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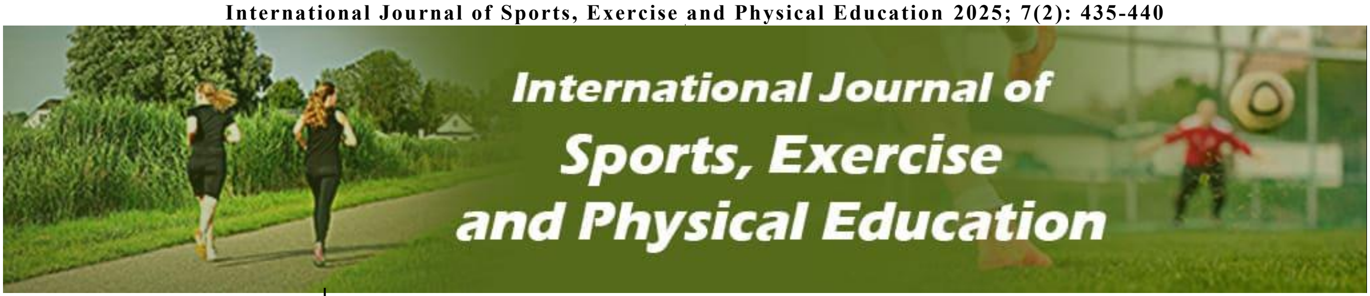

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Strength beyond miles: Impact of maximum strength, endurance, and hypertrophy training on youth endurance performance

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Abstract
Strength training is increasingly recognized as an important factor in enhancing athletic performance, yet limited evidence exists on its specific effects in youth endurance athletes, particularly during adolescence, which is a critical period of physical development. This study aimed to address this gap by evaluating the impact of three different strength training approaches, that are maximum strength, strength endurance, and hypertrophy on performance in adolescent male endurance runners. Sixty participants aged 13-17 were randomly assigned to a control group or one of three experimental groups (n = 15 each). Each experimental group undertook targeted strength training in addition to their regular running program. Performance was assessed through 1500 m run times, with additional strength and physiological measures (1RM test, push-up test, and anthropometric data) collected for the respective training modalities. Results from mixed ANOVA indicated that maximum strength training produced the greatest improvements in both running performance and strength, followed by strength endurance training, which also enhanced running efficiency. Hypertrophy training improved body composition but had limited effect on endurance performance. These findings highlight the importance of integrating structured strength training, particularly maximum strength and strength endurance, into adolescent endurance programs to optimize both athletic development and long-term performance outcomes.

Keywords: Adolescent athletes, endurance performance, hypertrophy, maximum strength, strength endurance, strength training

Introduction

The main factors influencing endurance running performance are running economy, lactate threshold, and aerobic capacity. To maximize these physiological factors, endurance athletes have historically concentrated nearly solely on high-volume aerobic training [1]. Without sacrificing endurance capacity, however, there is mounting evidence that adding strength training to endurance programs can greatly improve performance through neuromuscular and biomechanical adaptations [2]. Increased maximum strength, decreased ground contact time, increased musculotendinous stiffness and improved running economy are all benefits of strength training that have been demonstrated to improve endurance performance [3].

The three main areas into which strength training is usually separated are hypertrophy training, maximum strength training, and strength endurance training [4]. Usually incorporating moderate to high repetitions with moderate weights, hypertrophy training seeks to enhance muscle size and cross-sectional area [5]. The goal of maximum strength training is to increase the neuromuscular system's capacity to produce force with high loads and few repetitions [2]. By postponing tiredness and enhancing muscular efficiency during long-distance races, strength endurance training, which emphasizes the capacity to sustain muscle contractions over time, can help endurance athletes [6].

Hypertrophy training, which usually consists of moderate to high repetitions (6-12 reps), moderate loads (60-80% of 1RM) and shorter rest intervals is intended to enhance the size and cross-sectional area of skeletal muscle fibers [7]. By stabilizing joint movement and improving neuromuscular control, this type of training increases muscle mass, which can lead to increased force output and possibly improve running economy [8]. The effects of each training modality on endurance performance can differ based on the demographic, intensity and duration of the study. Each modality addresses a distinct physiological mechanism [9].

Fewer studies have examined adolescent runners, who are in a crucial stage of neuromuscular development, despite the fact that the majority of research on the benefits of strength training for endurance athletes has been done on elite or adult populations [8]. To further limit comparison insights between training modalities, previous studies frequently used a single-mode strength training intervention [10].

A significant gap exists in the literature about the effects of strength training types, including hypertrophy, maximum strength, and strength endurance, on endurance runners' performance characteristics, especially throughout a planned training cycle. To address this research gap, the current study employs a quasi-experimental design to compare the effects of these three distinct strength training programs on key performance outcomes in adolescent male endurance athletes. This study intends to give coaches, sport scientists, and athletic trainers evidence-based insights to maximize performance development strategies in youth endurance populations by analyzing changes in VO_2 max, 1.5-mile run performance, muscular endurance, lower-body power and maximal strength. The study design, participant selection, intervention procedures and performance evaluations employed in this inquiry are all described in depth in the methodological section that follows.

Materials and Methods

This study applied a quasi-experimental design with a pre-test and post-test control group to investigate the impact of different strength training programs on the performance of endurance runners. The intervention lasted 16 weeks and consisted of three experimental groups that received different strength training protocols, as well as a control group that continued ordinary endurance training without any additional strength work.

Study participants

A total of 60 male endurance athletes aged between 15 and 17 years were considered for inclusion in the study. 45 athletes were chosen by purposive sampling based on voluntary participation and inclusion criteria. All participants had at least one year of endurance running experience and no injuries or medical issues that would preclude strength training.

Participants were randomly assigned to four groups (n = 15 per group):

- **Group A (Hypertrophy training group):** 16 weeks of hypertrophy-focused strength training.
- **Group B (Maximum strength group):** 16 weeks of maximum strength training.
- **Group C (Strength endurance group):** 16 weeks of strength endurance training.
- **Group D (Control group):** No any strength training intervention.

Written informed consent was obtained from all participants and their legal guardians. Ethical clearance was granted by the institutional ethics committee prior to the commencement of the study.

All experimental groups participated in specific strength training sessions three times per week, following standardized training principles personalized to their respective group objectives (Table 1).

Table 1: Study procedure

Training type	Duration	Intensity (% of 1RM)	Volume (Sets × Reps)
Hypertrophy training (Group A)	16 weeks	65-75%	3-4 sets × 8-12 reps
Maximum strength training (Group B)	8 weeks	85-95%	4-5 sets × 3-6 reps
Strength endurance training (Group C)	8 weeks	40-60%	2-3 sets × 15-20 reps

The control group continued with their consistent endurance training throughout the study duration and received no strength training intervention

Data gathering

Performance testing was conducted one week prior to and one week after the intervention period. The following variables were measured:

- **Running performance:** Time taken to complete a 1.5-mile run
- **Hypertrophy training:** Anthropometric measurements
- **Maximal strength:** 1RM (One repetition maximum)
- **Strength endurance:** Maximum repetitions of push-ups

All tests were performed under standardized conditions and supervised by trained assessors blinded to group allocation.

Data analysis

Data were analyzed using SPSS software. Descriptive statistics (mean ± SD) were calculated for all variables. A Mixed Design ANOVA was used to evaluate the training methods' efficacy. The level of statistical significance was set at $p<0.001$.

Results

This section presents the results of an intervention-based study conducted to evaluate the effects of three different strength training programs hypertrophy training, maximum strength training, and strength endurance training on the performance of school-level endurance runners. The sample comprised 60 male athletes, aged 13 to 17 years, who actively participated in school athletics. Participants were divided into a control group (n = 15) and an experimental group (n = 45). The experimental group was further split into three sub-groups, hypertrophy training (n = 15) 12-week program, maximum strength training (n = 15, 8-week program) and strength endurance training (n = 15) 8-week program.

The primary objective was to determine which training modality most effectively enhances endurance performance, as measured by 1500m timing. It was hypothesized that all three training methods would positively influence endurance performance, with Maximum Strength and Strength Endurance Training expected to produce the most significant improvements due to their specific focus on neuromuscular efficiency and fatigue resistance. The control group continued with their regular endurance running routines without any additional strength training.

A mixed-design ANOVA was used to analyze both within subject (pre-test vs. post-test) and between subject differences. The following sections present the descriptive statistics, inferential results and performance trends observed across all training interventions. According to the above information Table 2 shows the descriptive analysis results for the maximum strength training program.

Table 2: Descriptive results - maximum strength training

Source	F	p-value	Partial η²
1RM - time	117.67	< .001	0.808
1RM - time x group	37.03	< .001	0.569
Performance - time	734.46	< .001	0.963
Performance - time x group	6.319	0.018	0.184

The implementation of maximum strength training over an eight-week period led to notable improvements in both muscular strength and endurance performance among the experimental group of adolescent male runners. Participants who underwent the intervention demonstrated a substantial increase in maximal strength, as measured by the One Repetition Maximum (1RM) test, compared to the control group, which followed a standard endurance training routine without additional strength work.

Moreover, performance in the 1500m run improved significantly in the experimental group, with a marked reduction in completion time observed from pre-test to post-test. This improvement reflects enhanced neuromuscular efficiency and running economy, key factors linked to maximum strength development. While the control group also exhibited minor gains, likely attributable to continued endurance training, the magnitude of improvement was considerably lower than that observed in the strength trained athletes. These results highlight the effectiveness of maximum strength training in improving both explosive force and aerobic endurance when integrated into the training programs of adolescent endurance runners. The statistical output of the mixed-design ANOVA is shown in Table 3, indicating significant improvements of maximum strength.

Table 3: Mixed ANOVA results - maximum strength

Test	Group	Pre-test mean ± SD	Post-test mean ± SD
1RM (kg)	Control	62.00 ± 4.93	65.00 ± 5.35
1RM (kg)	Experimental	60.67 ± 5.30	71.33 ± 7.67
Performance test (Min: Sec)	Control	17:30.40 ± 35.18	16:42.13 ± 35.59
Performance test (Min: Sec)	Experimental	18:50.54 ± 29.41	17:52.32 ± 24.59

The results of the mixed-design ANOVA revealed statistically significant main effects of time for both the One Repetition Maximum (1RM) and 1500m performance measures, indicating that participants overall improved from pre- to post-intervention. Additionally, a significant interaction effect between time and group was observed for both variables, demonstrating that the experimental group experienced significantly greater improvements compared to the control group. These findings confirm that the maximum strength training intervention produced a more pronounced enhancement in both muscular strength and endurance performance than regular endurance training alone. Descriptive statistics for strength endurance performance are reported in Table. 4 highlighting substantial group differences.

Strength endurance training

Table 4: Descriptive results - strength endurance training

Test	Group	Pre-test (mean ± SD)	Post-test (mean ± SD)
Push-up count	Control	27.53 ± 4.49	31.20 ± 5.21
Push-up count	Experimental	28.93 ± 5.97	48.53 ± 10.43
SE performance (Minus)	Control	18:25.08 ± 39.10	17:30.41 ± 35.18
SE performance (Minus)	Experimental	19:05.40 ± 45.15	17:56.15 ± 37.05

The strength endurance training intervention resulted in significant improvements in both muscular endurance and overall performance among adolescent endurance runners. Following the eight-week program, participants in the experimental group exhibited a marked increase in upper body muscular endurance, as evidenced by a substantial rise in the number of push-ups performed during the post-test assessment. In addition to strength gains, a notable reduction in 1500m run timing was observed, indicating improved endurance capacity and fatigue resistance. These enhancements suggest that strength endurance training effectively supports the physiological demands of middle-distance running by improving muscular stamina and delaying the onset of muscular fatigue during performance. Although the control group also showed some improvements, likely due to continued exposure to regular endurance training, the experimental group demonstrated significantly greater progress across both performance metrics. These findings underscore the value of integrating strength endurance protocols into the training regimes of young endurance athletes to enhance both muscular and aerobic performance parameters. Mixed-design ANOVA results are shown in Table 5, strength endurance emphasizing both time and interaction effects.

Table 5: Mixed ANOVA results - strength endurance

Source	F	p-value	Partial η²
Push-up - time	97.42	< .001	0.777
Push-up - time × group	45.69	< .001	0.622
SE performance - time	497.19	< .001	0.947
SE performance - time × group	7.24	0.012	0.205

The mixed-design ANOVA revealed significant main effects of time for both push-ups count and 1500m performance, indicating overall improvements among participants following the intervention. Furthermore, the significant interaction effects between time and group for

both variables demonstrate that the experimental group achieved greater enhancements in muscular endurance and running performance compared to the control group. These findings validate the effectiveness of the strength endurance training program in producing superior physiological adaptations relevant to endurance running.
In below, Body composition outcomes from the hypertrophy training are detailed in Table 6 using descriptive results.

Hypertrophy training

Table 6: Descriptive results - hypertrophy training

Variable	Group	Pre-test (Mean ± SD)	Post-test (Mean ± SD)
Fat %	Control	18.23 ± 4.71	17.80 ± 4.81
Fat %	Experimental	11.87 ± 6.47	10.39 ± 6.08
Arm circumference	Control	26.40 ± 1.84	26.67 ± 1.72
Arm circumference	Experimental	25.27 ± 3.31	28.47 ± 3.36
Performance time	Control	19:23.57 ± 38.56	18:25.08 ± 39.10
Performance time	Experimental	19:18.35 ± 39.20	18:11.30 ± 31.29

The hypertrophy training intervention produced notable changes in body composition and muscle development among the adolescent endurance runners. Participants in the experimental group demonstrated moderate reductions in body fat percentage alongside significant increases in limb circumferences, particularly in the arms, chest, and thighs. These changes are indicative of muscular hypertrophy, reflecting the effectiveness of the 12-week resistance-based training protocol in promoting muscle growth. While both the experimental and control groups showed improvements in 1500m run performance time, the difference between groups was not statistically significant. This suggests that although hypertrophy training contributed to physical development, its direct impact on endurance performance may be less pronounced compared to other training modalities. Nevertheless, the observed improvements in muscular dimensions highlight its potential value as a supportive strategy within a comprehensive training program for young endurance athletes. Table 7 summarizes statistical differences across anthropometric variables, confirming the impact of hypertrophy training.

Table 7: Mixed ANOVA results - hypertrophy

Variable	F (Time)	p (Time)	η^2 (Time)	F (Time x group)	p (Time × group)
Fat %	49.293	< .001	0.638	14.922	.001
Arm circumference	20.136	< .001	0.418	14.417	.001
Chest circumference	67.009	< .001	0.705	37.237	.001
Thigh circumference	141.862	< .001	0.835	78.670	.001
Performance time	349.628	< .001	0.928	1.503	0.231

The mixed-design ANOVA revealed statistically significant main effects of time across nearly all measured variables, indicating meaningful improvements in body composition and muscular development following the hypertrophy training intervention. However, significant interaction effects between time and group were observed only for select anthropometric measures, such as fat percentage and limb circumferences while no significant interaction effect was found for performance outcomes. This suggests that although both groups improved over time, the hypertrophy training produced greater physical changes in the experimental group, without yielding a distinct advantage in 1500m run performance compared to the control group. According to the above details below Table 8 highlights which training modality had the most influence on endurance performance.

Table 8: Summary of training effects

Training plan	F (Time)	F (Time × group)	Partial η^2
Maximum Strength	734.46	6.319	0.963
Strength Endurance	497.19	7.236	0.947
Hypertrophy	349.63	1.503	0.928

Comparative analysis of the three strength training interventions highlights distinct outcomes in terms of performance enhancement and physiological adaptation. The maximum strength training program produced the most substantial gains in 1500m run performance, demonstrating its superior effectiveness in improving endurance-related outcomes. Strength endurance training also led to notable improvements in muscular endurance and running efficiency, though to a slightly lesser extent. In contrast, the hypertrophy training program primarily contributed to positive changes in body composition, such as reduced fat percentage and increased limb circumference without a corresponding advantage in endurance performance. These findings underscore the specific benefits of each training modality and support the integration of strength focused strategies to enhance the overall athletic development of endurance runners.

Discussion

The present study aimed to evaluate the impact of three different strength training programs maximum strength, strength endurance, and hypertrophy on the endurance performance of adolescent male school athletes aged 13 to 17 years. All training protocols were implemented over a controlled period with a consistent focus on 1500m timing as the key performance indicator. The findings demonstrate that while all three experimental groups exhibited improvements, the nature and extent of enhancement varied according to the specific training method employed. The maximum strength training group achieved the most significant gains in both 1RM and 1500m performance. These results support the notion that increased maximal force production can improve running economy, neuromuscular coordination, and fatigue resistance factors closely associated with enhanced endurance performance [11]. This outcome is consistent with earlier findings which emphasize the role of strength development in improving performance metrics among middle-distance runners [9].
Participants in the strength endurance group also demonstrated meaningful improvements. Notably, they recorded a substantial increase in push-up repetitions and a marked decrease in 1500m timing, indicating enhanced muscular endurance and aerobic capacity. These adaptations suggest that strength endurance training is effective in sustaining posture and reducing fatigue, thereby supporting prolonged physical activity and performance efficiency [12].
The hypertrophy training group displayed modest improvements in endurance performance, yet showed more significant positive changes in body composition including reductions in fat percentage and increases in limb circumference. These results indicate that while hypertrophy

training contributes to muscle development and physical conditioning, its direct effect on running performance may be limited in comparison to other modalities [13]. However, it may serve as a valuable adjunct for overall physical development, particularly in youth athletes [14].

Taken together, the findings of this study indicate that maximum strength and strength endurance training interventions are more effective in enhancing 1500m performance than hypertrophy focused protocols. These results have practical implications for coaches and trainers seeking to optimize performance in adolescent endurance runners [4]. Integrating strength-based methods that target either maximal output or muscular stamina can yield considerable improvements in race times and overall conditioning [15]. The study has limitations despite these encouraging results. The sample was limited to male adolescent athletes within a specific age range, limiting the generalizability of the results to broader populations. As well as the relatively short duration of the interventions particularly the eight-week maximum strength and strength endurance programs may not fully capture the long-term benefits of these training modalities. Future research should consider extended study periods, the inclusion of biomechanical performance indicators, and the impact on female and mixed-gender athletic populations.

Conclusion

This study demonstrates that structured strength training, particularly programs emphasizing maximum strength and strength endurance, is highly effective in improving the performance of adolescent male endurance runners. While all three training modalities such as maximum strength, strength endurance, and hypertrophy that produced some degree of benefit, the nature and extent of improvement varied. Maximum strength training delivered the greatest performance gains, enhancing both 1RM and 1500 m run times, reflecting improvements in running economy, neuromuscular coordination, and fatigue resistance. Strength endurance training also led to notable improvements, particularly in muscular stamina and aerobic efficiency, as evidenced by increased push-up repetitions and reduced race times. In contrast, hypertrophy training primarily improved body composition, including reduced fat percentage and increased muscle mass, but its impact on running performance was comparatively modest. These findings highlight the need for targeted, method-specific approaches to strength training when the objective is endurance enhancement. Importantly, the study contributes to youth sports science by addressing a research gap on the comparative effects of distinct strength training methods in adolescent endurance athletes. Coaches, trainers, and practitioners can apply these insights by prioritizing maximum strength and strength endurance programs in youth training regimens, using hypertrophy protocols as a complementary tool for overall conditioning and physical development. While encouraging, these results are limited by the male-only sample, short intervention duration, and focus on a single performance metric. Future research should extend the scope by including longer-term interventions, biomechanical indicators, and mixed-gender cohorts. Ultimately, adopting targeted strength training in youth endurance programs offers a practical pathway to optimize both athletic performance and long-term development.

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