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ECCENTRIC TRAINING: PHYSIOLOGICAL MECHANISMS, ACUTE RESPONSES, AND CHRONIC ADAPTATIONS - A NARRATIVE REVIEW

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ABSTRACT

Resistance training is an extremely popular form of exercise, used for a variety of purposes, ranging from recreational exercisers to athletes and individuals with significant clinical conditions. Different variables, exercises, and muscle actions can be used in resistance training to achieve various adaptations. Eccentric training is a unique method with wide applicability in sports performance, injury prevention, rehabilitation, training for older adults, and training for clinical populations. Therefore, the objective of this narrative review is to analyze the available literature on eccentric training, exploring mainly the physiological mechanisms, acute responses, and chronic adaptations related to this modality. This narrative review included a comprehensive search in PubMed and Google Scholar, plus backward citation tracking from eligible articles. The search was conducted without date restrictions and in English and Portuguese. Overall, eccentric training is an effective modality, with applicability in sports, recreational, and clinical settings. However, it requires careful implementation due to the high muscle damage induced by exercise, especially in the initial sessions.

Key words: Resistance training. Eccentric training. Muscle damage. Hypertrophy.

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RESUMO

Treinamento excêntrico: mecanismos fisiológicos, respostas agudas e adaptações crônicas - uma revisão narrative

O treinamento resistido é uma modalidade de exercício extremamente praticada, sendo utilizada para diversos fins, abrangendo desde o público que treina de maneira recreativa, até os atletas, e indivíduos com alterações clínicas relevantes. Diferentes variáveis, exercícios e ações musculares podem ser utilizadas no treinamento resistido, a fim de se obter adaptações variadas. O treinamento excêntrico é um método único, com ampla aplicabilidade no desempenho esportivo, na prevenção de lesões, na reabilitação, no treinamento para idosos e no treinamento para populações clínicas. Portanto, o objetivo desta revisão narrativa é analisar a literatura disponível acerca do treinamento excêntrico, explorando principalmente os mecanismos fisiológicos, as respostas agudas, e as adaptações crônicas relacionadas a essa modalidade. A presente revisão, com busca abrangente da literatura, foi realizada em duas bases de dados: PubMed e Google Acadêmico. E em lista de referências de artigos selecionados. A busca foi realizada sem restrição de data e nos idiomas inglês e português. Conclui-se que o treinamento excêntrico é uma modalidade eficaz, com aplicabilidade em ambientes esportivos, recreativos e clínicos. No entanto, requer implementação cautelosa devido ao alto dano muscular induzido pelo exercício, principalmente nas sessões iniciais.

Palavras-chave: Treinamento resistido. Treinamento excêntrico. Dano muscular. Hipertrofia.

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INTRODUCTION

Resistance training (RT) is a widely practiced type of training that continues to expand each year (Machado et al., 2022), involving high-performance athletes seeking to improve their performance (jump height, speed, agility, and sport-specific tasks) (ACSM, 2009), individuals seeking to improve their health (prevention/treatment of coronary heart disease, obesity, diabetes, osteoporosis, as well as cognitive and psychological benefits) (Fragala et al., 2019; Pollock and Vincent, 1996; Warburton et al., 2006), and recreational practitioners who aim for functional and morphological gains (strength, endurance, reduction in body fat percentage, hypertrophy, and quality of life) (ACSM, 2009). RT is, therefore, an effective modality for promoting such adaptations.

The success of these results depends on a series of variables and mechanisms that must be used and/or stimulated, such as training principles (specificity, variability, and progressive overload), periodization and/or programming (linear ascending/descending, undulating, block), stimulus characteristics (mechanical tension, muscle damage, and metabolic stress), and training variables (intensity, volume, frequency, selection and order of exercises, intervals, speed of execution, with or without volitional failure), in addition to the type of muscle action prioritized (concentric, eccentric, and isometric) (ACSM, 2009; Kraemer and Ratamess, 2004; Machado et al., 2022; Schoenfeld, 2010; Schoenfeld et al., 2021).

In general, concentric and eccentric actions are performed consecutively within a training program, since both are important for most of the desired purposes (Higbie et al., 1996).

However, when analyzed in isolation, eccentric actions exhibit mechanical, neuromuscular, and metabolic properties, accompanied by acute responses and chronic adaptations that differ from those observed in other actions (concentric and isometric) (Hody et al., 2019).

Therefore, this article presents a narrative review on eccentric training (ET), focusing on physiological mechanisms, acute responses, and chronic adaptations related to it.

MATERIALS AND METHODS

In the present study, a narrative review was conducted using two databases: PubMed and Google Scholar. A secondary search was conducted by screening the reference list of eligible articles. The search was performed using terms associated with ET, in English and Portuguese, with no date restrictions. A narrative synthesis was chosen, which is appropriate when the objective is to describe and integrate multiple lines of evidence, offering critical synthesis and practical implications.

Priority was given to clinical trials and reviews that investigated ET in humans (healthy individuals, athletes, older adults, and clinical populations), reporting acute characteristics and/or chronic adaptations. Exclusively concentric studies, case reports, and studies not directly related to ET were excluded.

RESULTS AND DISCUSSION

Eccentric Training

The American College of Sports Medicine (ACSM, 2009) indicates that a strength training program should include single- and multi-joint, bilateral and unilateral exercises, with dynamic repetitions involving concentric and eccentric actions, as well as isometric actions applied in a more secondary manner (muscle stabilization, core strength, grip strength, pauses between concentric and eccentric actions, and specific isometrics).

Muscle actions can be characterized by constant length (isometric), shortening (concentric), and lengthening (eccentric) (Herzog, 2014), and all these modes are common components of everyday movement (Fridén and Lieber, 2001).

Eccentric actions are present in most everyday and sports movements, contributing to mobility, stability, and muscle strength (Hessel et al., 2017).

In most training programs, the concentric and eccentric phases are performed consecutively, since, for most training objectives, both must be present (Higbie et al., 1996).

However, eccentric actions, because they involve force production during the stretching of the muscle-tendon complex, exhibit unique characteristics, with acute responses and chronic adaptations that differ

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from those observed in concentric and isometric actions (Hody et al., 2019).

Titin

The mechanisms of isometric and concentric actions are classically described by the cross-bridge theory and the sliding filament theory (Huxley and Hanson, 1954; Rayment et al., 1993).

However, ET, which can exert higher levels of residual force, is not entirely explained. Hypotheses such as the non-uniformity of sarcomere or half-sarcomere length help to describe part of the phenomenon, but do not fully explain the effects observed in ET (Hessel et al., 2017).

The most widely accepted explanation involves the active role of titin during muscle activation and the increase in its stiffness during active stretching (Herzog, 2014).

Titin is a protein that extends from the Z disc to the M line, with more than 25,000 amino acids, and is considered the largest known protein. It acts by stabilizing the position of contractile filaments and contributing to the return of the muscle to its resting length, and is aided by nebulin, which aligns the actin filaments (Silverthorn et al., 2019).

In skeletal striated muscle, titin modulates its stiffness according to muscle activation, behaving like a molecular spring that stores elastic energy during stretching and restores it in the subsequent phase, optimizing the efficiency of cross-bridges (Lindstedt et al., 2001; Ortega et al., 2015). With chronic exposure to eccentric stimuli, this muscle spring property can become more rigid, compatible with structural adjustments (Lindstedt et al., 2001).

The change in titin resistance has been attributed to interactions with the actin filament, Ca^{2+} binding, and reorientation of stiffer segments of the molecule itself. The increase in stiffness after activation would explain the maintenance/increase in force when the muscle is actively stretched, even with less actin-myosin overlap and less demand on cross-bridges, which helps explain the high force production at low metabolic cost (Herzog, 2014; Hessel et al., 2017).

Properties of eccentric training

During daily locomotion, eccentric actions dissipate energy in the form of heat, reduce kinetic energy through braking, and, conversely, store potential energy, which can be restored to the production of movement, as if it were a “spring” (Lindstedt et al., 2001).

In structured programs, ET enhances these aspects, triggering mechanical and cellular events, whose recovery process culminates in adaptation. When the stimulus is excessive or without adequate progression, more intense acute reactivity may emerge, as detailed below (Butterfield et al., 2010).

Whenever the external load exceeds the force produced by the muscle, the muscle lengthens while producing force (Lindstedt et al., 2001).

Skeletal muscle is more efficient in this type of work (eccentric) than in conventional work (concentric), being designed to remain stable throughout its range of motion (Butterfield et al., 2010).

The prescription of ET, however, requires caution in the initial phase and careful progression. It is up to the professional to be aware of possible acute responses, as well as ways to avoid exacerbating these effects (Hody et al., 2019).

In summary, ET combines neural, mechanical, and physiological properties that distinguish it from other exercises: high force production capacity; greater anabolic signaling; lower metabolic cost; lower subjective perception of effort; lower cardiorespiratory demand; and lower electromyographic (EMG) activity (Hody et al., 2019; Hortobágyi et al., 1998; Kelly et al., 2015; Ortega et al., 2015; Peñailillo et al., 2013; Reeves et al., 2009; Şenışık et al., 2021). These properties coexist with specific acute responses, which are also found in eccentric exercises.

Acute responses

Although ET has mechanical and metabolic advantages, its acute responses require special attention, especially due to the combination of tissue damage/repair with slower recovery during the first exposures. These responses may temporarily hinder the maintenance of high intensities and impact trainability in the first sessions, in addition to discouraging the continuation of training (Hody et al., 2019; Hyldahl and Hubal, 2014; Krentz and Farthing, 2010).

Exercise-Induced muscle damage

Exercise-induced muscle damage (EIMD) describes the set of structural, functional, and perceptual changes that emerge after mechanical stress, mainly associated with ET. The time window varies according to the marker analyzed (strength, ROM, pain, edema, CK, or myoglobin), but in general, it appears from the post-exercise period up to 24 hours, culminates between 24 and 72 hours, and regresses over 5 to 7 days (Matta et al., 2019), and may remain longer when direct markers (Z-line streaming) are analyzed (Damas et al., 2016).

Among the most common clinical and functional manifestations are transient loss of function, through decreased muscle strength, jump performance, and range of motion (ROM), delayed onset muscle soreness (DOMS), muscle swelling (edema), and ultrastructural changes in muscle architecture. Changes in biochemical markers (CK, myoglobin) are also observed (Howatson and Van Someren, 2008; Peake et al., 2005; Peñailillo et al., 2013).

A sequence of events is proposed as the cause of EIMD: ultrastructural disruptions (myofibers/filaments), impaired excitation-contraction coupling, increased Ca^{2+} influx, and activation of Ca^{2+}-dependent proteolytic pathways (calpains). In parallel, changes in membrane permeability and extracellular matrix (ECM) remodeling occur, with a subsequent inflammatory response (Howatson and Van Someren, 2008; Peake et al., 2005; Peñailillo et al., 2013).

The magnitude of EIMD is modulated both by training variables (muscle group exercised, muscle activation mode, volume, training load, and execution speed) and by individual characteristics (sex, training level, pre-existing muscle disease, statin use, genetics, and nutritional supplement use), and, above all, by exposure to a "new" stimulus (Hyldahl and Hubal, 2014).

Loss of muscle function

The molecular mechanisms that explain the loss of strength after eccentric actions are not yet fully understood, but there are converging explanations: high tension during active stretching favors non-uniform sarcomere length and sarcomere overstretching (so-called "popped sarcomeres"), which would result in loss of strength and overload of membrane and T-tubule structures, precipitating the opening of stretch-activated channels; membrane rupture; excitation-contraction coupling dysfunction; and the subsequent influx of extracellular calcium, promoting the degradation of contractile proteins and/or excitation-contraction coupling proteins via calcium-activated calpains; finally, molecular changes in some proteins and genes, such as α-actinin-3 (ACTN3), γ-actin, ankyrin repeat 1 (ANKRD1), FK506 binding protein (FKBP12), protein kinase B (AKT), and cytotoxic T cells, also appear to be involved in functional decline after EIMD (Hyldahl and Hubal, 2014).

Macroscopically, this cascade manifests as a transient reduction in strength (isometric, concentric, and eccentric) and ROM, peaking between 24 and 48 hours post-exercise, with progressive recovery in subsequent days (Fridén and Lieber, 2001). There may also be changes in biomechanical patterns (walking, running, sports movements), decreased athletic performance, and proprioceptive impairment (Hody et al., 2019).

In terms of magnitude, 48 hours after an ET session, declines of approximately 37% in strength and 28% in EMG are observed (Hortobágyi et al., 1998). In elbow flexors, the immediate decline can reach approximately 50%, with attenuation over time, but still with a 37% reduction 72 hours post-exercise (Matta et al., 2019). In eccentric cycling, initial declines in strength and performance (vertical jump) have also been described (Peñailillo et al., 2013).

Apparently, loss of function is modulated by factors such as training level (trained individuals tend to show smaller decreases in strength/ROM) (Newton et al., 2008), muscle group (elbow flexors often exhibit a greater magnitude of decline) (Şenışık et al., 2021), and type of training (maximum ET generates greater loss of muscle function than submaximal ET) (Nosaka and Newton, 2002). With familiarization and planned progression, the magnitude and duration of deficits decrease, a phenomenon discussed in more detail in the Repeated Bout Effect (RBE) topic.

Muscle swelling

Muscle swelling after ET is predominantly interstitial. Microlesions in myofibrils and ECM trigger the release of Damage-Associated Molecular Patterns (DAMPs), cytokines, and chemokines, with subsequent leukocyte recruitment. Mediators such as histamine, bradykinin and prostaglandins increase microvascular permeability, promoting plasma protein extravasation and elevation of interstitial oncotic pressure, which attracts water to the extracellular space (Hyldahl and Hubal, 2014; Luttrell and Halliwill, 2017; Peake et al., 2017).

Muscle swelling is another acute response to ET. In the elbow flexors, significant muscle edema is observed between 48 and 72 hours after an ET session. Regional assessment did not reveal a single spatial pattern, with proximal increases at 48 hours (16%) and 72 hours (22%), and distal increases only at 72 hours (18%) (Matta et al., 2019).

The magnitude of edema appears to depend on the characteristics of the practitioner and the protocol. Individuals with previous experience in resistance training show smaller changes in circumference after eccentric exercise than untrained individuals (Newton et al., 2008). From a stimulus perspective, maximal protocols tend to induce greater swelling than submaximal protocols (Nosaka and Newton, 2002).

Delayed onset muscle soreness

The DOMS mechanism is related to the inflammatory response following mechanical stress and damage to contractile structures. The process involves the production/release of chemokines by interstitial cells, their entry into the circulation, and the activation of pro-inflammatory cells, which infiltrate the muscle and release mediators (e.g., bradykinin and prostaglandins). These mediators sensitize nociceptors and modulate extracellular receptors, promoting local hyperalgesia. There is also the possibility of chemical mediators being released by resident interstitial cells of the ECM, contributing to the persistence of pain (Hyldahl and Hubal, 2014).

Macroscopically, DOMS is characterized by pain and stiffness, exacerbated by palpation and contraction/stretching (Proske and Morgan, 2001). In many ET protocols, the peak occurs between 24 and 48 hours after the session, with a progressive reduction in the following days (Hody et al., 2019; Matta et al., 2019). In regional assessments, diffuse pain can be observed throughout the muscle belly, with no consistent distinction between proximal and distal portions (Matta et al., 2019). In practice, DOMS reduces tolerance to high intensities and can compromise the quality of subsequent sessions when recovery time is not respected (Hody et al., 2019).

Other responses associated with ET

In the muscle structure, eccentric actions cause disorganization (Matta et al., 2019) and ultrastructural damage (cytoskeletal ruptures, myofibrillar rupture, Z-disc disintegration, A-band disorganization, loss of intracellular desmin, loss of cellular integrity, evidenced by sarcolemmal damage, hyperconcentration of damaged fibers, and invasion of inflammatory cells) (Fridén and Lieber, 2001). In the muscle membrane, there is an increase in permeability and the appearance of muscle proteins in the circulation, with the most accepted mechanism being the activation of stretch-activated Na^+ and Ca^{2+} channels, along with other mechanosensitive channels. These pathways may remain upregulated for several days after training. Unusual ET can also result in clinically significant leakage of muscle proteins into the blood, in addition to that caused by membrane permeability, characterizing exertional rhabdomyolysis (Hyldahl and Hubal, 2014).

In the ECM, interactions between multiple compartments and myofibrils play a key role in molecular responses derived from eccentric stress (Hyldahl and Hubal, 2014), generating changes in ECM composition, expressed by increased type IV collagen staining in the muscle endomysium (Mackey et al., 2004), and elevated serum matrix metalloproteinases (MMPs) and tissue inhibitors of metalloproteinases (TIMPs) after eccentric exercise (Hyldahl and Hubal, 2014).

At the same time, ET also triggers inflammatory and immune responses, such as the early accumulation of leukocytes, mainly neutrophils, in the blood vessels of the injured muscle, as well as in the perimysium, immediately after exercise (Hody et al., 2019).

Some factors appear to mediate these inflammatory responses, such as sex, age, type of exercise (in eccentric exercises involving large muscle mass, circulating leukocyte counts and systemic cytokine concentrations appear to increase more than in isolated eccentric exercises, in addition to returning to baseline levels more quickly), and prior eccentric loading (Nosaka and Clarkson, 1996; Peake et al., 2005).

These effects on inflammatory responses may lead to the progression of EIMD to myotendinous injury caused by ET, which appears to be dependent on a series of excessively aggressive inflammatory responses that, over time, do not allow the muscles to adapt to the stress and mechanical load applied (Butterfield et al., 2010).

As for biochemical markers, creatine kinase (CK) and myoglobin increase after ET, with CK levels peaking between 24 and 48 hours (Fridén and Lieber, 2001) and increases of up to 220% in certain protocols (Hortobágyi et al., 1998). The magnitude of these increases depends on the muscle group (elbow flexors tend to respond with greater magnitude) (Şenışık et al., 2021) and training level (individuals with previous RT experience show smaller changes than untrained individuals) (Newton et al., 2008).

Repeated bout effect

To mitigate the effects of EIMD, various therapeutic and/or prophylactic interventions have been tested. These include nutritional and pharmacological strategies (supplementation with antioxidants or β-hydroxy-β-methylbutyrate), manual therapies and exercises (stretching and massage), electrical therapies, and cryotherapy. However, the effectiveness of these approaches is generally moderate and the results inconsistent (Howatson and Van Someren, 2008). On the other hand, a strategy with consistent evidence is RBE, obtained through previous ET sessions, especially when applied with linear progression (Howatson and Van Someren, 2008), and modulated by intensity, speed, volume, muscle length, muscle group, sex, and age (Hyldahl et al., 2017). In summary, repeated sessions of submaximal ET, with progressive load increases, are currently the most robust approach to mitigate EIMD (Hody et al., 2019; Hyldahl and Hubal, 2014).

The mechanisms underlying RBE remain partially elucidated (Hody et al., 2019). The phenomenon, understood as protection against deleterious responses to subsequent stimuli after an initial session, involves neural adaptations, changes in mechanical properties (remodeling of the muscle-tendon complex), structural remodeling of the ECM, and biochemical signaling (inflammatory responses). These components may act independently (e.g., ECM remodeling, which improves tendon compliance, reducing muscle tension and subsequent damage), but it is plausible that they operate together: initial adaptations (24 hours to 14 days) are mainly attributed to neural/inflammatory mechanisms, while later adjustments (14 days to 42 days) are more related to ECM remodeling (Hyldahl et al., 2017).

From an experimental point of view, repeating eccentric exercise 3 and 6 days after the first session does not enhance the acute responses of that session, with no indication of newly produced pain after subsequent sessions, suggesting that the initial session induces substantial damage, but the following sessions do not exacerbate the damage or impair recovery (Nosaka and Clarkson, 1995).

Forty-eight hours after a second ET session, strength, EMG, CK, and pain tend not to change significantly, although evidence of myofibrillar rupture persists (Hortobágyi et al., 1998). There is also an attenuation in neutrophil count and leukocyte surface receptor expression, while large differences in cytokines are not evident, a pattern consistent with a reduction in the degree of EIMD (Peake et al., 2005).

Similar effects are described in eccentric cycling: in a second session held two weeks after the first, almost no symptoms of EIMD (strength, vertical jump, and DOMS) are observed, with reduced EMG (probable reduction in motor neuron activation), lower metabolic stress (35% reduction in blood lactate), and lower heart rate (12% reduction) (Peñailillo et al., 2013).

Together, these results support that faster recovery of strength after eccentric exercise is partly mediated by neural adaptations and may occur independently of the presence of cell rupture. This pattern is consistent with greater control of force production and better distribution of workload among muscle fibers (Hortobágyi et al., 1998; Nosaka and Clarkson, 1995; Peñailillo et al., 2013).

Chronic adaptations

In the long term (chronic adaptations), ET is associated with improved muscle function (strength, power, hypertrophy, muscle architecture, cross-education, length-tension relationship), greater neuromuscular efficiency, tendon remodeling, low metabolic demand (low cardiac output and energy cost), low perceived

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exertion, improvements in health-related parameters (reduction in fat mass, increased resting energy expenditure, improved fat oxidation and insulin sensitivity, and improved lipid profile), and improved quality of life in older adults (reduced risk of falls, prevention and reduction of sarcopenia) (Hessel et al., 2017; Hody et al., 2019; Peñailillo et al., 2013; Reeves et al., 2009).

The magnitude and direction of these adaptations vary according to the protocol (load, duration, exercises, mode of resistance, and equipment used) and target population. In the following topics, we will discuss in greater detail neural adaptations, strength, athletic performance, hypertrophy, muscle architecture, injury prevention and recovery, applicability to older adults, and clinical context.

Neural adaptations

Eccentric actions have unique properties, combining high force production with low energy cost. As a result, muscles exposed to ET over time tend to respond with increases in strength and size, as well as changes in muscle elastic properties, mainly attributed to neural and structural adaptations (Lindstedt et al., 2001).

This improvement in neuromuscular control is described by changes in muscle morphology and peripheral and central neural activity (recruitment and firing rate of alpha motor neurons, cortical activation, corticospinal excitability, and sarcolemma excitability) (Lepley et al., 2017).

There are also reports of increased monosynaptic reflex activity (Hortobágyi et al., 1998), with improved neuromuscular function (Hedayatpour and Falla, 2015), greater activation of agonist muscles and reduced coactivation of antagonist muscles (Krentz and Farthing, 2010), as well as improved coordination and optimization of tension development at higher degrees of muscle stretch (Vogt and Hoppeler, 2014).

Another neuromuscular benefit caused by ET is the reduction of EMG signals for the same task relative to baseline, observed, for example, in the pectoralis major (Montalvo et al., 2021). With repeated training, there is an additional reduction in motor neuron activation (Peñailillo et al., 2013), consistent with greater neuromuscular system efficiency without compromising mechanical performance.

Strength and athletic performance

ET, especially due to the possibility of manipulating high external loads for the same task, is a powerful stimulus for mechanical function, morphological/architectural adaptations, and improvements in strength, power, and speed (Douglas et al., 2017).

Compared to concentric training, ET tends to produce more significant strength gains in specific tests (ET → eccentric strength, concentric → concentric strength) (Higbie et al., 1996; Roig et al., 2009), possibly due to the ability to use higher loads (Reeves et al., 2009).

In the bench press, for example, eccentric 1RM reaches approximately 124% of concentric 1RM, with a higher number of repetitions at 90% of specific 1RM (Kelly et al., 2015). In the short term (four weeks), increases of approximately 6.5% in 1RM are reported (Montalvo et al., 2021).

In knee flexors, partial transfer between modes is observed, with gains in concentric and eccentric strength regardless of the type of training performed (Timmins et al., 2015).

In addition to strength, eccentric actions improve mobility, flexibility, balance, and power in healthy individuals (Ansari et al., 2023; Lindstedt et al., 2001; Montalvo et al., 2021). In sports, these actions support athletic performance in specific tasks.

Plyometric exercises are often associated with improved speed, jumping and changing direction, running, and throwing (Beato et al., 2021; Hody et al., 2019; Vogt and Hoppeler, 2014).

Eccentric cycling is becoming a viable option for gains in strength, functional capacity, aerobic power, hypertrophy, and body composition (Barreto et al., 2023). In sports with high deceleration/stretching demands (e.g., alpine skiing), the eccentric emphasis optimizes the shock-absorbing role of the muscles (Vogt and Hoppeler, 2014).

When we analyze eccentric overload training (Flywheel), we find greater gains in concentric and eccentric strength, muscle power, and hypertrophy, as well as improvements in speed and countermovement jump performance, compared to conventional training (Maroto-Izquierdo et al., 2017).

Hypertrophy

Within a training program aimed at hypertrophy, it is important to use concentric and eccentric actions. When comparing ET with concentric training, ET appears to have a slightly greater effect on increases in muscle thickness and cross-sectional area. However, this difference is not statistically significant in most studies (Higbie et al., 1996; Krentz and Farthing, 2010; Roig et al., 2009; Schoenfeld et al., 2017).

It is worth noting that most of these investigations compared total repetitions, not total work, suggesting that the greater work often associated with ET (due to the use of heavier loads) may contribute to this slight advantage (Schoenfeld et al., 2017).

Thus, when volume and intensity are equalized, ET and concentric training tend to produce gains of similar magnitude. However, the possibility of accumulating greater volume at a lower metabolic cost gives ET a practical advantage, especially in populations with low exercise tolerance (Hyldahl and Hubal, 2014).

When comparing ET with supramaximal loads to ET with submaximal loads, significant differences in hypertrophy are observed, which are more pronounced in supramaximal protocols (Krentz et al., 2017). This pattern points to load as a potential mediator of hypertrophic adaptations in eccentric exercises.

In general, ET increases muscle mass, fascicle length, range of motion, and the cross-sectional area of type II fibers, in addition to enhancing fiber type transitions, with a more longitudinal (serial) adaptation pattern (Douglas et al., 2017; Lepley et al., 2017; Vogt and Hoppeler, 2014). When performed with fast movements, ET can increase the proportion of type II fibers and reduce that of type I fibers (Paddon-Jones et al., 2001).

In combined protocols (concentric plus reinforced eccentric), increases are observed in the cross-sectional area of type IIX fibers, the percentage of type IIA fibers, the expression of myosin heavy-chain (MHC) IIX mRNA, mRNAs in fast glycolytic fibers, and post-exercise lactate compared with conventional training (Friedmann-Bette et al., 2010).

Muscular architecture

Despite the similar magnitude of hypertrophy between concentric and eccentric actions, the characteristics of this hypertrophy differ. In the biceps femoris, ET increases fascicle length and reduces the pennation angle, whereas concentric training reduces fascicle length and increases the pennation angle (Timmins et al., 2015).

In knee extensors, analogous patterns are found: ET increases fascicle length with little change in pennation angle, while concentric training increases pennation angle with minimal change in fascicle length (Franchi et al., 2014). In older adults, ET generated an increase in fascicle length and muscle thickness, with no significant change in the pennation angle. Concentric training increased all three outcomes.

However, the percentage increase in fascicle length was greater in ET (Reeves et al., 2009).

Together, these results suggest distinct myogenic responses: concentric training would tend to favor parallel adaptations (associated with the pennation angle), while ET would favor fascicle lengthening (associated with serial adaptations) (Franchi et al., 2014).

The addition of sarcomeres in series is often pointed out as a beneficial mechanism, increasing contractile speed, extensibility, and force production at longer lengths (Butterfield et al., 2010).

However, Pincheira et al., (2022) did not observe sarcomerogenesis after nine sessions of eccentric exercise. Instead, they reported an increase in fascicle and sarcomere length, especially in the distal region, consistent with connective tissue remodeling, titin alterations, and adjustments in the ECM. Estimates indicated no addition of sarcomeres in series in the regions analyzed, which is not consistent with some of the findings in animal models or with the traditional hypothesis that sarcomereogenesis necessarily supports fascicle increase. In light of this study, fascicular increase may predominantly reflect sarcomere hypertrophy in series and tissue remodeling, rather than possible sarcomerogenesis.

These adaptations of the ET on fascicular length are relevant in the prevention of injuries, given that hamstring strains usually occur with the muscles in an elongated position (a topic discussed further below). ET in an elongated position has been associated with fascicular lengthening and a reduction in the pennation angle, as well as improvements in neuromuscular aspects (higher level of activation and concentric/eccentric/isometric strength) (Marušič et al., 2020).

As for detraining, after ET, a reduction in fascicle length and an increase in the pennation angle are observed, with returns to

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baseline levels in approximately 28 days. After concentric training, architectural adaptations seem to persist longer (Timmins et al., 2015).

Heterogeneous hypertrophy

When analyzing the biceps brachii, it is observed that the medial and distal regions show greater hypertrophy after ET when compared to concentric training, especially when both are performed at high speed (Farthing and Chilibeck, 2003).

In the vastus lateralis, heterogeneous hypertrophy is also identified: there is a more significant increase in the distal region after ET, and a more significant increase in the medial region after concentric training (Franchi et al., 2014).

Analyzing the biceps femoris, after three weeks of performing Nordic curls, more pronounced adaptations are observed in the distal portion (increase in sarcomere length and fascicle length) compared to the medial portion (Pincheira et al., 2022).

Taken together, the studies cited here describe the occurrence of regional hypertrophic adaptations after ET, although the direction and magnitude of these responses vary depending on the muscle analyzed and the protocol employed.

However, this variability is accompanied by differences in the characteristics of the exercises performed and the measurement strategies, which require caution in comparisons and/or associations between studies.

Extrapolation to other muscles should not be encouraged, given that each muscle has different characteristics (size, range of motion, architecture, and force production capacity) (Ward et al., 2009).

Injuries

ET has multiple applications in prevention and rehabilitation (Hody et al., 2019), establishing itself as a safe and effective form of exercise for the recovery of patients with muscle weakness after injury (Lepley et al., 2023).

Eccentric interventions have been shown to be superior to conventional interventions in the rehabilitation of sports injuries, in increasing bone mineralization and improving post-injury tendon remodeling (Hessel et al., 2017), possibly due to the induction of greater muscle stiffness, which provides protection against myotendinous injuries (Lindstedt et al., 2001).

In addition, in scenarios with partial impairment in one limb, unilateral eccentric training can generate contralateral protective adaptation, although to a lesser extent than ipsilateral adaptation (Hyldahl et al., 2017).

In programmatic terms, effective preventive protocols using ET usually last from 21 to 30 weeks, with a weekly frequency of twice a week being the most appropriate (Hu et al., 2023).

Eccentric conditioning of the knee flexors appears to be one of the main factors responsible for reducing the risk of injury to the lower limbs (28%), hamstrings (46%), and knees (34%), as well as hips and ankles, when compliance is adequate (Bourne et al., 2018; Hu et al., 2023).

These benefits are likely mediated by an increase in fascicle length, a change in the angle of peak knee flexor torque, and improved eccentric strength (Bourne et al., 2018).

In elite soccer players, higher levels of eccentric strength and longer fascicles are associated with a lower incidence of hamstring injuries (Timmins et al., 2016).

In amateur athletes, ET also reduces the incidence of hamstring injuries but does not alter the severity of injuries sustained (Van der Horst et al., 2015).

In rehabilitation, ET is a relevant component for hamstring recovery (Macdonald et al., 2019).

In practical terms, programs aimed at the prevention and/or rehabilitation of strain injuries should consider the selection of eccentric exercises that impact muscle activation, architecture, morphology, and function of the hamstrings (Bourne et al., 2018).

Associated with adjuvant therapy, ET has shown benefits in reducing pain and improving function in the management of lateral elbow tendinopathy (Yoon et al., 2021), and, in isolation, has been shown to be effective in Achilles tendon, patellar tendon, rotator cuff, and lateral elbow tendinopathies (Murtaugh and Ihm, 2013).

ET also shows promise for strengthening and gaining quadriceps muscle mass after anterior cruciate ligament (ACL) reconstruction. Isokinetic ET appears to be the most effective, compared to conventional ET (Vidmar et al., 2020).

RBPFEX
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Elderly and clinical populations

Eccentric exercise is an attractive alternative to traditional exercises for encouraging sedentary people to engage in physical activity, mainly because it is easier to perform than traditional exercises (e.g., walking downhill versus level walking) (Ansari et al., 2023), due to its effects on strength and power, and its low energy cost (Lindstedt et al., 2001).

Older adults can perform eccentric exercises at high and low intensities with a low risk of injury, accumulating benefits such as improved performance of activities of daily living, prevention of sarcopenia, osteoporosis, and tendinopathy, maintenance of muscle density, increased bone mineralization, mitigation of functional decline, greater autonomy, improved quality of life, and prevention of chronic diseases (Cvečka et al., 2023; Hessel et al., 2017; Hody et al., 2019).

In older adults and clinical patients with obstructive pulmonary disease or heart failure, ET is particularly interesting due to its lower energy cost, low perceived exertion, and low cardiac output, concomitant with strength gains and support for sarcopenia prevention (Hessel et al., 2017; Lindstedt et al., 2001).

Eccentric cycling is also a relevant option, with advantages over concentric cycling in terms of strength and aerobic power in patients with cardiopulmonary diseases (Barreto et al., 2023).

The demonstration that ET can be used with good tolerance broadens its clinical applicability (Hody et al., 2019).

When compared to traditional modalities, eccentric exercise does not offer benefits for glucose control; on the other hand, it increases overall muscle strength (isometric, concentric, and eccentric), reduces cardiovascular health markers (systolic and diastolic blood pressure) (Ansari et al., 2023), improves the lipid profile (Hody et al., 2019), and benefits post-surgical patients and populations with neuromuscular diseases (Hyldahl and Hubal, 2014).

CONCLUSION

Based on the studies analyzed in this review, it can be considered that ET has good applicability in performance and health, supported by its high mechanical and metabolic efficiency. Its acute responses require caution, especially regarding recovery.

However, they are progressively attenuated due to RBE. In chronic contexts, ET proves effective in strength gains, architectural changes, neural adaptation, and functional improvements. It demonstrates broad applicability, from high performance to rehabilitation, chronic diseases, and aging.

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Recebido para publicação em 13/10/2025
Aceito em 22/01/2026