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Strength training and bodybuilding: scientific basis, physiological adaptations, and methodological applications.

Treinamento de força e musculação: bases científicas, adaptações fisiológicas e aplicações metodológicas

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Abstract
Strength training, also known as weight training, is one of the most relevant forms of physical exercise in the contemporary context of health, athletic performance, and rehabilitation. This article aims to present a systematic review of the bases... scientific what they base their arguments the training resisted, discussing to the adaptations physiological changes promoted by mechanical and metabolic stimuli in skeletal muscle tissue, the mechanisms of hypertrophy and gain of strength, good as to the main methodologies of Prescription techniques used in clinical and sports practice. The review covers aspects related to skeletal muscle physiology, neuroadaptations, training variables, periodization principles, and applications in special populations. and protocols based in evidence. A analysis Literature demonstrates that strength training, when prescribed with scientific rigor, promotes profound adaptations in the muscular, skeletal, endocrine, and cardiovascular systems, with positive impacts on body composition, quality of life, and longevity. It is concluded that the systematization and periodization of resistance training are crucial for achieving safe and effective results in different population contexts.
Keywords: Strength training. Bodybuilding. Muscle hypertrophy. Periodization. Exercise physiology.

RESUMO
O treinamento de força, também denominado musculação, constitui uma das modalidades de exercício físico de maior relevância no contexto contemporâneo da saúde, do desempenho esportivo e da reabilitação. Este artigo tem por objetivo apresentar uma revisão sistemática das bases científicas que fundamentam o treinamento resistido, discutindo as adaptações fisiológicas promovidas pelos estímulos mecânicos e metabólicos no tecido muscular esquelético, os mecanismos de hipertrofia e ganho de força, bem como as principais metodologias de prescrição utilizadas na prática clínica e esportiva. A revisão abrange aspectos relacionados à fisiologia do músculo esquelético, neuroadaptações, variáveis de treinamento, princípios de periodização, aplicações em populações especiais e protocolos baseados em evidências. A análise da literatura demonstra que o treinamento de força, quando prescrito com rigor científico, promove adaptações profundas nos sistemas muscular, ósseo, endócrino e cardiovascular, com impactos positivos na composição corporal, na qualidade de vida e na longevidade. Conclui-se que a sistematização e a periodização do treinamento resistido são determinantes para a obtenção de resultados seguros e eficazes em diferentes contextos populacionais.
Palavras-chave:
Treinamento de força. Musculação. Hipertrofia muscular. Periodização. Fisiologia do exercício.

1 INTRODUCTION

Resistance training, popularly known as weight training, has emerged over the last few years. decades as one of forms more studied and applied of exercise physical

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structured. Its scientific relevance has been consolidated from the growing interest of researchers in understanding the mechanisms by which skeletal muscle responds to the mechanical overloads imposed during resistance exercise. The set of Evidence accumulated over the last few decades demonstrates that the benefits of training... Strength transcends aesthetic or athletic performance goals, reaching clinical and preventive dimensions of great importance for public health (AMERICAN COLLEGE OF SPORTS MEDICINE, 2009).

Understanding the physiological fundamentals of strength training requires mastering related concepts. the biochemistry of the contraction muscular, the morphology From muscle fibers to the neurophysiology of movement and adaptive mechanisms in response to physical stress. Muscle hypertrophy, understood as the increase in the cross-sectional area of muscle fibers, is mediated by cellular signaling pathways that involve the activation of growth factors, protein synthesis, and the regulation of myofibrillar degradation. These processes are directly influenced by the intensity, volume, frequency, and type of exercise prescribed, which makes periodization an indispensable tool in the development of effective training programs (KRAEMER; RATAMESS, 2004).

In this context, this article proposes an integrative review of the scientific literature on strength training and bodybuilding, with emphasis on the physiological mechanisms of muscle adaptation, the variables for prescribing resistance exercise, and methodological applications in different populations. The systematization of knowledge produced in this area contributes to the improvement of professional practice in Physical Education, supporting the development of training programs that are simultaneously safe, effective, and individualized.

2 PHYSIOLOGY DO MUSCLE SKELETAL AND MECHANISMS OF CONTRACTION

Skeletal muscle is a highly organized structure, composed of individual muscle fibers that contain contractile elements called actin myofilaments and Myosin. Each muscle fiber is a multinucleated cell, whose functional unit is the... The sarcomere is responsible for generating force during contraction. The muscle contraction process is initiated by the action potential propagated by motor neurons, which stimulates the release of calcium from the endoplasmic reticulum, allowing the interaction between actin and myosin through the cross-bridge cycle (POWERS; HOWLEY, 2014).

The fibers skeletal muscles They are classified into two major functional groups: contractile fibers slow, called type I, and fibers of contraction fast, called type II, being

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These are subdivided into type IIa and type IIx. Type I fibers exhibit high resistance to fatigue, high mitochondrial density, and greater oxidative capacity, being predominantly recruited in low-intensity, long-duration exercises. In contrast, type II fibers have a higher contraction speed, greater capacity to generate maximum force, and lower resistance to fatigue, being primarily activated in high-intensity, short-duration exercises, such as those performed in strength training (FLECK; KRAEMER, 2017).

The size principle, proposed by Henneman, establishes that motor units are recruited in ascending order of size, with the smallest being activated first and the largest being progressively incorporated as the force demand increases. This principle has direct implications for the prescription of resistance training, as it indicates that the recruitment of type II fibers, with greater hypertrophy potential, requires the use of moderate to high intensity loads. Understanding the biomechanics of motor unit recruitment is therefore fundamental for optimizing weight training protocols (ENOKA; DUCHATEAU, 2008).

Muscle tissue exhibits elastic and viscoelastic properties that influence the production and transmission of force during movement. The series elastic component, located in the tendons and titin, and the contractile component, represented by the actin-myosin complex, interact dynamically during eccentric, concentric, and isometric contractions. The use of the stretch-shortening cycle, characteristic of explosive movements, enhances... production of strength by middle of storage and release of elastic energy in connective tissues, being widely explored in high-speed strength training modalities (KOMI, 2003).

From a metabolic standpoint, strength training predominantly activates the ATP-PC system and the anaerobic glycolytic pathway in energy production, due to the short duration and high intensity of the efforts. The accumulation of lactate and hydrogen ions during sets of repetitions to fatigue constitutes one of the metabolic mechanisms associated with hypertrophic stimulation, although its exact role in the muscle adaptation process is still debated in the specialized literature. Understanding energy metabolism during resistance exercise is essential for the proper prescription of intervals of... recovery and training volume (HOWLEY; POWERS, 2014).

3 MECHANISMS MOLECULAR FROM THE HYPERTROPHY MUSCULAR

THE hypertrophy muscular skeletal result of one balance positive between the synthesis and the degradation

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Protein synthesis is conditioned by the magnitude and frequency of training stimuli. The main intracellular mechanism associated with hypertrophy is the activation of the mTORC1 pathway (mechanistic target of rapamycin complex 1), which acts as a central sensor for nutrients and energy, promoting the synthesis of myofibrillar proteins in response to mechanical stimuli. The mechanical tension generated during muscle contraction activates mechanoreceptors in the cell membrane. triggering waterfalls of signaling what culminate in transcription and translation of genes related to muscle growth (SCHOENFELD, 2010).

Three main mechanisms are recognized in the scientific literature as mediators of the hypertrophic process: mechanical tension, metabolic stress, and muscle damage. Mechanical tension, produced by the load imposed on the muscle during resistance exercise, is considered the primary stimulus for the activation of anabolic signaling pathways, including the IGF-1/PI3K/Akt/mTOR pathway. Metabolic stress, associated with the accumulation of metabolites such as lactate, inorganic phosphate, and hydrogen ions, is proposed as a complementary mechanism that can potentiate protein synthesis through the additional recruitment of motor units and the release of anabolic hormones (SCHOENFELD, 2010; KRAEMER; RATAMESS, 2005).

Exercise-induced muscle damage, particularly from eccentric contractions, causes microlesions in the myofibrils and sarcoplasmic membrane, triggering a local inflammatory response that activates satellite cells, also known as muscle stem cells. Satellite cells proliferate, differentiate, and fuse with existing fibers, contributing new nuclei and consequently increasing the capacity for protein synthesis. This regeneration and remodeling process is fundamental for long-term hypertrophic adaptation, although the quantitative role of satellite cells in hypertrophy is still debated in the literature (LIEBER; FRIDEN, 2002).

The hormonal response to strength training also plays a relevant role in regulating muscle hypertrophy. Testosterone, growth hormone (GH), and insulin-like growth factor type 1 (IGF-1) are the main anabolic substances secreted in response to high-intensity, high-volume resistance exercise. Studies demonstrate that training protocols with multiple sets, short recovery intervals, and moderate to high loads promote more significant acute increases in these hormone concentrations, creating an endocrine environment favorable to muscle protein synthesis (KRAEMER et al., 1992).

The synthesis of myofibrillar proteins, especially myosin heavy chain, is primarily responsible. for the increase of volume muscular observed after periods of training

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Resistance training. The rate of muscle protein synthesis remains elevated for 24 to 48 hours after a session. of training of strength, the what highlights the importance from the nutrition protein node period Post-exercise nutrition is crucial for optimizing hypertrophic adaptations. Adequate intake of essential amino acids is essential. especially leucine, acts as one powerful activator from the via mTORC1, synergizing with the mechanical stimulus of training in promoting muscle anabolism (PHILLIPS; VAN LOON, 2011).

4 NEUROADAPTATIONS TO THE TRAINING RESISTED

Neural adaptations constitute the first and fastest responses of the organism to strength training, being responsible for the significant strength gains observed in the initial phases of a weight training program, before any significant muscle hypertrophy can be detected. These adaptations involve modifications in the efficiency of nerve signal conduction, in the recruitment pattern of motor units, and in the synchronization of muscle activity. The improvement in intermuscular and intramuscular coordination results in greater mechanical efficiency during movements, allowing the practitioner to use a greater proportion of their available muscle mass for force generation (AAGAARD et al., 2002).

THE increase in encoding rate, that is, the frequency of firing of units motors, This is one of the main neural mechanisms responsible for strength gains in the initial stages of training. Electromyography studies demonstrate that trained subjects exhibit significantly different firing rates and recruitment patterns compared to untrained individuals, reflecting the neural efficiency acquired through systematic training. The reduction of autogenic inhibition mediated by Golgi tendon organs, with a consequent decrease in the activity of inhibitory Ib interneurons, is considered an important mechanism by which strength training allows the muscle to generate higher tensions during maximal exercise (SALE, 1988).

The plasticity of the corticospinal tract in response to strength training has been documented using transcranial magnetic stimulation techniques, revealing modifications in cortical excitability and the amplitude of evoked motor potentials. Increased cortical activation and improved cortical representation of trained muscles are indicative of neuroplastic reorganization, which supports the gains in strength and motor coordination observed throughout a resistance training program. This evidence reinforces the importance of considering... you aspects neural in prescription and assessment of training resisted (CARROLL et

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al., 2011).

The co-activation of antagonist muscles progressively decreases with strength training, which contributes to a net increase in the force production of the agonist muscle. This reduction in antagonist activity, although seemingly counterintuitive from the point of view of joint stability, results from a fine-tuning of the nervous system that recognizes the trained movement pattern as safe, thus reducing the protective activation of the antagonists. The modulation of co-activation therefore represents a neuromuscular optimization strategy that significantly contributes to the functional strength gains observed in resistance training (AAGAARD, 2003).

Motor learning The process of developing strength training involves cognitive and cerebellar exercises that allow for the refinement of execution technique over time. Motor memory, consolidated through repeated practice, improves the biomechanical efficiency of movements and reduces the energy cost of their execution. The motor skill acquired through strength training is relatively specific to the movement pattern practiced, which justifies the... The importance of selecting exercises that encompass motor patterns relevant to the practitioner's or athlete's goals (SCHMIDT; WRISBERG, 2010).

5 VARIABLES OF PRESCRIPTION DO RESISTANCE TRAINING

Prescribing strength training involves manipulating several variables that These factors interact in a complex way to determine the total stimulus imposed on the organism. The main variables to be considered include intensity, volume, frequency, recovery interval, execution speed, exercise selection and order, and the type of muscle action. Intensity is often expressed as a percentage of one repetition maximum (1RM), and the relationship between intensity and the number of repetitions performed forms the basis for prescribing different training goals, such as maximum strength, hypertrophy, and localized muscular endurance (AMERICAN COLLEGE OF SPORTS MEDICINE, 2009).

Training volume, defined as the product of the number of sets, repetitions, and load used, is considered one of the main determinants of the adaptive response to resistance exercise. The relationship between volume and hypertrophic response follows a dose-response pattern, where progressively larger volumes provide greater stimuli for muscle growth, up to the point where excess volume results in overtraining and decreased performance. Recent studies indicate that weekly volumes of 10 to 20 sets per muscle group are beneficial. muscular they are sufficient to maximize to the adaptations hypertrophic in practitioners

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Intermediate and advanced levels are available, although the individual response is highly variable (SCHOENFELD et al., 2017).

The recovery interval between sets significantly influences the metabolic and hormonal environment generated by training, as well as the ability to maintain intensity throughout the session. Short intervals, from 30 to 60 seconds, maximize metabolic stress and the acute hormonal response, while longer intervals, from 3 to 5 minutes, They allow for almost complete recovery of muscle phosphagens and the maintenance of higher loads. Current literature indicates that for hypertrophy goals, intervals between 1 and 2 minutes are recommended. represent one commitment effective between the recovery metabolic and the maintenance of anabolic stimulus (WILLARDSON, 2006).

Training frequency, expressed as the number of sessions per week dedicated to a specific muscle group, interacts with the volume of each session to determine the total weekly stimulus. The debate about the optimal training frequency has been widely discussed. This has been explored in the literature, with evidence suggesting that training each muscle group at least twice a week is superior to a single weekly session for maximizing performance. hypertrophy and strength gain. Training organization strategies, such as muscle group or whole-body programs, should be selected based on the planned weekly volume and the practitioner's recovery capacity (SCHOENFELD; OGBORN; KRIEGER, 2016).

The speed at which repetitions are performed, although often overlooked in training prescription, influences motor unit recruitment, time under tension, and... The type of adaptation promoted. Slower execution speeds, especially in the eccentric phase, increase muscle damage and time under tension, potentially amplifying the hypertrophic stimulus. On the other hand, explosive speeds in the concentric phase maximize the recruitment of high-threshold motor units and are particularly indicated for the development of muscle strength and power. The prescription of execution speed should, therefore, to be aligned to the objectives specific of practitioner and to the internship of training in where he is (PAREJA-BLANCO et al., 2017).

6 PERIODIZATION DO TRAINING OF STRENGTH

Periodization is the systematic and planned organization of training over time, with the goal of maximizing adaptations, preventing overtraining, and ensuring peak performance. occur node moment desired. THE concept of periodization he has your roots in theory

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The general adaptation of Seyle's model and the planning model developed by the Soviet scientist Tudor Bompa, later refined by numerous researchers and professionals. of the area. Classical periodization, also called linear periodization, predicts the systematic progression of intensity, with reduction concomitant of volume, to far away of cycles called mesocycles, microcycles and macrocycles (BOMPA; HAFF, 2009).

Undulating, or non-linear, periodization emerged as an alternative to the classical approach, proposing the variation of training variables in shorter intervals, such as within the same week or even in alternating sessions. This type of periodization aims to explore different neuromuscular stimuli more frequently, preventing burnout. Excessive adaptation to the stimulus and enhancing adaptive responses. Comparative studies between different forms of periodization indicate that both produce significant results, with the superiority of one over the other depending on factors such as the training level, objectives, and the sport modality of the practitioner (RHEA; ALDERMAN, 2004).

The concept of block periodization, developed by Issurin, organizes training into sequential blocks, each with specific and concentrated adaptive objectives, such as the development of maximum strength, speed strength, or muscular endurance. This approach aims to maximize adaptations in each biomotor capacity sequentially, taking advantage of the transfer effects between blocks to optimize performance. Block periodization has found increasing application both in the context of high-performance athletics and in bodybuilding focused on aesthetic and health goals (ISSURIN, 2010).

The principles of progressive overload and specificity are fundamental to any periodization model for resistance training. The principle of progressive overload establishes that the training stimulus must be continuously increased so that adaptations are maintained, as the body tends to adapt to the level of effort to which it is habitually subjected. The principle of specificity, in turn, determines that the adaptations promoted by training are specific to the characteristics of the imposed stimulus, including the type of muscle contraction, the range of motion, the speed, and the magnitude of the load (AMERICAN COLLEGE OF SPORTS MEDICINE, 2009).

Detraining, or the detraining period, is equally relevant from a long-term periodization perspective. Studies show that neural adaptations are lost more rapidly during detraining than morphological adaptations, such as muscle hypertrophy. The incorporation of periods of reduction intentional of volume and from the intensity, called

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Tapering, or detoxification, is a widely used strategy to promote complete recovery of the body and optimize performance at specific times, such as competitions or periodic assessments (MUJIKA; PADILLA, 2000).

7 TRAINING OF STRENGTH IN POPULATIONS SPECIALS

Resistance training has relevant applications in populations with specific characteristics and needs, requiring methodological adaptations that consider the physiological, biomechanical, and clinical particularities of each group. Among the special populations most studied in the scientific literature on strength training are the elderly, women, children and adolescents, individuals with chronic non-communicable diseases, and athletes from various sports. In each of these groups, the prescription of training resisted requires care specific as the selection of exercises, intensity, volume and load progression (FAIGENBAUM; MYER, 2010).

In aging, sarcopenia, defined as the progressive loss of muscle mass and function, represents one of the main risk factors for functional disability, falls, and mortality in older adults. Strength training has become established as the most effective non-pharmacological intervention for the prevention and treatment of sarcopenia, promoting... increases significant in mass muscular, in strength, node balance and in Functional capacity in older adults. Resistance training protocols adapted to the elderly population should prioritize gradual progression, joint safety, and the functionality of the selected exercises, with emphasis on the muscle groups involved in activities of daily living (HUNTER; MCCARTHY; BAMMAN, 2004).

Women respond to resistance training in a qualitatively similar way to men. although to the differences hormonal, especially us levels of testosterone and Estrogen, in addition to typically resulting in smaller magnitudes of muscle hypertrophy, leads to the production of estrogen. Its role in regulating body composition exerts protective effects on muscle and bone tissue, influencing the inflammatory response to exercise and muscle recovery kinetics. Strength training in women has demonstrated additional health benefits. bone, the control metabolic and the prevention of conditions as the osteoporosis and the metabolic syndrome, making it a strategy fundamental in the promotion of women's health throughout the life cycle (WEST; PHILLIPS, 2012).

In children and adolescents, strength training, when properly supervised and prescribed, and insurance and promotes benefits related to the development engine, the health bone

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and to physical fitness. The historical concern about possible negative effects on growth plates has been largely refuted by the scientific literature, which demonstrates that the risk of injury in supervised strength training is lower than that observed in various sports practiced in this age group. International guidelines recommend that the prescription of resistance training for young people prioritize technical learning, gradual progression, and qualified supervision (FAIGENBAUM; MYER, 2010).

Individuals with chronic diseases, such as type 2 diabetes, hypertension, obesity, and cardiovascular disease, constitute a group for whom strength training offers widely documented therapeutic benefits. Improved insulin sensitivity, reduced resting blood pressure, decreased visceral adiposity, and improved lipid profile are some of the positive cardiometabolic effects associated with regular resistance training. Prescribing strength training for this population should be based on prior clinical evaluation, adapting training variables to the specific limitations and contraindications of each condition (AMERICAN COLLEGE OF SPORTS MEDICINE, 2010).

8 METHODOLOGY, APPLICATION AND METHODS OF ASSESSMENT

This review was conducted through a bibliographic survey in the PubMed, SciELO, Google Scholar, and LILACS databases, using the following descriptors in Portuguese and English: strength training, weight training, muscle hypertrophy, periodization, exercise physiology, strength training, resistance training, and muscle hypertrophy. Articles were selected. Original articles, systematic reviews, meta-analyses, and guidelines published between 1988 and 2023 were included, with priority given to studies with a high level of scientific evidence. Inclusion criteria encompassed studies with human samples, published in indexed journals, and addressing the topics of resistance training physiology, exercise prescription, and adaptations to strength training.

The assessment of muscle strength and training adaptations can be performed using different methods, each with its specific advantages and limitations. The one-repetition maximum (1RM) test is considered the gold standard for assessing maximum strength in specific exercises, offering high ecological validity and being widely used in both research and clinical and sports practice. Indirect methods, such as the maximum repetition test with submaximal loads, offer safer alternatives for populations with contraindications to maximal effort, although they present lower precision in the estimation. from the 1RM. THE dynamometry isokinetic, although more sophisticated and expensive, allows

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to assess muscle function at specific joint speeds and angles, with particular relevance in rehabilitation contexts (BROWN, 2000).

Measuring body composition using techniques such as dual-energy X-ray absorptiometry (DEXA), magnetic resonance imaging, and muscle ultrasound allows for the direct quantification of morphological adaptations to resistance training, including muscle mass and body fat. Anthropometry and bioelectrical impedance, although less precise, constitute accessible alternatives for the periodic monitoring of body composition in practical contexts. The choice of assessment method should be guided by the objectives of the assessment, the available resources, and the characteristics of the population being assessed, ensuring the validity and reproducibility of the measurements over time (HEYWARD; WAGNER, 2004).

CONCLUSION

Strength training and bodybuilding represent constantly expanding fields of scientific knowledge, whose physiological, molecular, and methodological bases have been progressively elucidated by academic research in recent decades. The literature review presented in this article shows that the benefits of resistance training are broad, multisystemic, and of great relevance to both health and athletic performance, justifying its recommendation by international public health guidelines as an essential component of a physically active lifestyle.

The physiological mechanisms underlying adaptations to strength training are complex and interdependent, involving neural, hormonal, cellular, and molecular responses that interact dynamically to determine the final adaptive outcome. Understanding these signaling pathways is essential for the scientific basis of resistance exercise prescription, allowing physical education professionals to make informed decisions. evidence is key when developing individualized training programs.

Muscle hypertrophy, resulting from a positive balance between protein synthesis and degradation, is mediated by multiple stimuli, with mechanical tension being the primary factor, complemented by metabolic stress and muscle damage. The conscious manipulation of these variables, through the careful prescription of intensity, volume, frequency, and recovery intervals, allows for the optimization of adaptive responses for different goals and populations.

To the neuroadaptations to the training resisted, what precede and complement to the adaptations

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Morphological characteristics are crucial for gains in strength, coordination, and neuromuscular efficiency. The plasticity of the central and peripheral nervous system in response to strength training reinforces the importance of considering neural aspects in the evaluation and prescription of resistance exercise, recognizing that performance gains are not limited to muscle growth.

Periodization in strength training, whether in its linear, undulating, or block models, is a fundamental methodological tool for the long-term organization of training stimuli, ensuring the continuous progression of adaptations, preventing overtraining, and planning for peak performance. The choice of periodization model he must to be guided by the objectives of practitioner, by your level of training and due to the specific demands of their sport or life context.

The application of strength training to special populations, such as the elderly, women, young people, and those with chronic diseases, reinforces its therapeutic and preventive character, expanding its scope of action beyond the sporting or aesthetic context. Individualizing training protocols for these populations, considering their physiological and clinical specificities, is an ethical and scientific requirement that should guide professional practice in Physical Education.

THE assessment systematic of the adaptations to training resisted, by middle of Validated methods for measuring strength, body composition, and neuromuscular function are essential for monitoring the practitioner's progress and making necessary adjustments to the training prescription. The use of assessment tools appropriate to the characteristics of the population and the objectives of the program is the responsibility of the professional prescribing the training.

The continuous advancement of sports and exercise science, with the development of new imaging technologies, molecular biology, and performance analysis, promises to further deepen the understanding of the mechanisms of adaptation to strength training in the coming decades. The incorporation of these advances into professional practice in Physical Education and related fields depends on the ongoing training of professionals and the valuing of applied scientific research as the foundation of practical intervention.

In conclusion, strength training and weightlifting, when based on solid scientific foundations and prescribed with technical competence, constitute powerful tools for promoting health, quality of life, and human performance across all age groups and population contexts. Therefore, deepening knowledge in this area is a permanent necessity for Physical Education professionals committed to excellence in their practice.

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