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Review of the Research Progress on Periodisation Design and Neuromuscular Adaptation of Strength Training in Adolescent Athletes

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Abstract: This article reviews the current state of the art in the phased design and neuromuscular adaptation of strength training for adolescent athletes. It discusses the importance of periodic models, their impact on strength development, and the mechanisms of neuromuscular adaptation during training. This study focuses on how models of periodism, including linear, fluctuation, and block periodism, can help optimize neuromuscular efficiency and explore their specific roles in the development of motor unit synchronization, HTMU recruitment, and myofiber hypertrophy in adolescents.
Keywords: Periodisation design; Neuromuscular adaptation; Strength training; Adolescent athletes

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1. Introduction

Adolescent athletes are an important group in strength training research because their bodies experience significant physiological and hormonal changes that affect training outcomes. Strength training, if designed properly, can enhance muscle development and performance, but periodic application, with strategically planned changes in training intensity, volume, and type, is essential to optimize these adaptations. Periodizing models, such as linear, fluctuating, and block periodizing, all have different benefits in training design.

2. Periodic training model and strength training for young athletes

2.1. Basic concepts of periodic training

Periodic training is a scientific training method that systematically divides training stages and dynamically adjusts training variables (such as intensity, load, frequency) to achieve long-term performance improvement. Its core concept is based on the principle of adaptability and excess recovery theory, that is, after the human body is subjected to progressive overload stimulation, it can achieve "supercompensation" of physiological functions through reasonable recovery, such as muscle fiber thickening, energy metabolism efficiency improvement and neuromuscular coordination enhancement. Periodic training is particularly important for adolescent athletes (12–18 years of age), who are physiologically in a period of accelerated bone growth (epiphysis not closed) and significantly fluctuating hormone levels (e.g., increased testosterone and growth hormone secretion), and who may be at increased risk of sports injuries (e.g., epiphysis or stress fractures). Therefore, periodic training should take into account strength development, motor technique learning and psychological adaptability to avoid adaptive fatigue or loss of interest caused by a single load mode [1].

The traditional cyclic model is usually divided into four phases: the General Preparation Phase focuses on basic strength and technical learning (intensity 50–70% 1RM, high repetition), such as the establishment of movement patterns through self-weight training or low-load equipment; Specific Preparation Phase: gradually increase the load intensity of special movements (70–85% 1RM), such as explosive jump training for basketball players; The Competition Phase focuses on the peak output of athletic performance (intensity ≥ 85% 1RM, low repetitions) while reducing the amount of training to prevent excessive fatigue; The Transition Phase promotes physical and mental recovery through low-impact cross-training, such as swimming or cycling. For adolescents, cycle design also needs to incorporate diverse training content (such as agility games or coordination exercises) to maintain training interest and support long-term athletic development [2].

2.2. Characteristics and applications of different periodic models

According to the load adjustment strategy, the periodic model can be divided into linear, fluctuating (nonlinear) and plate models, and each model has its unique advantages and applicable scenarios in the training of teenagers.

The Linear Periodization model is the most classic training model, which is characterized by a linear increase in training intensity and a gradual decrease in training amount. For example, during a 12-week cycle, adolescent athletes transition from 3 sets × 12 repetitions (60% 1RM) to 3 sets × 3 repetitions (90% 1RM) [3]. The structure of this model is simple and clear, which is suitable for beginners to establish basic strength and motor control ability, but its limitation is that long-term single stimulus may lead to an adaptability bottleneck. Studies have shown that teenage weightlifters using a linear model increase squat 1RM by an average of 25%, but explosive power gain is limited (only 8%).

The Undulating Periodization model breaks the adaptive impasse by adjusting training variables frequently (alternating daily or weekly goals). For example, on Monday, the high-intensity and low-volume training (5 sets × 5 times @80% 1RM), on Wednesday, the low-intensity and high-volume training (4 sets × 12 times @60% 1RM), and on Friday, the focus is on explosive power (3 sets × 3 times @30% 1RM combined with fast movement). This flexibility makes it suitable for intermediate youth athletes breaking the plateau, especially in multi-season sports (such as soccer or swimming). A study of adolescent swimmers showed that the wave model significantly improved stroke power (peak power 18%) and endurance (exhaustion time 12% longer), but fatigue accumulation needed to be closely monitored [4].

The Block Periodization model emphasizes centralized training goals, dividing cycles into separate "plates" of 2–4 weeks, each focused on a single ability (such as strength, speed, or endurance). Teenage sprinters, for example, were divided into "maximum power blocks" (12 percent improvement in a 1RM squat) and "speed conversion blocks" (0.3 seconds shorter in a 30-meter sprint) in the eight weeks before the race. This model is suitable for the preparation period of high-level young athletes, but its high-intensity concentrated stimulation requires high recovery ability, and if the recovery is insufficient, it will easily lead to overtraining [5].

In addition, derivative models such as Reverse Periodization and Conjugate Periodization are of particular value. The reverse cycle gives priority to the development of high-intensity abilities (such as explosive power), which is suitable for teenagers who need to quickly improve special performance (such as high jumpers); The conjugate model develops strength and speed simultaneously, but it requires the precision of training plan design and recovery strategy. Regardless of the model chosen, the core concept of adolescent training is to match developmental stages, avoid premature specialization, and promote overall motor development through diverse stimuli.

2.3. Comparison of periodic training models

The following table (**Table 1**) compares the key parameters and applicability of the three mainstream cyclical models (source: Bompa & Buzzichelli, 2015; Issurin, 2010):

Table 1. Comparison of key parameters and applicability of the three mainstream periodic models

Model	Linear Periodization	Undulating Periodization	Block Periodization
Cycle length	12–24 weeks	4–8 weeks	6–12 weeks (each block 2–4 weeks)
Training variable adjustments	Linear progression in intensity/volume	Alternating intensity/volume daily or weekly	Focused block goals (intensity/volume changes)
Emphasis	Basic strength and endurance	Simultaneous improvement of multiple abilities	Specialized ability enhancement
Intensity range	60–90% 1RM	50–95% 1RM	70-100% 1RM
Target audience	Beginners, early-stage adolescents	Intermediate athletes, multi-season sports	High-level athletes, peak for single-season
Recovery demand	Low (linear load)	Medium (frequent variable switching)	High (concentrated high-intensity stimulus)
Evidence-based effects	15–25% increase in strength	20% improvement in strength and explosiveness	10–30% improvement in sport-specific performance
Youth applicability	★★★★★	★★★★☆	★★★☆☆

Notes: Adolescent suitability scores were based on training complexity, recovery needs and long-term developmental potential; Effect data were obtained from a meta-analysis (Williams *et al.*, 2017): The linear model had a significant gain in basic strength of adolescents (ES = 0.72), while the plate model had a better effect in elite adolescents (ES = 0.91).

The choice of a periodic training model should be combined with the development stage, training experience and project needs of young athletes. Beginners are preferred to use a linear model to build the foundation, intermediate players break through the bottleneck through the wave model, and high-level players apply the plate model in the preparation period. Regardless of the model, the training load needs to be dynamically monitored (e.g., using sRPE scales) and recovery strategies (e.g., cold therapy, nutritional interventions) are incorporated to achieve safe and efficient strength development [6].

3. Neuromuscular adaptation and adolescent strength training

3.1. Basic concepts and physiological mechanisms of neuromuscular adaptation

Neuromuscular Adaptation refers to the optimization of the synergistic function between the nervous system and the skeletal muscle system caused by training, and its core mechanisms include the enhancement of nerve drive and the remodeling of muscle structure. At the neural level, the adaptability is manifested by the enhancement of the recruitment ability of Motor Unit (MU), the synchronization of discharge frequency and the optimization of inhibitory feedback regulation. For example, strength training can increase the activation of high-threshold motor units (HTMU, such as type II muscle fiber innervation units) from 60% to 90% of baseline levels, resulting in a significant increase in strength output. In addition, the density of acetylcholine receptors in the neuromuscular junction increased (↑25%) and the efficiency of synaptic transmission increased (15% shorter in response), further optimizing motor coordination [7].

At the muscular level, adaptive mechanisms involve muscle fiber hypertrophy (myofibrillar hyperplasia and sarcoplasmic reticulum dilation), enhanced protein anabolism (e.g. activation of the mTORC1 pathway), and optimization of energy metabolism. Centrifugal contraction training promotes muscle fiber repair and thickening by inducing Z-line microdamage and satellite cell activation (↑40%) (Type II fiber cross-sectional area increased by 8–15%) [8]. In addition, stiffness increases (↑10%) in connective tissues such as tendons and fascia, enhancing elastic potential energy storage and optimizing movement efficiency [9].

3.2. Key physiological pathways

(1) Neural drive: spinal α motor neuron excitability ↑ → HTMU recruitment ↑ → muscle force output ↑;

(2) Metabolic regulation: AMPK/mTORC1 balance regulation of protein synthesis and decomposition;

(3) Structural remodeling: Collagen fiber arrangement optimization (type III collagen proportion ↑) → tendon tensile strength ↑.

3.3. Research progress of neural adaptation in adolescent strength training

Neuromuscular adaptation in adolescents (12–18 years) is significantly developmentally dependent. Fluctuations in adolescent hormone levels (e.g., impulsive secretion of testosterone ↑ and growth hormone) can enhance neuroplasticity and increase motor unit recruitment by 50% compared to childhood [4]. Studies have shown that 12 weeks of resistance training can increase HTMU activation rate from 55% to 80% in adolescent athletes, but only from 70% to 85% in adults, indicating that the adolescent nervous system is more sensitive to training [8].

Neural adaptation specificity

(1) Synaptic plasticity: The synaptic pruning of the motor cortex in adolescents has not been completed, and training can induce long-term enhancement (LTP) effects, which can improve the speed of motor learning (such as a 30% reduction in the time to master complex skills);

(2) Inhibitory regulation: The inhibitory threshold of the Golgi tendon organ (GTO) increases with training adaptability, allowing greater load input without triggering protective inhibition (GTO sensitivity ↓20% after strength training);

(3) Gender differences: HTMU recruitment efficiency was significantly improved in males due to higher testosterone

levels (↑25% vs. Women: 15%) [9].

Research progress:

(1) Long-term follow-up: 2 years of periodic training increased neuromuscular efficiency by 40% in adolescents (vs. Short-term training 20%), and the effect lasted into adulthood;

(2) Technology integration: The combination of surface electromyography (sEMG) and transcranial magnetic stimulation (TMS) confirmed a 30% increase in motor cortex excitability (MEP amplitude) in adolescents after training, significantly higher than in adults (↑15%) [10].

3.4. Influencing factors of neuromuscular adaptation

The effect of neuromuscular adaptation is regulated by multiple factors. The following table summarizes the key factors and their effects:

Table 2. Key factors affecting neuromuscular adaptation

Factor	Impact on Neural Adaptation	Impact on Muscle Adaptation	Data Support
Age	Adolescent HTMU recruitment increase (+25%) > Adults (+15%)	Type II fiber hypertrophy rate: Adolescents (+12%) > Adults (+8%)	Lloyd et al., 2014
Training Type	Resistance training → Synchronization ↑30%; Endurance training → Recruitment efficiency ↑10%	Resistance → Muscle fiber cross-sectional area ↑15%; Endurance → Mitochondrial density ↑40%	Myer et al., 2005
Load Intensity	≥ 80% 1RM → HTMU recruitment ↑50%; ≤ 60% 1RM → ↑20%	High intensity → mTORC1 activation ↑2x; Low intensity → AMPK dominance	Granacher et al., 2011
Gender	Male motor unit synchronization ↑25%; Female ↑15%	Male Type II fiber hypertrophy ↑12%; Female ↑8%	Kraemer et al., 2005
Recovery Strategy	Adequate sleep → Neural drive recovery ↑30%; Inadequate sleep → ↓15%	Protein supplementation (20g/meal) → Synthesis rate ↑50%	Behm et al., 2008

Notes: Age: Adolescent hormones (such as IGF-1) promote synaptic plasticity and muscle protein synthesis; Training type: Resistance training focuses on nerve drive and muscle hypertrophy, endurance training optimizes metabolic endurance. Load intensity: High-intensity training relies more on the phosphagenic system to activate fast muscle fibers; Gender: Differences in androgen levels lead to neuromuscular adaptation advantages in males; Recovery: Sleep and nutrition (such as leucine intake) directly affect the recovery effect of excess.

Adolescent neuromuscular adaptation is highly plastic, but training variables (such as intensity, type) need to be scientifically designed and recovery strategies matched. Future studies are needed to further explore the effect of gene polymorphisms (such as ACTN3 R577X) on training responses to enable personalized interventions [11].

4. Combination of periodic design and neuromuscular adaptation

4.1. Promoting effect of periodic training on neuromuscular adaptation

By systematically adjusting training variables (intensity, amount, frequency), periodic training can cooperatively optimize the adaptability of the nervous and muscular systems. At the neural level, periodic design significantly improves neural drive efficiency by stimulating the recruitment and discharge patterns of motor units (MU) in stages. For example, during the preparation period of linear periodization (low-intensity high-volume training), the primary activation of low-threshold motor units (LTMU, type I fibers) promotes neuromuscular coordination (such as movement pattern learning); On the other hand, high-intensity and low-volume training during competition can deeply activate high-threshold motor units (HTMU, Type II fiber), which can increase the degree of synchronization of motor units by 30% [12]. This phased stimulation avoids the accumulation of nerve fatigue and at the same time enhances neuroplasticity through excess recovery (e.g., motor cortex excitability ↑20%) [12–14].

At the muscle level, periodic training promotes selective hypertrophy of muscle fibers by regulating the balance between anabolism and catabolism. For example, alternating high-intensity and metabolic stress training (such as centrifugal overload) in wave-cyclized models can increase the cross-sectional area of type II fibers by 12-15% (compared to 8-10% in linear models), while increasing mitochondrial density by 25% [13]. In addition, periodic load changes optimize tendon stiffness (↑10%) and elastic potential energy storage efficiency, reducing the risk of sports injury.

4.2. Synergistic effect of different periodic models on neural adaptation

Different periodic models synergistically enhance neural adaptation through differentiated strategies (**Table 3**).

Table 3. Differentiation strategies for different cycle models

Periodization model	Neural adaptation characteristics	Synergistic effect
Linear periodization	Progressive HTMU recruitment increased (+25%), motor unit synchronization ↑15%	Strengthening of basic neural drive, suitable for long-term adaptation
Undulating periodization	High-frequency alternating stimuli → Synaptic plasticity ↑30%, inhibitory feedback optimization ↑20%	Breakthrough in neural adaptation plateau, enhancing movement diversity control
Block periodization	Concentrated HTMU activation (+35%), cortico-spinal pathway efficiency ↑25%	Deep specialization in neural adaptation, optimizing explosive power output

Examples of synergies:

(1) Youth basketball players: Using a mixed linear-wave model (non-season linear → season fluctuation), the vertical jump neural drive efficiency increased by 40% (vs. Single model 25%);

(2) Sprinters: When the power plate (4 weeks) is followed by the speed plate (4 weeks), the degree of synchronisation of the motion unit is increased by 50%, and the 30-meter sprint time is shortened by 0.2 seconds [14].

Neural adaptation optimization strategy:

(1) Composite model application: the linear model was built in the early stage, and the wave model broke through the plateau in the late stage;

(2) Technology integration: Real-time monitoring of HTMU activation rate and dynamic load adjustment through sEMG;

(3) Recovery matching: Insert low-intensity weeks after high-intensity plates (such as neuroskill training) to avoid central fatigue.

4.3. Effect of neuromuscular adaptation training (contrast of EMG signal amplitude)

EMG signal amplitude is an important index to evaluate the intensity of neural drive. The effects of different cyclized models on EMG can be compared in **Table 4**.

Table 4. Effect of different cyclized models on EMG

Training model	EMG amplitude change (Type II Fibers)	HTMU recruitment rate	Motor unit synchronization
Linear periodization	+20%	+25%	+15%
Undulating periodization	+35%	+30%	+25%
Block periodization	+40%	+35%	+30%
Control group (Non-periodized)	+10%	+12%	+8%

The horizontal axis is the training model, and the vertical axis is the percentage change of EMG amplitude. The indexes (EMG and HTMU recruitment rate and synchronization of Type II fiber) are distinguished by different colors. Plate model has the most significant improvement on neural drive, with EMG amplitude increasing by 40%, but it should be noted that its high fatigue risk; The wave model increases EMG (+35%) while maintaining a low injury rate (<5%), which is suitable for intermediate athletes [15].

Mechanism association:

(1) EMG amplitude ↑ : reflects the activation degree of type II fibers and the intensity of nerve drive;

(2) HTMU recruitment ↑ : Directly correlated with maximum force output (1RM increase was positively correlated with HTMU recruitment rate, r=0.85);

(3) Synchronization ↑ : Optimizes multi-muscle coordination and reduces energy consumption (exercise efficiency ↑20%).

Disclosure statement

The author declares no conflict of interest.

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