups in body mass, age, and training history (Table 1). During the competition season men performed on average 15.7 $km{\cdot}wk^{-1}$ of training above 80 percent of VO_2max and the women performed 14.6 $km{\cdot}wk^{-1}$, which was equivalent to 17.2 ± 2.5 % of men's and 20.7 ± 4.0 % of women's weekly training volume (Table 1). There was no substantial change in body mass from pre to post testing in men or women, and differences between groups were unclear. Small to moderate reductions in percent body fat were found within both male PRT (mean change score (%) ± SD; ±CL, -9.7 ± 23.0; ±10.8) and HRT (-18.5 ± 20.5; ±11.4) and both female PRT (-6.9 ± 9.4; ±6.6) and HRT (-11.8 ± 12.6; ±7.9) groups, but PRT had a possibly small negative effect relative to HRT. Baseline values of other outcome measures, statistics for effects, and inferences about the interventions within and between groups for men and women are presented in Tables 3 and 4 respectively.

Performance and Aerobic Measures. There were only small differences at baseline between groups for peak speed and running economy ($ml{\cdot}kg^{-1}{\cdot}km^{-1}$) in men and women, for vVO_2max and $\%VO_2max$ in men, and for VO_2max and running economy ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$) in women. Mean improvements in peak speed of small to very large magnitude were observed in both groups for men and women, but PRT was clearly harmful relative to HRT (Table 3 and Table 4). Following the intervention period male HRT showed small or moderate improvements in aerobic measures, whereas the effects from PRT on aerobic measures were trivial (Table 3). Both female groups showed small to moderate improvements in all aerobic measures (Table 4). Male and female HRT showed greater improvements in running economy compared with PRT. Differences between groups on all other aerobic measures were unclear.

Biomechanical Measures. In both training groups and both sexes, changes in contact time were opposite to those of flight time. The direction of the changes were opposite in the two training groups, and overall the changes with PRT were clearly positive and small-moderate in magnitude relative to those with HRT (Table 3 and Table 4).

Neuromuscular Measures. One-repetition max (1RM) improved in all groups, with male athletes improving by 20-40% (Table 3) and female athletes improving by 30-50% (Table 4). Improvements were greater with HRT. Changes in neuromuscular related measures from the 5-jump test were small to moderate improvements with HRT and trivial or negative with PRT (Table 3 and Table 4). Overall, PRT was associated with either unclear or negative effects on all neuromuscular measures in men and women. There was a moderate improvement in leg stiffness after HRT in men and women and unclear decrease (male) or possibly small improvement (female) after PRT (Table 3 and Table 4 respectively).

Competition Measures. The residual error in competition times calculated at the beginning of the season was ~2.0% for the training and control groups and at the end of the season was 1.3-1.4% in the training groups and 1.5% in the control group. Figure 2 shows the least-squares mean performance times for men and women in the competitions that the training groups entered. The mean effects of the training interventions on performance at each competition were generally consistent from Week 8 through the end of the season for male and female athletes. Overall, PRT resulted in possible harm to competition times (slower run times) by 0.8% (90% confidence limits ±1.5%) compared to control male athletes. Heavy-resistance training (HRT) was also possibly harmful to competition performance (0.1%; ±1.3%). The men's overall mean performance was worse (slower) than that of the control teams by 0.5% (±1.2%) after implementation of the two resistance-training interventions. There was an unclear difference between PRT and HRT (-0.7 ±1.5%). There was a likely beneficial effect of PRT training for females, resulting in -1.1% (±1.3%) faster run times (compared to control female athletes). Heavy-resistance training was also likely beneficial to competition performance, -1.4% (±1.4%). The women's overall mean performance was better (faster) than that of control teams by -1.2% (±1.3%). When compared to HRT, PRT was possibly harmful (0.3%; ±1.0%). Individual responses expressed as a standard deviation for both treatments combined was 0.3% (90% confidence interval -1.2% to 1.3%) for men and -0.6% (-1.0% to 0.5%) for women.

Discussion

Previous studies (17,36,43) have reported that various forms of resistance training may lead to improved endurance performance in trained subjects. However, the optimal prescription of resistance training to improve endurance running performance has yet to be firmly established. Accordingly, we investigated whether the combination of plyometric training and heavy-resistance training (PRT) may facilitate additional improvements in neuromuscular efficiency, strength, and running mechanics, compared to heavy resistance-training (HRT) alone during the competition phase of a men's and women's collegiate cross-country season. Interestingly, our data revealed distinct differences between the prescribed training regimes in terms of performance gains and physiological adaptations, and an apparent gender-specific response to resistance training.

To determine the effects of HRT and PRT on performance from competition data, the coefficient of variation (CV) representing typical variation in performance time for the faster male and female runners across the competition season was determined. The CV sets the benchmark for the smallest worthwhile change in an athlete's performance and for the typical (standard) error of measurement of tests used to assess the smallest important or worthwhile change (24). Our CV of ~2.0% at the start of the competitions and ~1.5% at the end are in line with the 1.5-1.7% reported by Hopkins and Hewson (23) and were the basis of using a ±0.5% threshold value for beneficial and harmful effects on performance (approximately 0.3 of the within-subject standard deviation top athletes show between competitions (23,24). Accordingly, there were substantial beneficial mean effects on competition performance for the female training groups compared to controls (-1.2 ±1.3%), whereas resistance training for males proved to be possibly harmful (0.5 ±1.2%). This observation could be an indication that endurance-trained female athletes may have a greater requirement in terms of resistance training maintenance (38), whereas this type of training for men might be beneficial in general only during the pre-season or build-up phase of training when there is less emphasis on competition and gains can be made in physiological measures without the risk of harm to competition performance. The differences in effects between men in women could also be due in part to differences in training intensity and competition distance. The proportion of training that occurred at ≥80% VO_2max for females was moderately higher than that for males (Table 1), which might have translated into performance enhancement over the women's shorter race distance (5-6 km vs 8-10 km for the men). Although we observed an overall benefit in competition performance from either form of resistance training in women and harm in men, HRT was substantially better for females (0.3%; ±1.0%) while PRT was worse (-0.7 ±1.5%).

In addition to actual competition data, we also observed a substantial increase in laboratory-derived peak running speed following HRT (4.6% and 4.4% in men and women respectively) compared to PRT (1.0% and 2.2% in men and women respectively). Peak running speed has been shown to be a good indicator of endurance performance in middle- and long-distance running events (4,34,35,41,47) and Noakes (34,35) has suggested that peak running speed could be used as a measure of the 'muscle power' factor in endurance runners. Muscle power is defined as an ability of the neuromuscular system to produce power during maximal exercise when glycolytic and/or oxidative energy production are high and muscle contractility may be limited (34). Indeed, in addition to the aerobic processes related to distance running performance, the neuromuscular and anaerobic characteristics related to peak running speed are also strongly involved in distance running performance.

In the present study, changes in physiological measures related to distance running performance were consistent with performance data, indicating greater improvements following HRT than matched volume-load PRT (Table 3 and Table 4). Specifically, the addition of HRT improved running economy by 1.7% and 3.4% in males and females respectively, while PRT only improved running economy by 0.2% and 1.0% [Table 3 (men), Table 4 (women)]. Although both HRT and PRT results are in accordance with growing literature demonstrating that heavy resistance-training or plyometric training improved the running economy of well-trained athletes ((15,25,33,36,42,43,46,48), the magnitude of enhancements were lower in our study compared to previous studies reporting effects following heavy-resistance (15,25,33,46) or plyometric training (36,42,43,48). This could be due to different phases of season that the studies were performed. Regardless, in both HRT and PRT, improvements in running economy occurred in the absence of any substantial change in VO_2max suggesting that improved running economy was a result of neuromuscular characteristics rather than improved cardiorespiratory fitness. This is a reasonable assertion since both HRT and PRT groups performed the same endurance training outside of their respective resistance training programs. In further support, running economy improved in accord with many of the neuromuscular measures (Table 3 and Table 4) which also coheres well with previous studies (10,33,36,42,43,46) reporting the importance of the neuromuscular characteristics in determining running economy and running performance following combined resistance and endurance training in runners.

With regards to changes in strength and neuromuscular measures that could be responsible for the greater improvements in running economy and peak running speed following HRT, it has been purported (3, 26) that the nervous system plays an important role in regulating muscle stiffness and utilization of muscle elasticity during stretch-shortening cycle exercises, such as running, in which high contraction velocities are used. In the present study, small to moderate increases in leg stiffness occurred in the male and female HRT groups and PRT training was associated with moderate negative effects on leg stiffness compared to HRT (Table 3 and Table 4). Interestingly, the group with the smallest improvement in 1RM (male PRT) was the only group not to elicit a concomitant increase in stiffness. One of the most important roles of the muscle during running is to modulate leg stiffness and storage-recoil of energy. The conversion of energy to motion involves recoil of some elastic energy in muscle and tendon, thus a "stiffer" muscle or tendon would be better at transferring energy economically or without the need for additional oxygen consumption (7,10,43). Indeed, previous evidence has shown a negative correlation between leg stiffness and cost of running (1,2). Kerdok et al. (27) have shown changes in both muscle-tendon stiffness and running economy when manipulating the running surface, indicating that runners adjust the level of leg stiffness towards the most optimal degree, to maintain consistent running mechanics on different surfaces. This could be important, particularly in cross-country runners like those in the present study where competitions often take place on a variety of undulating surfaces in a single competition. Conversely, the training-induced alterations in biomechanical measures support PRT training and therefore are not likely related to the changes in running economy, peak speed or competition performance. Other studies have indicated that these biomechanical adaptations also occurred in response to plyometric training (36,42). Collectively, these findings suggest that HRT had a positive influence on cross-country running performance because of the improved running economy, peak speed and neuromuscular characteristics.

Finally, it was not surprising to observe the magnitude of improvement in maximal strength (20-40% in the leg press for most athletes) in our sample of distance-runners with limited resistance-training experience. The enhancements in 1RM strength from HRT were 30 and 50% percent greater than PRT in men and women respectively, indicating a positive effect to HRT on strength parameters. The increased muscular strength due to resistance- and/or plyometric-training might primarily come from neural adaptations without observable muscle hypertrophy (16,39). The finding that no substantial change in body weight and small to moderate reductions in percent fat in both PRT and HRT groups, suggesting that little, if no hypertrophy occurred due to the resistance training interventions supports this suggestion. Increases in body mass are an undesirable side effect to resistance training that could be counter-productive to distance running performance.

In conclusion, both HRT and PRT had a likely beneficial effect on competition times in females while both treatments had possibly harmful effects in males. However, when comparing the two treatments, the addition of plyometric training to heavy resistance training was harmful to cross-country competition performance and most laboratory-based measures when compared to a matched volume-load heavy resistance-training program. The greater improvements in competition performance and an enhancement in running economy and peak speed following HRT, compared to PRT, was probably a result of improvements in lower limb strength, leg stiffness and utilization of stored elastic energy. Overall, our data indicate that females should include heavy-resistance training in their programs, but males may want to implement such training in-season with caution until more research establishes characteristics of positive or negative responders.

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Figure Legend

Figure 1. Schematic representation of experimental design, indicating pre- and post-testing, competition and intervention periods.

[a]Men did not race in weeks 3 and 13 competitions.

[b]Resistance training for all runners.

[c]Resistance training for top (fastest 7) male and female runners competing in weeks 12 and/or 13 championship competitions.

[d]Post testing for runners who did not qualify for weeks 12 or 13 championship competitions.

[e]Post testing for runners competing in weeks 12 and/or 13 championship competitions.

Figure 2. Least-squares mean of male and female performance times.

Figure 1

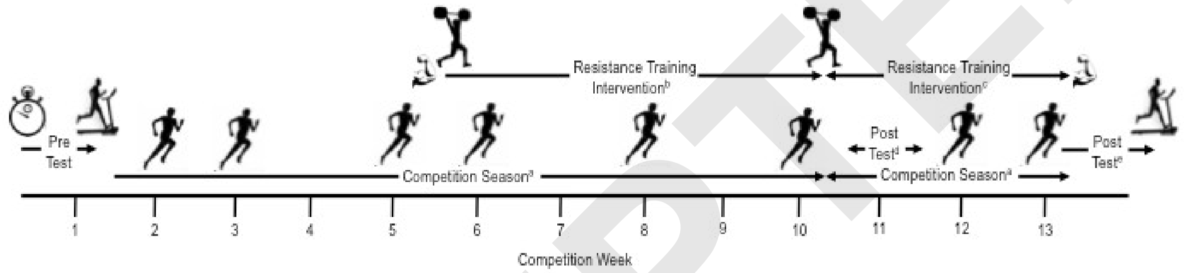
Resistance Training Intervention[b]
Resistance Training Intervention[c]
Pre Test
Post Test[d]
Post Test[e]
Competition Season[a]
Competition Season[a]
1
2
3
4
5
6
7
8
9
10
11
12
13
Competition Week

Figure 2

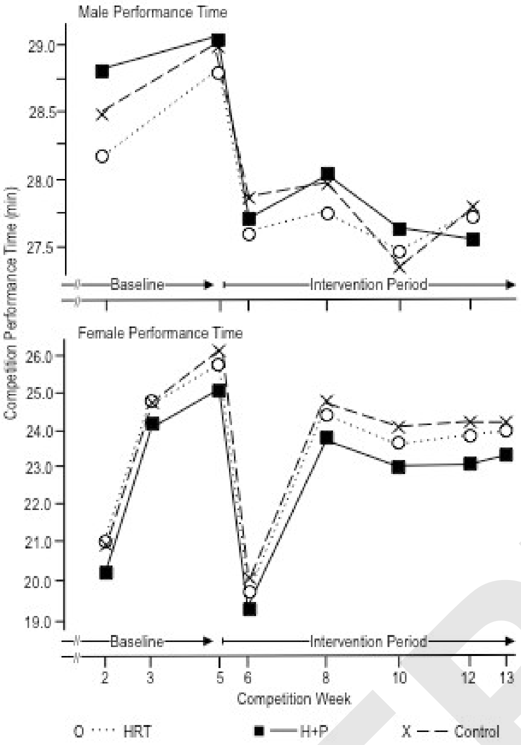
Male Performance Time
29.0
28.5
28.0
27.5
Competition Performance Time (min)
Baseline
Intervention Period
Female Performance Time
26.0
25.0
24.0
23.0
22.0
21.0
20.0
19.0
Baseline
Intervention Period
2
3
5
6
8
10
12
13
Competition Week
O ···· HRT
■ —— H+P
X — — Control

Table 1. Subject and training characteristics with effects and inferences about differences between groups.

Men (n = 23) Women (n = 19)		Group 1 - PRT (mean ± SD) (n = 10M, 10W)	Group 2 - HRT (mean ± SD) (n = 13M, 9W)	Qualitative interpretation of difference in means (Cohen ES)[a]
Age (y)	M	20.7 ± 1.2	19.6 ± 1.1	moderate (0.94)
	F	20.5 ± 1.2	19.7 ± 1.1	moderate (0.72)
Body mass (kg)	M	68.7 ± 8.8	65.4 ± 5.6	small (0.42)
	F	53.4 ± 5.8	55.9 ± 5.9	small (0.40)
Body fat (%)	M	6.8 ± 2.3	7.2 ± 2.1	trivial (0.14)
	F	16.1 ± 2.2	16.6 ± 3.6	trivial (0.18)
Training history (y)	M	6.5 ± 1.8	5.9 ± 0.8	small (0.40)
	F	6.9 ± 1.3	6.0 ± 1.3	moderate (0.67)
Training volume (km·wk^{-1})	M	93.7 ± 15.0	91.9 ± 12.1	trivial (0.13)
	F	73.6 ± 13.8	72.3 ± 13.3	trivial (0.10)
Training intensity ?80% VO_2max (%)[b]	M	17.4 ± 2.3	17.2 ± 2.8	trivial (0.07)
	F	20.9 ± 4.1	20.5 ± 4.2	trivial (0.08)
5-km time trial (min)	M	16.8 ± 0.9	16.7± 0.7	trivial (0.14)
	F	20.1 ± 0.9	20.2 ± 1.3	trivial (0.07)

M = male. F = female. HRT = heavy-resistance training. PRT = plyometric + heavy-resistance training. ES = effect size.

[a] <0.20 trivial; ?0.20 small; ?0.60 moderate; ?1.2 large

[b] Percent of weekly training volume that occurred at ?80% VO_2max.

Table 2. Nine-week resistance training program.

			Week							
			4 – 5		6 – 8		9 – 10		11 – 13[c]	
		Heavy exercise (Plyometric exercise)[a]	HRT	PRT[b]	HRT	PRT	HRT	PRT	HRT	PRT
Session 1	1	Back squat (Box Jump)	2× 6	1× 6/6	4× 5	3× 5/8	4× 4	3× 4/10	2× 3	1× 3/10
	2a	SL calf raise (SL forward hop)	2× 10	1× 10/10	4× 10	4× 10/10	4× 12	3× 12/12	2× 10	1× 10/10
	2b	Dumb bell military press	2× 15	2× 15	4× 20	4× 20	4× 15	4× 15	2× 15	2× 15
	3a	Glute/hamstring raise (CMJ)	2× 10	1× 10/10	4× 6	3× 6/8	4× 8	3× 8/10	2× 6	1× 6/10
	3b	Lateral pull down	2× 15	2× 15	4× 20	4× 20	4× 15	4× 15	2× 15	2× 15
	4	Box step-up (Alternate leg bound)	2× 6	1× 6/6	4× 5	3× 5/8	4× 4	3× 4/10	2× 3	1× 3/10
Session 2	1	Dead lift (Tuck jump)	4× 6	3× 6/6	4× 5	3× 5/8	4× 4	3× 4/10	2× 3	1× 3/10
	2a	SL calf raise (SL box jump)	4× 6	3× 6/6	4× 5	3× 5/8	4× 4	3× 4/10	2× 3	1× 3/10
	2b	Dumb bell incline bench press	4× 15	4× 15	4× 20	4× 20	4× 15	4× 15	2× 15	2× 15
	3a	Resisted monster walk (Side shuffle)	4× 8	3× 8/8	4× 10	4× 10/10	4× 12	3× 12/12	2× 10	1× 10/10
	3b	Pull-up	4× max	4× max	4× max	4× max	4× max	4× max	2× max	2× max
	4	Bulgarian split squat (Scissor jump)	4× 6	3× 6/6	4× 5	3× 5/8	4× 4	3× 4/10	2× 3	1× 3/10

SL = single leg. CMJ = countermovement jump. HRT = heavy-resistance training. PRT = plyometric + heavy-resistance training.

[a] Resistance training exercises are listed as the heavy-resistance training exercise (performed by both HRT and PRT groups) followed by the plyometric exercise (performed only by PRT).

[b] Values are number of sets × number of repetitions per set. Sets and repetitions are listed for HRT first (e.g. 4× 5) followed by sets and repetitions for PRT, listed as the number of sets × number of repetitions for each heavy/plyometric exercise (e.g. 3x 5/8 = 3 sets of 5 repetitions of the heavy exercise followed immediately by 8 repetitions of the plyometric exercise).

[c] Resistance training during weeks 11 through 13 was only performed by the top (fastest 7) athletes competing in championship events during weeks 12 and 13.

Table 3. Male outcome measures at baseline and statistics for effects and inferences about the interventions within and between groups.

	Group 1 - PRT		**Group 2 - HRT**		**Group Comparison (1 – 2)**	
	Baseline values (mean ± SD)	**Change score (%) (mean ± SD; ±CL)**	**Baseline values (mean ± SD)**	**Change score (%) (mean ± SD; ±CL)**	**Difference between groups (% mean ±CL)**	**Qualitative inference^a**
Performance Measures						
Peak speed	20.1 ± 1.2 km·h^{-1}	1.0 ± 3.7; ±1.8	19.6 ± 1.1 km·h^{-1}	4.6 ± 4.5; ±2.6	-3.4; ±3.0	small harm**
Aerobic Measures						
VO$_2$max	63.8 ± 4.6 ml·kg^{-1}·min^{-1}	0.1 ± 5.2; ±2.6	63.7 ± 4.7 ml·kg^{-1}·min^{-1}	1.2 ± 7.1; ±4.1	-1.1; ±4.6	unclear
vVO$_2$max	17.5 ± 0.8 km·h^{-1}	0.3 ± 3.9; ±1.9	17.5 ± 1.1 km·h^{-1}	1.6 ± 4.9; ±2.8	-1.3; ±3.3	unclear
RE at 14km·h^{-1}	50.8 ± 3.2 ml·kg^{-1}·min^{-1}	-0.2 ± 3.3; ±1.6	51.3 ± 3.3 ml·kg^{-1}·min^{-1}	-1.7 ± 4.1; ±2.3	1.5; ±2.7	small -ive*
RE at 14km·h^{-1}	218 ± 13 ml·kg^{-1}·km^{-1}	-0.2 ± 3.3; ±1.6	221 ± 14 ml·kg^{-1}·km^{-1}	-2.1 ± 4.5; ±2.6	2.0; ±3.0	small -ive*
%VO$_2$ at14km·h^{-1}	79.7 ± 4.2 %VO$_2$max	-0.2 ± 3.9; ±1.9	80.7 ± 4.0 %VO$_2$max	-2.8 ± 5.1; ±2.9	2.7; ±3.4	small -ive**
Biomechanical Measures						
Contact time	0.24 ± 0.02 s	-2.6 ± 5.6; ±2.7	0.23 ± 0.01 s	0.9 ± 2.4; ±1.4	-3.5; ±3.0	small +ive**
Flight time	0.12 ± 0.02 s	9.3 ± 17.1; ±8.1	0.12 ± 0.02 s	-1.8 ± 5.4; ±3.1	11.3; ±8.6	moderate +ive*
Neuromuscular Measures						
1RM	68.7 ± 13.6 kg	24.3 ± 5.6; ±2.7	70.7 ± 13.3 kg	31.1 ± 3.5; ±2.0	-5.2; ±3.3	small -ive**
Stiffness	9.6 ± 2.0 kN·m^{-1}	-3.0 ± 22.5; ±10.5	9.3 ± 2.0 kN·m^{-1}	15.0 ± 20.7; ±11.5	-15.7; ±15.2	moderate –ive*
5-Jump Test						
Peak force	64.6 ± 12.3 N·kg^{-1}	3.5 ± 11.4; ±5.5	65.2 ± 5.8 N·kg^{-1}	10.0 ± 9.3; ±5.3	-5.9; ±7.4	small -ive**
Peak power	67.2 ± 19.2 W·kg^{-1}	0.4 ± 21.1; ±9.9	68.5 ± 16.4 W·kg^{-1}	0.5 ± 5.8; ±3.3	-0.1; ±10.4	unclear

HRT = heavy-resistance training. PRT = plyometric + heavy-resistance training. SD = standard deviation. CL = confidence limits. 1RM = one repetition max. VO$_2$max = maximal aerobic capacity. vVO$_2$max = velocity at VO$_2$max. RE = running economy. %VO$_2$max = percent of VO$_2$max. +ive = positive or beneficial effect on Group 1 as compared to Group 2. -ive = negative or harmful effect on Group 1 as compared to Group 2.

[a] The inference for performance is clinical; those for other measures are non-clinical.

*25-75%, possible; **75-95%, likely; ***95-99.5%, very likely; ****>99.5%, most (or extremely) likely

?0.2 small; ? 0.6 moderate; ? 1.2 large; ? 2.0 very large; ?4.0 extremely large

Table 4. Female outcome measures at baseline and statistics for effects and inferences about the interventions within and between groups.

	Group 1 (PRT)		**Group 2 (HRT)**		**Group Comparison (1 – 2)**	
	Baseline values (mean ± SD)	**Change score (%) (mean ± SD; ±CL)**	**Baseline values (mean ± SD)**	**Change score (%) (mean ± SD; ±CL)**	**Difference between groups (% mean ±CL)**	**Qualitative inference^a**
Performance Measures						
Peak speed	17.6 ± 0.7 km·h^{-1}	2.2 ± 3.7; ±2.3	17.2 ± 1.0 km·h^{-1}	4.4 ± 3.9; ±2.2	-2.2; ±3.0	small harm*
Aerobic Measures						
VO_2max	51.3 ± 2.8 ml·kg^{-1}·min^{-1}	4.7 ± 5.2; ±3.2	52.3 ± 3.3 ml·kg^{-1}·min^{-1}	3.4 ± 6.3; ±3.6	1.3; ±4.6	unclear
vVO_2max	15.3 ± 0.9 km·h^{-1}	2.3 ± 4.5; ±2.8	15.2 ± 0.9 km·h^{-1}	1.6 ± 5.2; ±3.0	0.7; ±3.9	unclear
RE at 14km·h^{-1}	43.9 ± 2.3 ml·kg^{-1}·min^{-1}	-1.0 ± 2.2; ±1.3	44.9 ± 1.9 ml·kg^{-1}·min^{-1}	-3.4 ± 4.1; ±2.4	2.5; ±2.6	small -ive**
RE at 14km·h^{-1}	203 ± 10 ml·kg^{-1}·km^{-1}	-1.5 ± 3.5; ±2.1	207 ± 9 ml·kg^{-1}·km^{-1}	-3.4 ± 4.1; ±2.4	1.9; ±3.0	small -ive*
%VO_2 at14km·h^{-1}	84.8 ± 5.5 %VO_2max	-3.9 ± 4.0; ±2.5	84.6 ± 5.7 %VO_2max	-3.2 ± 4.0; ±2.3	-0.7; ±3.2	unclear
Biomechanical Measures						
Contact time	0.24 ± 0.02 s	-1.1 ± 3.8; ±2.4	0.24 ± 0.01 s	4.2 ± 2.6; ±1.6	-5.0; ±2.7	moderate +ive**
Flight time	0.09 ± 0.01 s	4.2 ± 15.2; ±9.2	0.10 ± 0.02 s	-10.2 ± 12.5; ±7.6	16.0; ±11.3	moderate +ive**
Neuromuscular Measures						
1RM	41.2 ± 8.0 kg	29.6 ± 8.7; ±5.3	35.9 ± 2.3 kg	44.5 ± 10.3; ± 5.8	-10.3; ±7.5	moderate -ive*
Stiffness	13.6 ± 1.5 kN·m^{-1}	4.5 ± 10.4; ±6.3	13.5 ± 1.5 kN·m^{-1}	11.5 ± 12.1; ±6.9	-6.3; ±8.9	moderate -ive*
5-Jump Test						
Peak force	70.7 ± 14.3 N·kg^{-1}	1.1 ± 14.3; ±8.6	64.9 ± 14.8 N·kg^{-1}	7.5 ± 14.8; ±8.3	-5.9; ±11.5	unclear
Peak power	53.4 ± 12.2 W·kg^{-1}	-6.3 ± 20.8; ±12.4	48.2 ± 11.2 W·kg^{-1}	5.3 ± 13.1; ±7.4	-10.9; ±14.0	small -ive**

HRT = heavy-resistance training. PRT = plyometric + heavy-resistance training. SD = standard deviation. CL = confidence limits. 1RM = one repetition max. VO_2max = maximal aerobic capacity. vVO_2max = velocity at VO_2max. RE = running economy. %VO_2max = percent of VO_2max. +ive = positive or beneficial effect on Group 1 as compared to Group 2. -ive = negative or harmful effect on Group 1 as compared to Group 2.

[a]The inference for performance is clinical; those for other measures are non-clinical.

*25-75%, possible; **75-95%, likely; ***95-99.5%, very likely; ****>99.5%, most (or extremely) likely

?0.2 small; ? 0.6 moderate; ?1.2 large; ? 2.0 very large; ? 4.0 extremely large