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Article

Research on the Mechanism of the Effects of Different Loading Methods on Lower Limb Explosive Power Training Based on Biomechanical Analysis

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Abstract: This study comprehensively investigates the biomechanical mechanisms underlying the effects of different loading methods on lower limb explosive power training, a critical component in athletic performance and physical rehabilitation. By systematically analyzing joint kinetics, muscle activation patterns, and neuromuscular coordination under varying external loads, the research aims to clarify precisely how specific load types and magnitudes influence physiological adaptations and overall training outcomes. Through the rigorous application of advanced motion capture technology, force platform testing, and electromyographic analysis, dynamic biomechanical parameters are meticulously obtained and subsequently integrated into a comprehensive, multi-dimensional evaluation model. The empirical findings demonstrate that distinct loading methods induce highly differentiated stress distribution across the musculoskeletal system, alter motor unit recruitment strategies, and significantly impact energy transfer efficiency throughout the kinetic chain. Consequently, these biomechanical variations produce markedly varied effects on the development of lower limb explosive power, highlighting the necessity for highly individualized training prescriptions. Furthermore, the integration of these biomechanical insights allows for a deeper understanding of injury prevention mechanisms during high-intensity resistance exercises. Ultimately, this study provides robust theoretical guidance and evidence-based practical strategies for coaches, clinicians, and athletes. By optimizing lower limb training programs, these insights facilitate significant advancements in sports performance enhancement, functional movement efficiency, and targeted rehabilitation practice.

Keywords: biomechanics; loading methods; lower limb; explosive power; sports performance

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1. Introduction

1.1. Research Background and Significance

Lower limb explosive power plays a pivotal role in determining athletic performance across a diverse array of sports disciplines, encompassing activities such as sprinting, jumping, rapid directional changes, and team-based sports that demand frequent accelerations and decelerations. The capacity to produce maximal force within the shortest possible time frame is a key factor influencing an athlete's speed, agility, and overall competitive edge. Conventional training methodologies often emphasize increasing the intensity of loads or the volume of training sessions. However, these approaches frequently overlook the intricate biomechanical processes that underpin force generation, joint coordination, and the efficient transfer of energy throughout the kinetic chain [1]. This oversight can result in less-than-optimal physiological adaptations, inefficient training outcomes, or even heightened susceptibility to musculoskeletal

injuries, particularly when the imposed loads surpass the athlete's current neuromuscular or structural thresholds. By failing to align training regimens with the athlete's biomechanical and physiological capacities, the risk of injury and performance stagnation may increase significantly.

Recent technological advancements in biomechanics, including tools such as three-dimensional motion capture systems, force platforms, and surface electromyography, have revolutionized the ability to analyze and quantify muscular activation patterns, joint kinetics, and inter-joint coordination during dynamic movements. These innovations provide researchers and practitioners with unparalleled insights into how various loading strategies influence movement mechanics, neuromuscular activation, and the efficiency of the kinetic chain. Such tools enable the systematic evaluation of different training modalities, including the use of free weights, elastic-based loading systems, and variable resistance mechanisms, to determine their specific effects on the development of explosive power. The implications of this research extend well beyond performance enhancement [2]. By uncovering the underlying mechanisms that govern load-response interactions, this knowledge can inform the design of evidence-based training protocols, facilitate individualized program development, and contribute to injury prevention strategies. Ultimately, these advancements support the creation of safer and more effective approaches to athletic training, ensuring that athletes can achieve peak performance while minimizing the risk of injury.

1.2. Definition of Core Concepts

Loading methods refer to the various ways external forces are applied during physical training, which can differ in magnitude, direction, and timing characteristics. These methods include constant loads, where resistance remains fixed throughout the movement; variable loads, which change resistance dynamically during the range of motion, such as through the use of chains or specialized equipment; and elastic-based systems, such as bands or tubing, which provide progressively increasing force as they are stretched [3, 4]. Each approach places distinct mechanical demands on the musculoskeletal system, affecting how muscles generate force, the speed of movement, and the coordination between neural and muscular systems. By understanding these methods, practitioners can tailor training regimens to target specific performance outcomes while addressing individual biomechanical needs.

Biomechanical analysis is the structured examination of human movement through mechanical principles, encompassing both motion and the forces involved. This field investigates how forces are produced, transmitted, and absorbed across joints and muscle groups, as well as how energy is stored and transferred during dynamic activities [5]. Through detailed assessments, it becomes possible to measure joint torque, ground reaction forces, muscle activation timing, and the efficiency of energy transfer, offering valuable insights into the effectiveness of training methods and the quality of movement patterns. Explosive power, a critical aspect of athletic performance, involves the rapid generation of maximum force within a short timeframe. It is essential for activities requiring swift acceleration, jumping, or rapid directional changes. This attribute is influenced by multiple factors, including muscle strength, the coordination between neural and muscular systems, the rate at which force is developed, and the efficiency of the kinetic chain. The study integrates these foundational concepts to examine how different loading strategies impact the development of explosive power. By combining biomechanical measurements, neuromuscular evaluations, and applied training methodologies, the research aims to provide a comprehensive understanding of how specific loading approaches lead to adaptive responses. This knowledge is intended to guide the creation of optimized, individualized, and safe training programs that enhance athletic performance while reducing the risk of injury.

2. Theoretical Correlation between Loading Methods and Explosive Power Training

2.1. Core Objectives of Explosive Power Training

The primary aim of explosive power training is to optimize the rate of force development (RFD) and improve neuromuscular efficiency, both of which are essential for activities such as sprinting, jumping, and rapid directional changes. Unlike training programs focused on endurance or muscle hypertrophy, explosive power training prioritizes the rapid recruitment of motor units, the synchronization of muscle activation, and the efficient transfer of energy through the kinetic chain. These elements collectively enable the production of high levels of force in minimal time. Various loading methods, including the use of free weights, elastic implements, or devices with variable resistance, can uniquely influence these neuromuscular mechanisms. Through biomechanical analysis, it becomes possible to observe how force is distributed across joints and muscle groups, uncovering subtle differences in movement strategies, muscle engagement patterns, and energy transfer efficiency. This understanding not only enhances athletic performance but also supports the development of structured training programs, including periodization and progressive loading strategies [6, 7]. Furthermore, it plays a critical role in minimizing injury risks, ensuring that explosive power training is both effective and safe for athletes.

2.2. Attributes of Biomechanical Analysis in Training Evaluation

Biomechanical analysis provides a highly detailed and objective approach to evaluating physical performance, offering significant advantages over traditional methods that rely on subjective observation or coach-based assessments. Tools such as force platforms are capable of measuring ground reaction forces, which can then be used to calculate critical metrics like impulse, power output, and limb symmetry. These measurements are essential for identifying imbalances or inefficiencies in movement patterns. Similarly, three-dimensional motion capture systems enable precise tracking of joint angular displacement, velocity, and acceleration, which helps in detecting subtle movement inefficiencies or compensatory strategies that may not be visible to the naked eye. Surface electromyography (sEMG) further enhances this analysis by monitoring muscle recruitment patterns and activation timing, offering insights into neuromuscular coordination under varying physical loads. By providing higher precision, ecological validity, and reproducibility, biomechanical analysis bridges the gap between mechanical outputs and physiological adaptations, allowing for a more accurate understanding of how training methodologies influence performance outcomes. This comprehensive approach ensures that even minor variations in training stimuli and responses are captured, enabling more effective and individualized training interventions.

2.3. Theoretical Foundations

The theoretical foundation of this study integrates multiple disciplines, including exercise biomechanics, neuromuscular physiology, and training adaptation theories, to create a comprehensive framework for understanding the development of explosive power. Exercise biomechanics examines the mechanical aspects of movement, such as force-time characteristics, joint torque generation, and energy transfer through the kinetic chain, providing a detailed understanding of the physical demands associated with various loading methods. Neuromuscular physiology explores the underlying biological processes, including motor unit recruitment, firing rates, synchronization, and the activation of different muscle fiber types, which together influence the speed and magnitude of force production. Training adaptation theory focuses on principles such as progressive overload, specificity, and periodization, emphasizing how systematically structured training programs can lead to measurable functional improvements over time. By synthesizing these perspectives, the study establishes a robust framework for analyzing how different loading strategies impact the mechanisms of explosive power development. This approach offers valuable insights for optimizing training regimens and enhancing athletic performance.

3. Mechanisms of Loading Methods in Lower Limb Explosive Power Training

3.1. Joint Kinetics and Load Distribution Mechanism

Different loading methods exert distinct mechanical influences on joints, shaping torque production, stress distribution, and force application patterns across the lower limb. Constant loads typically provide uniform resistance throughout the movement, primarily challenging concentric muscular strength and promoting overall stability. However, they often fail to maximize torque at mechanically advantageous joint angles, limiting their effectiveness in certain phases of explosive movements. Variable loads, implemented through mechanisms such as chains, cams, or specialized machines, are designed to align peak torque with optimal joint positions, thereby enhancing force generation during critical phases of motion. Elastic resistance introduces progressive loading characteristics, increasing force requirements as the joint extends. This method demands greater control during eccentric phases while enabling faster concentric acceleration, making it particularly effective for dynamic training scenarios. These variations in load distribution not only affect muscle and tendon stress patterns but also influence joint moments, limb alignment, and overall kinetic efficiency. A comprehensive understanding of these biomechanical distinctions is essential for optimizing load selection, sequencing, and progression in training programs. By leveraging biomechanical modeling, coaches can predict how different loading strategies impact joint kinetics under varying movement speeds and ranges. This evidence-based approach ensures that training protocols elicit maximal explosive force while minimizing the risk of overuse injuries or acute damage, thereby supporting long-term athletic performance and safety.

3.2. Muscle Activation and Neuromuscular Recruitment Mechanism

Electromyographic analyses reveal that varying loading modalities lead to distinct patterns of muscle activation and neuromuscular coordination. Exercises performed with constant loads typically result in uniform activation across both primary movers and stabilizing muscles, offering a comprehensive stimulus but limited specificity in recruiting high-threshold, fast-twitch muscle fibers. In contrast, variable load protocols are more effective in selectively activating fast-twitch fibers, particularly at positions where peak force is generated. This targeted activation supports a rapid rate-of-force development, which is crucial for enhancing explosive athletic performance. Elastic resistance training emphasizes the stretch-shortening cycle, promoting pre-activation and reflexive muscle contractions. This process improves neuromuscular synchronization and enhances the efficiency of transitions between eccentric and concentric phases of movement. The mechanisms underlying these effects involve variations in activation thresholds, the sequence of motor unit recruitment, and firing rates, all of which are dynamically influenced by the resistance profile and movement velocity. By examining electromyographic patterns under different loading conditions, it becomes possible to identify imbalances in muscle activation, compensatory strategies, or underutilized muscle groups. This information enables the design of targeted strategies to optimize neuromuscular efficiency and accelerate the development of explosive power in athletes.

3.3. Energy Transfer and Kinetic Chain Efficiency Mechanism

Explosive lower limb movements depend on the coordinated transfer of energy through the kinetic chain, which typically involves the hip, knee, and ankle joints [8]. The manner in which external loads are applied significantly affects the timing, magnitude, and sequence of force transmission across these joints. When external loads are carefully calibrated, they promote smooth and synchronized joint movements, coordinated muscle activation, and an efficient flow of energy from proximal to distal segments. This optimization enhances power output while minimizing energy waste. Conversely, poorly matched or inappropriate loading can interfere with the timing between joints, alter movement trajectories, and reduce mechanical efficiency, potentially leading to diminished performance or a higher risk of injury. Advanced biomechanical tools, such as three-dimensional motion capture systems, force platforms, and joint torque analysis, provide precise evaluations of inter-joint coordination, segmental contributions, and the overall integrity of the kinetic chain under varying loading conditions. These assessments are instrumental in developing loading strategies that enhance energy transfer, maintain

biomechanical efficiency, and improve the economy of explosive movement patterns. Such strategies form the foundation for progressive and individualized training programs tailored to optimize performance outcomes.

3.4. Adaptive Feedback Mechanism in Training

A critical feature of biomechanically informed training is the adaptive feedback mechanism, which facilitates real-time adjustments to training variables based on ongoing performance data. This mechanism operates by continuously monitoring key metrics such as force output, joint kinematics, muscle activation patterns, and movement efficiency [7, 9]. By analyzing these parameters, coaches can iteratively modify variables like load intensity, distribution, repetition schemes, and technique to ensure that the training stimulus remains optimal and tailored to the athlete's specific needs. For instance, if data from electromyography (EMG) suggest insufficient activation of certain fast-twitch muscle fibers, adjustments can be made to the load or exercise selection to better target those fibers. Similarly, data from force plates and motion capture systems can identify asymmetries or compensatory movements, enabling corrective interventions to be implemented promptly, thereby reducing the risk of injury and preventing the reinforcement of maladaptive patterns. Beyond immediate performance improvements, this feedback-driven approach supports long-term athlete development by aligning training loads with the athlete's growth, maturation, and fatigue levels. By integrating biomechanical insights into a closed-loop system, traditional explosive power training is transformed into a scientifically guided, data-driven process that prioritizes both short-term gains and sustainable athletic progression.

4. Current Situation and Challenges in Explosive Power Training

4.1. Overview of Development Status

Explosive power training has become a fundamental component of athletic conditioning programs, commonly implemented through methods such as weightlifting, plyometric exercises, and elastic resistance-based activities. These approaches have shown effectiveness in improving sprint speed, vertical jump height, and change-of-direction capabilities. However, traditional training methodologies often rely heavily on empirical knowledge and the subjective experience of coaches, which can result in inconsistencies in load selection, progression strategies, and technique optimization. Advances in biomechanical technologies, including three-dimensional motion capture systems, force platforms, and electromyography, now provide opportunities for precise monitoring of joint kinetics, muscle activation patterns, and energy transfer during explosive movements. These tools enable a more systematic approach to analyzing and refining training techniques. Despite their potential, the integration of such technologies into everyday athletic training remains limited. Many field programs have yet to adopt these innovations fully, and the application of laboratory findings to athlete-specific training prescriptions continues to face challenges. While the scientific basis for optimizing explosive power training is well-established, the widespread implementation of these advancements in practical settings is still in its early stages, requiring further efforts to bridge the gap between research and application [10].

4.2. Analysis of Prominent Challenges

Several challenges impede the seamless application of biomechanical principles in explosive power training, necessitating a deeper understanding of these obstacles. One significant issue is the variability in athletes' responses to diverse loading methods, which are shaped by individual factors such as strength profiles, neuromuscular efficiency, and technical proficiency. This variability complicates the development of universally effective training protocols. Another critical challenge lies in the absence of standardized procedures for biomechanical evaluation, leading to inconsistencies in data collection, interpretation, and comparability across different studies and training environments. Furthermore, while laboratory measurements like joint torque curves and muscle

activation patterns provide precise insights, translating these findings into practical, sport-specific training regimens remains a complex task. This difficulty is exacerbated in dynamic contexts where real-time adjustments are required. Additionally, an excessive focus on load magnitude without adequate attention to movement quality, coordination, and timing can elevate the risk of musculoskeletal injuries. These interconnected challenges underscore the need for systematic approaches that effectively bridge the gap between biomechanical research and practical training design, ensuring both scientific rigor and field applicability.

5. Path Optimization for Loading-Based Explosive Power Training

5.1. Standardization of Biomechanical Evaluation Models

To optimize explosive power training, it is crucial to establish comprehensive and standardized protocols for biomechanical assessment. These protocols should define consistent criteria for analyzing force-time curves, evaluating joint torque, assessing muscle activation levels, and measuring movement efficiency. Additionally, they must specify precise guidelines for sensor placement, data sampling frequencies, and testing conditions to ensure that measurements remain consistent and comparable across athletes, research studies, and training sessions. Standardization plays a pivotal role in enhancing the reliability, reproducibility, and validity of biomechanical evaluations, enabling practitioners to monitor performance adaptations systematically over time. Furthermore, such protocols provide a structured framework for identifying technical deficiencies in athletes, refining loading strategies, and tailoring training programs to meet individual needs with greater precision. By establishing evidence-based benchmarks for explosive power development under various loading conditions, these standardized models support progressive and scientifically guided improvements. This approach not only optimizes athletic performance but also minimizes the risk of injury by addressing biomechanical inefficiencies. Moreover, standardized frameworks enable large-scale data aggregation and cross-study comparisons, fostering advancements in the broader fields of sports biomechanics and applied training science. Such efforts contribute to a deeper understanding of performance optimization and the development of best practices in athletic training.

5.2. Intelligent Data Processing and Modeling Path

The integration of machine learning, artificial intelligence, and computational modeling into biomechanical analysis signifies a transformative advancement in optimizing training methodologies. By leveraging advanced algorithms, it becomes possible to automatically detect movement patterns, identify deviations from ideal techniques, and predict individual responses to specific training stimuli. This enables the generation of actionable insights that facilitate precise adjustments to training regimens. Intelligent data processing supports the development of adaptive models that account for an athlete's unique physiological and biomechanical characteristics, including strength profiles, motor control capabilities, fatigue levels, and injury history. These models provide real-time feedback and predictive analytics, allowing for dynamic modifications to training variables such as load intensity, movement velocity, and range of motion [11]. Such adjustments aim to maximize neuromuscular adaptation while simultaneously reducing the risk of overtraining or injury. Additionally, intelligent modeling enhances longitudinal performance tracking, enabling the identification of trends in force production, joint kinetics, and other critical metrics over extended periods. This data-driven approach empowers coaches to make informed decisions regarding periodization strategies and progressive overload planning. Ultimately, this paradigm shifts biomechanical assessment from a static evaluative process to an interactive, continuously adaptive system that enhances both training efficiency and effectiveness.

5.3. Individualized Training Design Path

Explosive power training should be tailored to align with athletes' physical capabilities, technical skills, and developmental stages, utilizing insights from standardized evaluations and advanced modeling techniques. Training modalities, including constant weights, adjustable loads, and elastic bands, can be strategically employed to address specific performance gaps such as peak torque generation, stretch-shortening cycle efficiency, or joint stabilization [3, 12]. Customized programs enable precise enhancement of neuromuscular activation patterns, inter-joint coordination, and overall kinetic chain functionality, fostering optimal force production while minimizing inefficient movement patterns. Additionally, individualized approaches facilitate progressive adaptation by dynamically adjusting load intensity, movement complexity, and repetition schemes based on real-time biomechanical feedback. This ensures that training stimuli are effectively aligned with the athlete's unique physiological and biomechanical profile. Such personalized designs not only promote immediate performance improvements but also contribute to sustainable, sport-specific development over time, establishing a robust foundation for both short-term achievements and long-term athletic progression.

5.4. Safety and Sustainable Development Path

Safety and sustainability are paramount considerations in the realm of high-intensity explosive power training, as improper management of training loads can result in acute injuries or chronic overuse conditions [8]. To mitigate these risks, training protocols must be meticulously designed to balance intensity, frequency, and recovery periods. This involves continuous monitoring of biomechanical risk factors, such as joint asymmetry, excessive muscle activation, and abnormal force distribution, which can serve as early indicators of potential injury. The application of progressive overload principles, when implemented within safe and controlled limits, ensures that athletes achieve consistent performance improvements without jeopardizing their physical well-being. Sustainable training practices also require a collaborative, multidisciplinary approach, integrating the expertise of coaches, sports scientists, physiotherapists, and medical professionals. This collaboration facilitates the development of comprehensive strategies that encompass performance monitoring, injury prevention, and recovery optimization. By leveraging evidence-based training prescriptions, real-time biomechanical feedback, and adaptive adjustments tailored to individual needs, programs can enhance long-term effectiveness while minimizing injury risks. Such an integrated approach not only supports athletes in reaching their peak performance potential but also prioritizes their overall health and resilience, ensuring that explosive power training remains both ethical and sustainable throughout their careers.

6. Conclusion

This study systematically examines the biomechanical mechanisms through which different loading methods affect lower limb explosive power training. Joint kinetics, muscle activation characteristics, kinetic chain efficiency, and adaptive feedback processes are identified as core determinants of training effectiveness, performance transfer, and movement quality. The analysis indicates that loading strategies influence not only force production and rate of force development, but also neuromuscular coordination, segmental sequencing, and the stability of technical execution under varying training demands. Despite persistent challenges involving methodological standardization, individual response differences, and injury risk management, several practical optimization pathways remain available. These include the establishment of standardized evaluation systems, the application of intelligent data modeling, the refinement of personalized training prescriptions, and the development of long-term safety management frameworks. Overall, the study deepens the biomechanical understanding of load-based explosive power training and offers a structured foundation for improving athletic performance through evidence-based training strategies.

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