

EXAMINING THE NEUROMUSCULAR FATIGUE THRESHOLDS IN MALE ADOLESCENT SPRINTERS

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Abstract. Aim. Neuromuscular fatigue is a critical determinant of sprint performance, particularly in adolescent athletes. This study aims to assess the effects of 8 weeks of neuromuscular training on the fatigue thresholds and its impact on sprint performance. **Materials and methods.** Thirty-six adolescent sprinters aged 15–17 years were recruited from three different academies in Lahore city. The forty-meter sprint test was conducted through Brower Timing Systems, a laser timing gate, followed by the analysis of the vastus lateralis and biceps femoris during maximal sprints, measured through electromyography (EMG), while the Borg Rating of Perceived Exertion (RPE) scale (6–20) was used to measure the perception of the subjective fatigue among the participants. **Results.** Significant improvements in sprint performance were observed at 10 m ($p^* = 0.012$) and 40 m ($p^* = 0.003$) times decreased in post-intervention. Increased root mean square (RMS) amplitude in both vastus lateralis ($p^* = 0.008$) and biceps femoris ($p^* = 0.021$) in EMG analyses was noted, reflecting improved neuromuscular activation. Moreover, perceived exertion (RPE) decreased significantly ($p^* < 0.05$), highlighting improved fatigue tolerance. **Conclusion.** Neuromuscular training improves fatigue thresholds in adolescent sprinters by delaying the onset of fatigue. Future research may explore long-term adaptations and include female athletes for broader generalizability and applicability.

Keywords: efficacy, endurance, muscles, tolerance, training

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ОЦЕНКА ПОРОГОВ НЕЙРОМЫШЕЧНОГО УТОМЛЕНИЯ У ПОДРОСТКОВ-БЕГУНОВ НА КОРОТКИЕ ДИСТАНЦИИ

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Аннотация. Цель. Нейромышечное утомление определяет результативность в беге на короткие дистанции, особенно среди спортсменов подросткового возраста. Целью настоящего исследования является оценка влияния 8-недельной программы нейромышечной тренировки на пороги утомления

и их влияние на результативность в беге на короткие дистанции. **Материалы и методы.** В исследовании приняли участие 36 бегунов на короткие дистанции в возрасте 15–17 лет, обучающиеся в трех разных академиях города Лахора. Тест на бег на 40 метров проводили с использованием лазерной системы хронометража Brower Timing Systems с последующей электромиографической оценкой *vastus lateralis* и *biceps femoris* во время максимальных спринтерских попыток. Субъективную оценку утомляемости регистрировали с использованием шкалы воспринимаемого напряжения Борга (Rating of Perceived Exertion, RPE) с диапазоном 6–20 баллов. **Результаты.** Зарегистрированы значимые улучшения результативности в беге на 10 м ($p = 0,012$) и 40 м ($p = 0,003$), что выражалось в сокращении времени прохождения этих дистанций после исследования. Отмечено увеличение среднеквадратичной амплитуды мышц *vastus lateralis* ($p = 0,008$) и *biceps femoris* ($p = 0,021$) по данным ЭМГ-анализа, что свидетельствует об улучшении нейромышечной активации. Кроме того, зарегистрировано значимое ($p < 0,05$) снижение оценки воспринимаемого напряжения, свидетельствующее о повышении устойчивости к утомлению. **Заключение.** Нейромышечная тренировка повышает пороги утомления у подростков-бегунов на короткие дистанции за счет отсрочки наступления утомления. Последующие исследования могут быть направлены на изучение долгосрочных адаптаций при участии спортсменов для большей обобщаемости и применимости результатов.

Ключевые слова: эффективность, выносливость, мышцы, устойчивость, тренировка

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Introduction. Neuromuscular fatigue is a critical determinant of sprint performance, particularly in adolescent athletes passing through rapid physiological and biomechanical development [8]. Fatigue is a threshold of muscle performance decline due to sustained exertion associated with the metabolic, neural, and mechanical factors [6]. Muscular fatigue is a common experience of sports life, whether it is training or competition [7]. Understanding these thresholds in adolescent sprinters is essential for optimizing training programs, minimizing injury risks, and improving their overall performance. Adolescence is a period marked by significant changes due to musculoskeletal growth, hormonal fluctuations, and neuromuscular maturation; all these factors are linked with the ability to resist fatigue and the capacity for recovery [12]. Sprinting requires maximal neuromuscular recruitment and rapid energy supply on the one hand; however, fatigue-induced performance decrements can have substantial consequences for both competition outcomes and long-term athletic development [5]. Adolescent athletes experience unique neuromuscular adaptations due to ongoing growth and maturation [12]. During this developmental stage, muscle-tendon stiffness, motor unit recruitment efficiency, and energy metabolism undergo significant changes, all of which affect the fatigue resistance of the person concerned [15]. Sprint performance relies significantly on the phosphagen energy system and anaerobic glycolysis, both of which are highly susceptible to fa-

tigue during repeated high-intensity exertions [4]. However, the detailed mechanisms by which neuromuscular fatigue functions in adolescent sprinters, particularly about growth-related biomechanical adjustments, remain insufficiently explored.

From a technical perspective, it is vital to understand neuromuscular fatigue thresholds in adolescent sprinters, which play a significant role in improving sports performance and enhancing adaptability. The phase of adolescence is very crucial for neuromuscular development, wherein fatigue thresholds directly affect sprint performance [1]. It is a matter of high significance for sports practitioners to know the fatigue thresholds, which help them design a structured training regime that leads to optimizing power, speed, and adaptability and minimizing the risk of injuries. Performance changes associated with fatigue help in preventing sports injuries like muscular strain and tendon sprain [16]. Neuromuscular fatigue in adolescent sprinters manifests decline in force production, deficient recruitment of motor units, and an extended duration of recovery [11].

Recent research suggests that adolescent athletes exhibit different fatigue responses compared to adults due to differences in muscle composition, motor control, and recovery capacity [8]. For instance, younger athletes may experience an earlier onset of peripheral fatigue due to metabolic accumulation in muscle fibers but demonstrate faster recovery rates due to enhanced

oxidative capacity and mitochondrial efficiency [15]. Conversely, central fatigue, mediated by reduced neural drive from the central nervous system, may be more prominent in adolescents due to ongoing neural maturation [3]. These distinctions highlight the need for age-specific fatigue monitoring and training strategies to maximize performance while mitigating injury risks [10]. The significance of this research extends beyond performance optimization. Fatigue-related biomechanical alterations, such as reduced stride frequency, decreased ground contact efficiency, and compromised postural stability, increase the likelihood of acute and overuse injuries [5]. Adolescent athletes are particularly vulnerable to growth plate injuries, muscle strains, and tendinopathies due to the asynchronous development of bone, muscle, and connective tissues [4]. By identifying fatigue thresholds and their neuromuscular correlates, coaches and sports scientists can design more effective training interventions that balance performance enhancement with injury prevention.

Neuromuscular fatigue in sprinting arises from a complex interplay of peripheral and central mechanisms [6]. Peripheral fatigue primarily stems from metabolic byproduct accumulation, e.g., inorganic phosphate, hydrogen ions, that impair cross-bridge cycling and calcium release within muscle fibers [8]. This is particularly relevant in short-duration, high-intensity sprints, where rapid ATP depletion and glycolytic flux lead to the onset of early fatigue [15]. Additionally, impaired sodium-potassium pump activity during repeated sprints can disrupt sarcolemma excitability, which further compromises force production [5]. Central fatigue, on the other hand, involves reduced motor cortex output and altered spinal reflex modulation, limiting voluntary muscle activation [12]. Studies using transcranial magnetic stimulation (TMS) have demonstrated that adolescent athletes exhibit greater central fatigue following high-intensity sprint repetitions compared to adults, possibly due to immature corticospinal pathways [8]. This has critical implications for training prescription, as excessive fatigue accumulation may hinder motor skill acquisition and technical proficiency in developing sprinters. Biological maturation significantly influences neuromuscular fatigue thresholds in adolescent athletes [15]. The rapid growth spurts associated with adolescence can also introduce biomechanical inefficiencies such as altered limb lever lengths and temporary reductions in coor-

dination that worsen fatigue [5]. Emerging evidence suggests that sex differences further modulate fatigue responses in adolescent sprinters [8]. Female athletes, for instance, may experience greater neuromuscular fatigue due to lower baseline muscle mass and differences in neuromuscular activation patterns [15]. These findings underscore the need for individualized fatigue monitoring strategies that account for maturation status, sex, and training background.

Despite growing recognition of fatigue's impact on adolescent sprint performance, few studies have systematically examined fatigue thresholds in this population [6]. Current training guidelines often infer from adult data, potentially overlooking the unique physiological and biomechanical constraints of adolescent athletes [4]. Additionally, existing fatigue assessment tools, such as countermovement jump (CMJ) decrement tests or surface electromyography (EMG), have not been sufficiently validated in younger cohorts [5]. This study was undertaken to quantify the thresholds of fatigue among adolescent sprinters and to examine the effect of biological maturation on the ability of fatigue resistance among the participants. Exploring the relationship between the chemistry of fatigue and different factors associated with the development of adolescents, this study will provide scientific evidence-based information, ensuring safe and effective training mechanisms for adolescent sprinters.

Materials and methods. This experimental research study was conducted to assess the effect of an 8-week neuromuscular training intervention to determine the thresholds of fatigue and its effects on the sprint performance of adolescent male sprinters. Participants of the study comprised 36 volunteer adolescent male sprinters aged between 15–17 years recruited from three different academies, namely (1) Glowing Star, (2) Health Support, and (3) Fitness and Health, in Lahore city. Inclusion criteria included ≥ 2 years of competitive experience, falling within the prescribed age limit, and having no musculoskeletal issues for the last six months. Participants with any chronic medical condition, cardio-respiratory history, or recent surgery were excluded from the study. Before inclusion in the study, informed consent was obtained from all the participants. At the beginning, an initial evaluation of various aspects of fatigue-related factors was performed. This included a forty-meter sprint test conducted through Brower Timing Systems, a laser timing gate, followed by the analysis of the vastus late-

ralis and biceps femoris during maximal sprints, measured through electromyography (EMG), while the Borg Rating of Perceived Exertion (RPE) scale (6–20) was used to measure the pivot of the study: the perception of the subjective fatigue among the participants. The intervention program was followed for 8 weeks at a frequency of four sessions a week. Plyometric activities of depth jumps and bounding, added by resisted sprints with sled towing at 20% body mass, accompanied by endurance activities with gradual progressive overload. A two-phased implementation strategy was used; during the initial 1–4 weeks, moderate-intensity activities, focusing on technique development, were followed, and during the next 5–8 weeks, activities of high intensity were emphasized. After 8 weeks of treatment, post-treatment assessments were made to have post-treatment data and to see any possible changes in the sprint performance, neuromuscular coordination, and fatigue resistance capacity of the experimental group. For the analysis of data, Statistical Package for Social Sciences (SPSS) version 28.0 was used. Different metrics of pre- and post-treatment were compared by the paired t-tests. Similarly, relationships between the EMG-derived fatigue markers, median frequency shifts, and the timing of the sprint performance were examined by Pearson's correlation coefficients. For the analysis of data, statistical significance was set at $p < 0.05$, and Cohen's d was used for the assessment of effect size. Regular attendance of more than 90% and adherence of the participants to the principles of the training protocol were ensured during the entire course of intervention.

Results. To ensure the appropriateness of the parametric statistical analyses, the Shapiro – Wilk test was conducted to assess data normality for all variables. The Shapiro – Wilk test was used to assess normality (W-values close to 1 indicate normality). All variables had $*p* > 0.05$, confirming normal distribution, supporting the use of parametric tests (e. ., paired $*t*$ -tests) for comparisons. Since data were normally distributed, mean $\pm$ SD and $*p*$ -values from $*t*$ -tests (Tables 1–3) are valid for interpretation.

Table 2 shows the effect of the 8-week intervention, reflecting a statistically significant improvement in both 10 m and 40 m sprints. Because of the improved explosive acceleration proficiency, there was a 3.3% reduction in 10 m sprint time ($\Delta = 0.06$ s) and a 2.8% improvement in 40m performance ($\Delta = 0.16$ s) on account of better maintenance of velocity during the efforts for an extended period. Findings of the study support the notion that neuromuscular training plays a significant role in improving the initial acceleration and subsequent fatigue resistance capability during strenuous exertion in adolescent sprinters. Notable improvement in the 40 m sprint timing is a testimony to the efficacy of the intervention for withstanding the feelings of fatigue threshold during high-intensity sprinting activities.

Table 3 depicts that post-intervention electromyographic analyses confirm significant increases in the RMS amplitude ($*p* < 0.05$) for both variables, the vastus lateralis with a 15.6% increase and the biceps femoris with a 13.2% increase during maximal sprint efforts. These findings indicate enhanced neuromuscular recruit-

Normality Test (Shapiro – Wilk Test)

Variable	Pre-Test (W-value, $*p*$)	Post-Test (W-value, $*p*$)
10 m sprint (s)	0.97, $*p* = 0.421$	0.96, $*p* = 0.372$
40 m sprint (s)	0.98, $*p* = 0.512$	0.97, $*p* = 0.465$
Vastus lateralis (mV)	0.95, $*p* = 0.285$	0.96, $*p* = 0.340$
Biceps femoris (mV)	0.96, $*p* = 0.398$	0.97, $*p* = 0.410$
RPE (10m sprint)	0.94, $*p* = 0.210$	0.95, $*p* = 0.302$
RPE (40m sprint)	0.96, $*p* = 0.375$	0.95, $*p* = 0.276$

Table 1

Sprint performance changes in the experimental group

Variable	Pre-Test (Mean $\pm$ SD)	Post-Test (Mean $\pm$ SD)	p-value
10 m sprint (s)	1.82 $\pm$ 0.11	1.76 $\pm$ 0.09	0.012*
40 m sprint (s)	5.64 $\pm$ 0.23	5.48 $\pm$ 0.19	0.003*

Table 2

Table 3

EMG Activity (Root Mean Square Amplitude, mV)

Muscle	Pre-Test (Mean $\pm$ SD)	Post-Test (Mean $\pm$ SD)	*p*-value
Vastus lateralis	0.45 $\pm$ 0.08	0.52 $\pm$ 0.07	0.008*
Biceps femoris	0.38 $\pm$ 0.06	0.43 $\pm$ 0.05	0.021*

Table 4

Perceived Exertion (RPE Scale 6–20) Session Phase

	Pre-Test (Mean $\pm$ SD)	Post-Test (Mean $\pm$ SD)	*p*-value
After 10 m sprint	15.2 $\pm$ 1.4	13.8 $\pm$ 1.1	0.004*
After 40 m sprint	18.6 $\pm$ 1.8	16.3 $\pm$ 1.5	0.001*

*RPE (Rating of Perceived Exertion): a subjective scale (6–20) quantifying an athlete's effort perception, integrating physiological, e.g., cardiorespiratory stress, muscle fatigue, and psychological strain.

ment in the form of activation of high-threshold motor units, which are critical for sprint performance. Secondly, greater activation of the vastus lateralis (knee extensor) and biceps femoris (hamstring) has significant functional implications, particularly in sprinting activity, which correlates with improved acceleration, reducing the risk of injuries, and alternately improving stride efficiency. The interplay of training and adaptation works on physical as well as neural fronts, which finally supports fatigue resistance capability during strenuous exertions.

Table 4 shows a significant reduction in the post-intervention assessment in perceived exertion (*p* < 0.01), reflecting enhanced tolerance to heavy exertion of sprint efforts as the 10m sprint: 9.2% decrease (RPE 15.2 $\rightarrow$ 13.8) reflects lower neuromuscular and metabolic demand during acceleration. Lower RPE aligns with improved acceleration efficiency. Similarly, optimum fatigue resistance at maximal speed was also observed in the 40-meter sprint; a 12.4% decrease (RPE 18.6 $\rightarrow$ 16.3), which shows anaerobic proficiency and neuromuscular endurance. Greater RPE reduction suggests adaptations in anaerobic glycolysis buffering and/or delayed motor unit fatigue, supported by increased hamstring activation. In addition, reduced RPE implies improved movement efficiency, e.g., better stretch-shortening cycle utilization and reduced energy leakage. The greater RPE reduction in the 40m case particularly supports the effectiveness of the intervention in enhancing fatigue resistance capability.

Discussion. This study aims to quantify the thresholds of fatigue among male adolescent sprinters and to examine the effect of 8-week neuromuscular training on the ability of fatigue

resistance among the adolescent sprinters. Findings of the study have confirmed significant improvement in the fatigue thresholds and sprint performance of the participants. The structured and plyometric training of adolescents can enhance fatigue thresholds and sprint performance [17]. As depicted in Table 1, the improvement in the sprint performance is associated with the recruitment of the additional motor units. These results align with the research that high-intensity structured training enhances neural drive to muscles actively engaged in the activity [14]. Moreover, the EMG data manifest enhanced activation of muscles in the case of the vastus lateralis and biceps femoris. Neuromuscular adaptations guide towards morphological improvement in adolescents [13]. The improved fatigue management is linked with both physiological and psychological adaptations reflected in a reduction in perceived exertion (Table 3). The findings of the present study claim that on account of enhanced neuromuscular efficiency, adolescents manifest improved fatigue resistance [15]. However, short-term training intervention documents only nominal improvement in RPE of the adolescents [8]. This inconsistency in the findings is likely to be associated with the difference in the volume and intensity of the intervention.

The focus of the intervention of the present study was based on neuromuscular specificity employing sprints and plyometrics. EMG results of the present study confirm the activation of additional motor units during optimal efforts. In this regard, improving stretch-shortening cycle efficiency and motor unit synchronization [9]. Likewise, a decrease in the RPE reflects movement economy as neuromuscular training improves coordination among different organs and parts

of the body, thereby delaying symptoms of fatigue [6]. Regardless of the favorable results of the present study, there are a few studies showing conflicting evidence opposing the findings of this study. Maturation of the central nervous system, adolescents manifest limited neuromuscular adaptation in comparison to adults [2, 15]. Adolescents require prolonged intervention for proper neuromuscular adaptation [13]. Considering the findings of the present study, coaches, trainers, and sports practitioners should prioritize the integration of neuromuscular training into adolescent sprint conditioning programs. Firstly, it will enhance the recruitment of additional motor units during continuous exertion, and secondly, it will enhance the muscular efficiency of the stretch-shortening cycle. Using the progressive overload technique will lead to continuous adaptation and result in prolongation of the fatigue threshold among adolescents. For future research, it is suggested to conduct a research study to assess long-term (>12 weeks) neuromuscular adaptation and include athletes from both genders to view sex-specific responses toward neuromuscular adaptation and fatigue threshold. The present study highlights the role of a structured neuromuscular training program in improving neuromuscular adaptation and fatigue resistance; hence, properly tailored neuromuscular training improves fatigue thresholds among adolescent sprinters through the activation of additional motor units and perceived exertion.

Conclusions. The 8-week neuromuscular training program has potentially increased sprint performance and fatigue thresholds in adolescent sprinters aged 15–18 years. Visible improvements in 10 m and 40 m sprint times ($p < 0.05$) provide scientific evidence confirming the role of neuromuscular training in enhancing the explosive power and speed maintenance attributes in

adolescent sprinters. In addition to the improvement in performance, enhanced EMG performance of the vastus lateralis and biceps femoris, the basic sprinting muscles, was also observed, confirming greater recruitment of the additional motor units. Intervention efficacy is further strengthened by the subsequent reduction in perceived exertion in terms of enhancing fatigue resistance, which can be linked with the collective adaptation of metabolic, neural, and psychological aspects. Integration of the neuromuscular training in adolescent sprint training programs and monitoring of the sprint performance and physiological markers, EMG, and RPE will help the coaches and practitioners to make the training program more productive. The present study has advanced the understanding regarding the thresholds of fatigue in adolescent sprinters by recognizing different patterns of fatigue, decline in performance, and physiological adaptation. The present study concludes with evidence-based practical measures for enhancing training loads, improving recovery time, minimizing the risk of injuries, and adding useful insights to the field of sports sciences and physical education. It is suggested that future researchers include female participants, focus on longer-term adaptations (>12 weeks), and utilize the latest monitoring techniques, such as force plates and biomarker analysis, to better understand the biological and physiological factors underlying these improvements.

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