

Eccentric exercise: neuromuscular characteristics, muscle damage, training effects, and applications

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Abstract Eccentric contractions involve active muscle lengthening under load, and exercise modalities predominantly comprising eccentric contractions (eccentric exercise) get increasing attention in exercise physiology, rehabilitation, and clinical practice. Compared to concentric contractions, skeletal muscle can generate greater force during eccentric contractions at a lower metabolic cost and with less perceived effort. These characteristics make eccentric exercise particularly suitable for frail or older adults, and individuals with chronic diseases. A major limitation of eccentric exercise is that unaccustomed bouts induce muscle damage represented by delayed onset muscle soreness and prolonged reductions in muscle function. However, subsequent bouts of the same exercise result in substantially less damage (the repeated bout effect), and muscle damage is attenuated through preconditioning strategies, including low-intensity eccentric contractions and maximal voluntary isometric contractions at a long muscle length. Therefore, concerns regarding muscle damage should not discourage participation in appropriately prescribed eccentric exercise. When performed regularly, eccentric exercise provides a potent stimulus for increasing muscle strength and functional capacity, improving insulin sensitivity and blood lipid profiles, lowering systolic blood pressure, and promoting overall physical fitness. Emerging evidence suggests that eccentric exercise may elicit neural and cognitive stimulation. Although the concept that “exercise is medicine” is well established, the specific therapeutic and performance-related benefits of eccentric exercise have only recently gained broader recognition. This narrative review synthesizes current evidence on the neuromuscular characteristics of eccentric contractions, eccentric exercise-induced muscle damage and adaptations, and the applications of eccentric exercise in rehabilitation, ageing and frail populations, and clinical exercise prescription.

Keywords : eccentric contraction, muscle damage, delayed onset muscle soreness, repeated bout effect, resistance training, rehabilitation

Introduction

There are numerous review articles on eccentric exercise, addressing its physiological characteristics, exercise-induced muscle damage and adaptations, effects on physical fitness and health, applications in rehabilitation, and roles in injury prevention and athletic performance

enhancement. A PubMed search for review articles on “eccentric exercise” published within the past five years yields more than 200 publications, while over 400 articles related to eccentric exercise were published in 2025 alone. These figures highlight the growing interest in eccentric exercise as a major topic in exercise and sport science, sports medicine, and health and fitness research.

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Abbreviations: 1-RM: one-repetition maximum, ASW: ascending stair walking, CK: creatine kinase, COX-2: cyclooxygenase-2, DOMS: delayed onset muscle soreness, DSW: descending stair walking, fsTnI: fast-twitch skeletal muscle troponin I, HbA1C: glycated haemoglobin, HDL: high-density lipoprotein, HOMA: homeostasis model assessment, MVC: maximal voluntary contraction, NGF: nerve growth factor, LDL: low-density lipoprotein, OGTT: oral glucose tolerance test, RM: repetition maximum, ssTnI: slow-twitch skeletal muscle troponin I, STS: sit-to-stand, TNF- α : tumour necrosis factor- α , TUG: timed up-and-go



Despite the extensive literature, it remains valuable to synthesise current knowledge to identify gaps requiring further investigation and to optimise the application of eccentric exercise in physical fitness promotion, rehabilitation, and sports medicine practice. This narrative review summarises the current evidence regarding the neuromuscular characteristics of eccentric contractions, exercise-induced muscle damage and adaptation, and the practical applications of eccentric exercise across health and fitness promotion, prevention of injuries, falls, and diseases, and rehabilitation.

Eccentric exercise

In resistance exercise, several variables should be considered, including exercise intensity, the number of repetitions performed per session, training frequency, and type of muscle contraction. Eccentric exercise is defined as exercise that primarily involves eccentric (muscle lengthening) contractions¹⁾. During an eccentric contraction, the force produced by the muscle is less than the external load applied to it, resulting in active muscle lengthening while muscle activation is maintained [Fig. 1]. A typical example is the lowering phase of sitting down from an upright standing position, during which the knee extensor muscles perform eccentric contractions by generating less force than the body mass acting on them.

It should be noted that the term “eccentric contraction” has been criticised because it is considered an oxymoron, implying “lengthening shortening.” Accordingly, Cavanagh²⁾ suggested the term “eccentric action,” arguing that “contraction” should be reserved for situations in which a muscle shortens while generating force. Faulkner³⁾ proposed the term “lengthening contraction,” as it more accurately describes the behaviour of the muscle during this type of activity. Although these suggestions have merit, the terms “eccentric contraction” and “eccentric exercise” remain widely used in the scientific literature. Therefore, in the present article, “eccentric contraction” is used to refer to lengthening muscle contraction, and “eccentric ex-

ercise” is defined as exercise that predominantly involves or focuses on eccentric contractions.

Characteristics of eccentric exercises

There are several unique characteristics of eccentric contraction and eccentric exercise compared to concentric (muscle shortening) and isometric (static) contractions, as well as exercises that primarily involve these contraction modes [Fig. 2]. Skeletal muscles can generate greater force during eccentric contractions than during either isometric or concentric contractions, as demonstrated by the force–velocity relationship⁴⁾. The ratio of maximal voluntary eccentric to concentric force varies among studies depending on the measurement methods, muscle groups examined, and individual characteristics. For example, when maximal voluntary contraction (MVC) torque is assessed using an isokinetic dynamometer, eccentric torque is typically approximately 40% greater than concentric torque⁵⁾. This enhanced force-generating capacity provides a major advantage for eccentric exercise, as greater mechanical loading can be imposed on the muscles. Because of the greater force-generating capacity of eccentric contractions, the maximal load that can be handled (one-repetition maximum: 1-RM) is substantially higher in eccentric than in concentric movements. Consequently, when the same absolute load is used for both eccentric and concentric phases, the eccentric phase is perceived as easier to perform.

Eccentric exercise is also less metabolically demanding than concentric exercise. For example, oxygen consumption is approximately 50% lower, and heart rate is 20–30% lower during eccentric cycling (resisting pedals driven backward by a motor) than during conventional cycling performed at the same external workload⁶⁾. These characteristics may contribute to reduced fatigability during exercise period. Consistent with this notion, the number of contractions performed to failure is at least 60% greater during eccentric-only than during concentric-only elbow flexor exercise using a dumbbell⁷⁾. Similar findings

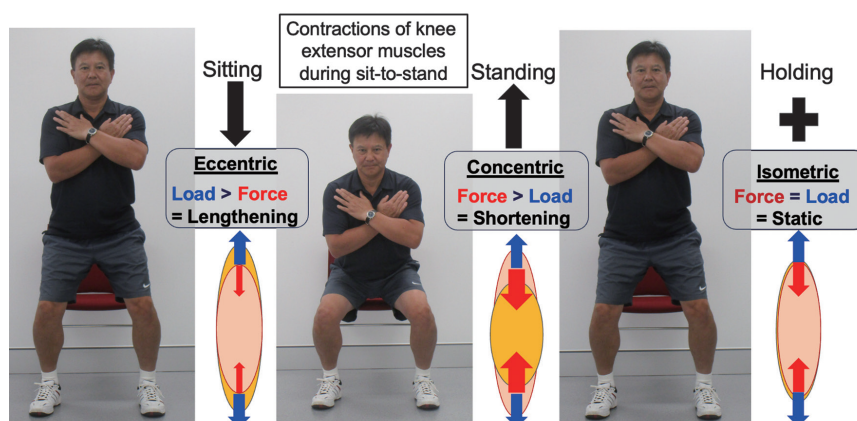


Fig. 1 Muscle contraction (action) types. Three types of muscle contractions (eccentric, concentric and isometric) in sit-to-stand movement are shown.

have been reported for other exercises, including the back squat and bench press⁸⁾.

Furthermore, eccentric exercise appears to impose greater cognitive demands than concentric exercise⁹⁾. For example, reaction time during a Stroop test performed while cycling was more than 15% longer during eccentric than concentric cycling and was accompanied by a higher error rate (20% vs. 10%). These findings suggest that eccentric exercise may provide a unique stimulus for maintaining or enhancing cognitive function, particularly in older adults.

Muscle strength declines with ageing; however, the reduction in eccentric strength is generally smaller than the decline observed for concentric and isometric strength¹⁰⁾. This phenomenon is likely related to the greater contribution of passive elastic structures during eccentric contractions, which appear to be relatively well preserved with ageing. As discussed later, eccentric exercise induces substantial neuromuscular adaptations, including increases in muscle strength and muscle size, despite being performed at relatively lower metabolic and perceived intensities than traditional resistance training emphasizing concentric or isometric contractions.

Muscle damage

A potential disadvantage of eccentric exercise is the induction of muscle damage, which is characterized by symptoms such as delayed onset muscle soreness (DOMS) and a prolonged loss of muscle function, including reductions in MVC force¹¹⁾ [Fig. 2]. In contrast, exercise consisting solely of concentric contractions induces little muscle damage¹²⁾. However, isometric contractions performed at long muscle lengths can also induce DOMS and prolonged strength loss¹³⁾. Additional symptoms of eccentric exercise-induced muscle damage include increased muscle stiffness and hardness, muscle swelling, impaired proprioception, and increased fatigue¹³⁾.

DOMS is thought to reflect mechanical hyperalgesia

resulting from nociceptor sensitization mediated by nerve growth factor (NGF) and glial cell line-derived neurotrophic factor (GDNF), which are upregulated by cyclooxygenase-2 (COX-2)¹⁴⁾. Koeda et al.¹⁵⁾ demonstrated that increases in NGF were associated with the development of DOMS in humans. Interestingly, eccentric exercise-induced muscle damage is generally less severe in older than younger adults¹⁶⁻¹⁸⁾. This age-related difference may be partly explained by the preferential atrophy of fast-twitch muscle fibres with ageing¹⁹⁾.

In addition to the symptoms described above, elevations in muscle proteins in the blood, such as creatine kinase (CK) activity and myoglobin concentration, are commonly used as indirect markers of muscle damage¹³⁾. Because CK is a relatively large molecule (molecular weight >80 kDa), it cannot readily enter the circulation through capillaries, and instead reaches the bloodstream via the lymphatic system²⁰⁾. Consequently, increases in serum CK activity are delayed, typically peaking two–five days after eccentric exercise.

Damage to the muscle membrane increases intracellular calcium (Ca^{2+}) concentration, activating proteolytic enzymes that degrade contractile proteins such as myosin and troponin. These proteins subsequently leak into the circulation. Among the skeletal muscle isoforms of troponin I, slow-twitch skeletal muscle troponin I (ssTnI) and fast-twitch skeletal muscle troponin I (fsTnI), only fsTnI has been shown to increase following eccentric exercise^{21,22)}. Furthermore, the time course of changes in serum fsTnI concentration closely parallels that of CK activity. These findings suggest that muscle fibre damage occurs predominantly in fast-twitch fibres.

Muscle damage can also be visualized using imaging techniques such as B-mode ultrasonography and magnetic resonance imaging (MRI), which reveal increases in echo intensity and T2 relaxation time, respectively¹³⁾. An increase in T2 relaxation time generally reflects elevated intracellular and/or extracellular water content and is therefore associated with muscle swelling. Accordingly, the greatest increases in T2 relaxation time are typically observed when swelling peaks, approximately four–five days after exercise. Similar temporal changes are observed for muscle echo intensity. However, the mechanisms underlying the increase in echo intensity remain unclear, as increased water content would normally be expected to decrease, rather than increase, echo intensity. It is possible that alterations in extracellular matrix structures, such as the endomysium and perimysium surrounding muscle fibres and fascicles, contribute to these changes¹³⁾.

Histological alterations are also observed following eccentric exercise-induced muscle damage. However, it is important to recognize that severe symptoms such as DOMS, strength loss, and swelling do not necessarily indicate extensive muscle fibre disruption. For example, transmission electron microscopy revealed no overt

Characteristics	Positive outcomes after training
• Less metabolic demand • Greater force generation capacity • Less fatigability • Less decrease with ageing • Less intensity required for muscle adaptations	• ➤ muscle function • ➤ muscle mass • ➤ coordination • ➤ balance • ➤ flexibility • ➤ walking ability • ➤ bone density • ➤ insulin sensitivity • ➤ blood lipid profile • ➤ cardiovascular function • ➤ brain health
• Greater muscle damage represented by DOMS and prolonged decreases in muscle function • The magnitude of muscle damage is attenuated by the repeated bout effect, "pre-conditioning exercise" and gradually increasing the intensity and volume	

Fig. 2 Main characteristics of eccentric contraction (exercise) in comparison to concentric contraction (exercise), and possible positive outcomes after repeated eccentric exercises (eccentric exercise training). For the characteristics, positive (top) and negative (bottom) aspects are listed.

muscle fibre disruption and only approximately 10% intracellular disruption with Z-line streaming at five, 24, 96, and 192 h after 240 maximal voluntary eccentric contractions of the knee extensors performed by untrained young men²³). Interestingly, when electrical stimulation was superimposed on the voluntary contractions, myofibril disruption increased to approximately 40%, and desmin-negative, dystrophin-negative, and vimentin-positive fibres were detected in more than 15% of the observed fibres at 192 h post-exercise. Despite these greater histological alterations, no significant differences in DOMS were observed between conditions, and the reductions in force and power were actually greater following voluntary contractions alone than following voluntary contractions combined with electrical stimulation.

Minimal muscle fibre disruption following eccentric exercise has also been reported in other studies. For example, after 300 maximal eccentric contractions of the knee extensors, muscle biopsy samples obtained from the vastus lateralis at 0.5, four, eight, 24, 96, and 168 h post-exercise showed only occasional infiltration of inflammatory cells (CD16⁺ and/or CD68⁺ cells) within muscle fibres in four out of 11 participants, affecting only 0.2–1.35% of fibres²⁴). In contrast, larger numbers of CD16⁺ cells were observed within the interstitial space at 96 and 168 h post-exercise. These findings further support the view that muscle fibre disruption is minimal following eccentric exercise of the knee extensors and that histological alterations are not necessarily related to DOMS or loss of muscle function.

Several factors influence the magnitude of eccentric exercise-induced muscle damage, with previous exposure to eccentric contractions being the most important determinant. Other factors include exercise intensity, the number of contractions performed, contraction velocity, and muscle length during eccentric action. As illustrated in Fig. 3, muscle damage generally increases with higher intensity, greater contraction volume, faster movement velocity, and longer muscle lengths¹³). Compared to arm

muscles, leg muscles are generally less susceptible to muscle damage, likely because they are routinely exposed to eccentric contractions during daily activities^{25,26}). Age also influences susceptibility, with children exhibiting less muscle damage than adults and older adults exhibiting less damage than younger adults^{27,28}). This may be partly attributable to differences in the proportion of fast-twitch muscle fibres, which are more susceptible to eccentric exercise-induced damage. Children, particularly before adolescence, and older adults generally possess a lower proportion of fast-twitch fibres. Sex differences have also been reported. Female animals appear less susceptible to muscle damage than males, possibly due to the protective effects of oestrogen on muscle membranes; however, evidence for such sex differences in humans remains limited¹³).

As discussed in the following section, the magnitude of muscle damage is markedly attenuated following a prior bout of eccentric exercise, a phenomenon known as the repeated bout effect. This protective adaptation can be induced even by low-intensity eccentric training of the target muscles. In contrast, when muscles are fatigued, they appear to become more vulnerable to eccentric exercise-induced muscle damage.

Repeated bout effect

The repeated bout effect refers to the attenuation of muscle damage when the same eccentric exercise is repeated days or weeks after an initial bout²⁹). For example, when maximal eccentric exercise of the elbow flexors is performed twice with intervals of four, eight, or 12 weeks, the second bout induces substantially less muscle damage than the first. This is evidenced by faster recovery of muscle function, less DOMS, and smaller increases in muscle swelling, plasma CK activity, and myoglobin concentration³⁰). However, the magnitude of the repeated bout effect gradually diminishes as the interval between bouts increases³¹). Importantly, older adults exhibit a repeated bout effect comparable to that observed in younger adults³²).

Preconditioning effect

Muscle damage does not appear to be a prerequisite for the development of the repeated bout effect. A protective adaptation can also be induced by submaximal eccentric exercise that produces little or no detectable muscle damage. For example, low-intensity eccentric contractions performed at 10%, 20%, or 40% of maximal eccentric force have been shown to attenuate the symptoms of muscle damage following a subsequent bout of maximal eccentric exercise^{32,33-36}). This phenomenon is known as the preconditioning effect. In general, the greater the intensity of the preconditioning exercise, the greater the resulting protective effect³³). However, the protection conferred by

— Muscle Damage Magnitude +		
Low	Intensity	High
Small	Repetition	Large
Slow	Velocity	Fast
Short	Muscle length	Long
Leg	Muscle	Arm
Child	Age	Older Adult Younger
Female	Gender	Male
Yes	Preconditioning	No
Yes	Training	No
No	Fatigue	Yes

Fig. 3 Factors affecting magnitude of muscle damage induced by eccentric contractions. Top four factors are factors relating to eccentric contraction, middle three are factors relating to exercise or participant, and bottom three are factors relating to conditioning.

low-intensity eccentric contractions does not persist as long as that induced by maximal eccentric exercise³⁴). It is also noteworthy that isometric contractions can provide a similar protective effect against muscle damage induced by maximal eccentric exercise, provided that the contractions are performed at a long muscle length³⁷).

Prevention of muscle damage

The most effective strategy for minimizing eccentric exercise-induced muscle damage is to avoid high-intensity, high-volume, high-velocity eccentric contractions performed at long muscle lengths during the initial training sessions. Instead, eccentric exercise should begin with contractions performed at shorter muscle lengths, which induce minimal muscle damage while providing protection against subsequent eccentric exercise at longer muscle lengths. Thereafter, exercise intensity and volume should be progressively increased. When increasing exercise intensity, it may be prudent to reduce the number of contractions, consistent with general principles of resistance training progression. High-velocity eccentric contractions should be introduced only after individuals have developed sufficient strength and motor control to perform eccentric contractions safely and effectively at slower velocities [Fig. 4].

The repeated-bout and preconditioning effects have important practical implications for exercise prescription, rehabilitation, and athletic training. By progressively exposing muscles to eccentric loading, it is possible to maximize the benefits of eccentric exercise while minimizing the risk of excessive muscle damage and its associated symptoms.

Benefits of eccentric exercises

Regular resistance exercise has been shown to attenuate age-related declines in muscle mass, strength, power, and functional capacity³⁸). However, the implementation

of traditional resistance training in older adults is often challenged by reduced baseline muscle strength, impaired physical function, and cardiovascular limitations³⁹). Moreover, conventional resistance exercises, which typically involve both concentric and eccentric contractions, are associated with relatively high levels of perceived exertion. This may reduce exercise tolerance, adherence, and long-term compliance, particularly among individuals with limited physical capacity⁴⁰). In addition, the external load used during conventional resistance exercise is constrained by the maximal load that can be lifted during the concentric phase of a movement, thereby limiting the mechanical stimulus that can be applied to the muscles⁴¹).

In contrast, eccentric exercise offers several unique advantages. As discussed previously, eccentric contractions are characterized by greater force-generating capacity, lower metabolic and energy demands^{42,43}), lower perceived exertion and effort⁴⁴), and a smaller age-related decline in force-generating capability compared with concentric contractions¹⁰). These characteristics enable the application of a greater mechanical stimulus to skeletal muscle while imposing relatively low cardiovascular and metabolic stress. Consequently, exercise interventions that primarily employ eccentric contractions appear particularly well suited to older adults, individuals with limited exercise capacity, and patients with chronic diseases. More broadly, eccentric exercise represents an effective and practical training modality for improving muscle function and physical performance across a wide range of populations [Fig. 5].

In addition to its suitability for older and frail individuals, substantial evidence now supports the safety and efficacy of eccentric exercise training for improving a wide range of health- and fitness-related outcomes. Eccentric training has been shown to elicit greater improvements in muscle strength, power, muscle mass, and functional performance than conventional concentric-based training⁴⁵⁻⁴⁸). For example, LaStayo et al.⁴⁷), a pioneering researcher in disseminating the beneficial effects of exercise, reported that older adults who performed 10–20 minutes of eccentric resistance exercise three times per week for 11 weeks demonstrated significant improvements in muscle strength (60%), balance (7%), and stair-climbing ability (21%). In contrast, participants who completed traditional resistance exercise training showed substantially smaller changes in these outcomes (15%, –7%, and 5%, respectively). Furthermore, the cross-sectional area of vastus lateralis muscle fibres increased more in the eccentric training group (60%) than in the traditional resistance training group (41%). Notably, only the eccentric training group improved from a high-risk to a low-risk category for falls⁴⁷).

The benefits of eccentric exercise extend beyond skeletal muscle adaptations. Improvements in cardiovascular and metabolic health, as well as cognitive function, have been reported following eccentric exercise training^{44,49-52}). These findings highlight the potential of eccentric ex-

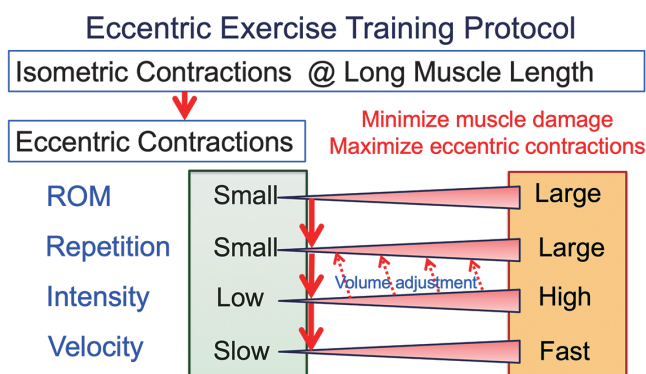


Fig. 4 Progression of eccentric exercise to minimize muscle damage, but maximize outcomes. ROM: range of motion; Repetition: number of repetitions and sets. Dashed arrow indicates that when increasing intensity, number of repetitions should decrease.

ercise as a comprehensive intervention for promoting healthy ageing and overall well-being.

As illustrated in Fig. 5, eccentric exercise training may help prevent or delay age-related declines in muscle strength and function (dynapenia and powerpenia) as well as the loss of muscle mass associated with sarcopenia. By preserving muscle function and mass, eccentric training may interrupt the vicious cycle in which reduced muscle performance leads to decreased physical activity, further accelerating functional decline. If left unchecked, this process may contribute to frailty, loss of independence, and an increased need for long-term care. Reduced physical activity is also associated with metabolic syndrome, insulin resistance, systemic inflammation, and reduced cognitive stimulation, all of which are important risk factors for the development of chronic diseases. Therefore, eccentric exercise training has considerable potential to increase health span and reduce the risk of a wide range of chronic conditions.

When evaluating exercise interventions for older adults, participant adherence is a critical consideration because the effectiveness of any training programme depends on long-term compliance. Raj et al.⁵³⁾ reported greater adherence to eccentric exercise programmes than to comparable concentric exercise interventions. This higher compliance may be attributable to the lower perceived exertion associated with eccentric exercise. Using a multi-joint lower-body eccentric training programme, LaStayo et al.⁵⁴⁾ reported that more than 90% of participants completed at least 81% of the prescribed exercise sessions over a six-month intervention period. Similarly, a 99% completion rate was reported for a six-week eccentric training programme in older adults⁵⁵⁾. These findings suggest that eccentric exercise is not only effective, but also highly acceptable and sustainable for older populations. Additional benefits of eccentric exercise training are summarized in Fig. 5.

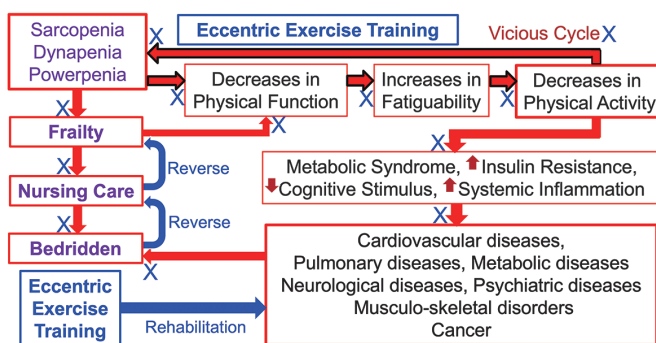


Fig. 5 Possible beneficial effects of eccentric exercise training. × indicates that eccentric exercise training could block sequence of events indicated by arrows. Eccentric exercise training is also effective for rehabilitation of chronic diseases, and reverses sequence from “frailty,” “nursing care,” to “bedridden.”

Different types of eccentric exercises

Eccentric exercise encompasses a variety of training modalities that can be categorized according to the force produced relative to MVC force or 1-RM strength. As illustrated in Fig. 6, eccentric exercise can be performed at different intensities and using a range of exercise modes, providing considerable flexibility for exercise prescription in both healthy and clinical populations.

The following sections review studies investigating the effects of various eccentric exercise training modalities on physical fitness and health-related outcomes. The benefits of eccentric exercise training have been reported in diverse populations, ranging from young healthy individuals to older adults, as well as frail and clinical populations. However, to provide a clear and focused overview, this article primarily uses older adults as an example population to illustrate the efficacy and practical applications of eccentric exercise training. Nevertheless, many of the physiological adaptations and health benefits described are likely to be applicable to other populations.

Maximal eccentric loading

In maximal eccentric loading, the external load exceeds the concentric 1-RM, and exercises are performed with assistance during the concentric phase or with the aid of specialized equipment. Because of the high mechanical demands, this type of training should be undertaken only by well-trained individuals or after a period of progressive adaptation using lower-intensity eccentric exercise.

The effects of a 12-week eccentric strengthening programme using a Biodex dynamometer have been investigated in older adults^{56,57)}. Symons et al.⁵⁷⁾ reported that maximal isokinetic eccentric-only resistance training effectively increased MVC strength and improved functional mobility. However, these improvements were not significantly greater than those achieved with maximal

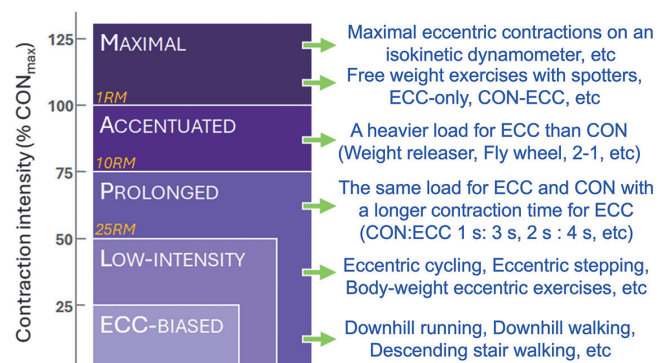


Fig. 6 Various eccentric exercises and corresponding intensity windows, expressed as percentage of maximal force developed during concentric contraction (CON_{max}) and repetition maximum (RM). CON_{max} is considered to be one repetition maximum (1RM). Some examples of each category are shown. ECC: eccentric contraction; CON: concentric contraction. Please refer to text for details.

isometric-only or isokinetic concentric-only resistance training. These findings differ from those of previous studies^{47,58}, which demonstrated that eccentric resistance training elicited greater improvements in isometric and isokinetic concentric strength than traditional resistance training in older adults.

The discrepancies among studies may be partly attributable to methodological differences and the relatively small sample sizes employed, limiting the generalizability of the findings to the broader older population^{56,57}. Nevertheless, Harris-Love et al.⁵⁶ proposed a periodized 12-week isokinetic eccentric strengthening programme targeting the knee extensors, incorporating an initial familiarization phase and progressive workload increases. Their findings suggest that such an approach is both feasible and safe for implementation in older adults within outpatient rehabilitation settings.

Accentuated eccentric loading

When the external load is greater during the eccentric phase than during the concentric phase of a movement, the training method is referred to as accentuated eccentric loading. This can be achieved by increasing the load during the eccentric phase, providing assistance during the concentric phase through spotters, performing the concentric phase with two limbs and the eccentric phase with one limb (the 2:1 method), or using specialized devices such as weight releasers, flywheels, and connected adaptive resistance exercise devices⁵⁹. It should be noted, however, that substantial muscular adaptations can also be achieved with submaximal eccentric loading.

Among the various methods designed to emphasize eccentric contractions, flywheel-based isoinertial devices have received considerable attention. These devices enable eccentric overload training by providing continuous resistance throughout the entire range of motion and allowing greater eccentric force production than traditional weight-based resistance training⁴². Flywheel eccentric exercise interventions have been investigated in healthy older adults⁶⁰⁻⁶⁵ as well as in older adults with chronic stroke⁶⁶. Collectively, these studies have demonstrated substantial improvements in muscle strength, postural stability, and functional performance following various flywheel training protocols^{42,62,63,67}.

Only a limited number of studies have directly compared flywheel training with other exercise modalities, such as traditional weight-based resistance training^{63,65} or high-intensity aerobic training^{60,61}. In a 12-week intervention, flywheel-based eccentric knee extension training was more effective than traditional resistance training for increasing peak isokinetic power of the knee extensors (28% vs. 4%) and gastrocnemius tendon stiffness (136% vs. 54%)⁶³. These neuromuscular adaptations were accompanied by a marked improvement in balance performance (45%).

Bruseghini et al.⁶⁰ compared flywheel leg-press training with aerobic interval training in healthy older adults. As expected, aerobic interval training improved aerobic fitness, blood pressure, and body composition, whereas flywheel training did not. However, flywheel training resulted in greater increases in quadriceps maximal voluntary isometric torque (7–10%) and eccentric–concentric isokinetic torque (5–9%). Importantly, the gains in maximal torque were strongly to moderately correlated with increases in quadriceps muscle volume and cross-sectional area. Furthermore, significant reductions in low-density lipoprotein (LDL) cholesterol (–13%) and total cholesterol (–11%) were observed only following flywheel resistance training.

While most of the aforementioned studies employed seated knee-extension flywheel ergometers, Sañudo et al.⁶⁴ examined the effects of squat-based flywheel training in healthy older adults (64 ± 4 years). Participants trained two to three times per week for six weeks, performing four sets of nine squat repetitions per session. Significant improvements were observed in mean propulsive velocity (48%), muscle power (63%), mobility (13% improvement in the timed up-and-go: TUG test), and postural balance (27% reduction in centre-of-pressure excursion with eyes open).

The squat exercise closely resembles the sit-to-stand (STS) movement and is therefore highly relevant for exercise prescription in older adults⁴². The ability to perform the STS manoeuvre is strongly associated with lower-limb muscle power and the capacity to carry out activities of daily living⁶⁸. Consistent with this, Spudić et al.⁶⁵ reported significant improvements in functional performance measures, including STS, TUG, and the 6-minute walk test, following an 8-week flywheel squat training programme in healthy women aged 65–74 years.

Similarly, Hill et al.⁶² reported reductions of approximately 18% in the time required to complete five STS repetitions and increases of approximately 24% in the number of STS repetitions completed within 30 seconds, accompanied by a 14% improvement in TUG performance. These findings are consistent with previous studies demonstrating improvements in TUG performance following six weeks of flywheel training (approximately 13%)⁶⁴ and other eccentrically biased exercise interventions in older adults (5–29%)^{45,47}.

Of particular interest, Hill et al.⁶² reported very large reductions in postural sway (approximately 60–80%) following a six-week flywheel training programme. In contrast, previous studies investigating seated⁶³ or standing⁶⁴ flywheel eccentric-overload training reported more modest improvements in postural stability (approximately 16–27%). A key difference among these studies is that the interventions of Onambélé et al.⁶³ and Sañudo et al.⁶⁴ primarily targeted the knee and hip extensors through squat and knee-extension exercises, whereas Hill et al.⁶² incorporated both squat and calf-raise exercises. These

findings suggest that including exercises targeting the ankle plantar flexors may enhance the postural adaptations achieved through flywheel-based eccentric overload training, given the critical role of the ankle musculature in balance control.

Prolonged eccentric loading

When the same external load is used during both the concentric and eccentric phases of a movement, the duration of the eccentric phase can be deliberately prolonged. This approach is commonly referred to as tempo eccentric training. For example, the concentric phase may be completed in 1 s, whereas the eccentric phase is extended to 3 s. The effectiveness of this strategy remains somewhat controversial, as studies have not consistently demonstrated superior adaptations compared with conventional resistance training. For instance, Dias et al.⁶⁹ compared eccentric training, in which the concentric and eccentric phases were performed over 1.5 and 4.5 s, respectively, with conventional resistance training, in which both phases were performed over 1.5 s, using traditional gym-based exercises such as the leg press, knee extension, and bench press in older women. Both training programmes resulted in significant improvements in knee extension 1-RM, TUG test, and 6-minute walk test, with no significant differences between the training groups.

Several eccentric training modalities that do not require specialized equipment have also proven effective. These include traditional resistance exercises as well as machine-based exercises performed with minimal modifications. Hortobágyi and DeVita⁵⁸ demonstrated that seven weeks of eccentric overload training produced substantially greater gains in quadriceps strength in older adults than conventional resistance training, with strength improvements approximately 1.8 times greater. Importantly, these benefits were achieved with significantly lower cardiovascular stress during exercise. In that study, participants performed unilateral knee extension–flexion exercises on a Cybex machine, with an additional 50% load applied during the lowering phase to create eccentric overload. The training programme was designed such that the total amount of weight lifted was comparable between the eccentric overload and conventional training groups.

Using a leg extension machine, Chen et al.⁴⁹ compared the effects of a 12-week progressive eccentric training programme with concentric training in older men. Eccentric training resulted in significantly greater improvements in maximal voluntary concentric torque (18% vs. 10%), maximal voluntary isometric torque (31% vs. 18%), 1-RM strength (49% vs. 35%), and upper-thigh circumference (1.1% vs. 0.5%) than concentric training. Functional performance also improved to a greater extent following eccentric training, as evidenced by superior gains in the 30-s chair-stand test (36% vs. 23%), the 8-foot up-and-go test (26% vs. 21%), and the one-leg stance test with eyes

open (59% vs. 13%). In addition, eccentric training was more effective in improving metabolic health markers, including insulin sensitivity, as reflected by reductions in the homeostasis model assessment (HOMA; –28%), glycated haemoglobin (HbA1c; –6%), and the two-hour oral glucose tolerance test (OGTT; –12%). Favourable changes in blood lipid profiles were also observed, including reductions in fasting triacylglycerols (–16%), total cholesterol (–8%), and LDL cholesterol (–7%), together with an increase in high-density lipoprotein (HDL) cholesterol (+12%).

Although eccentric resistance training in research settings often involves loads being lifted by research staff or specialized machines and then lowered eccentrically by the participants, more practical methods have been developed for clinical and community settings. One such approach is the *two-up, one-down* technique, in which the load is lifted concentrically using both limbs and lowered eccentrically using a single limb⁷⁰. This form of accentuated eccentric training has been successfully implemented in older adults and has been shown to increase vastus lateralis muscle thickness by approximately 5%, improve functional performance measures such as stair-climbing ability (5%) and 6-minute walk performance (7%), and increase knee extensor isometric torque (7%) and isokinetic torque across a range of contraction velocities (6–11%)⁵³.

Collectively, these findings demonstrate that prolonged and accentuated eccentric loading can be implemented using relatively simple and accessible exercise modalities. Such approaches are capable of improving muscle strength, functional performance, and metabolic health in older adults while remaining feasible for application outside specialized laboratory settings.

Eccentric-biased exercise and low-load eccentric exercise

Eccentric contractions occur naturally during many daily activities and forms of exercise, including downhill walking, descending stairs, landing after a jump, and sitting. These activities can be broadly classified as eccentric-biased exercises. Consequently, a wide range of exercise modalities involve muscles actively lengthening while resisting an external load. The intensity of eccentric-biased exercise can vary considerably, ranging from maximal efforts equivalent to 100% of MVC to very low intensities, such as 10% of MVC. However, the intensity of eccentric contractions in bodyweight activities is considered to be low.

Eccentric endurance exercises involving large muscle groups, such as eccentric cycling, stepping, downhill walking, and descending stair walking, have been increasingly used as interventions for older adults. These modalities minimize the substantial mechanical stress imposed on individual joints during traditional resistance training while still providing meaningful improvements in muscle

strength and mass^{41,71,72}).

In eccentric cycling, the pedals are driven backward by a motor, and the lower-limb extensor muscles resist the pedal motion to match a prescribed target torque^{47,48,73}. In a landmark study, LaStayo et al.⁴⁷ trained very frail older adults (mean age $\approx$ 80 years) on a recumbent eccentric cycle ergometer three times per week for 11 weeks. The intervention resulted in substantial improvements in muscle strength (60%), balance (7%), and stair-descent performance (21%), together with a reduction in fall risk. These benefits were not observed in a comparison group undertaking traditional resistance training. Notably, participants reported that eccentric cycling required relatively little effort despite the significant physiological adaptations achieved. This observation is consistent with findings by Clos et al.⁷⁴, who reported that eccentric cycling elicited a 37% lower rating of perceived exertion than concentric cycling performed at the same mechanical workload.

The seated position used during eccentric cycling further reduces the risk and fear of falling among individuals with limited mobility while still providing an adequate stimulus for improving muscle strength and function⁴⁷. Moreover, eccentric cycling requires motor learning, coordination, and skill acquisition⁷⁵, suggesting that it may also provide cognitive benefits that could help counteract age-related declines in cognitive function.

Another eccentric exercise modality of interest is the Eccentron® (BTE Technologies, Hanover, MD, USA), a seated stepping dynamometer that provides multi-joint, eccentric-dominant exercise^{76,77}. In this device, motor-driven pedals move toward the user in an alternating unilateral pattern, while real-time visual feedback allows participants to match a target force displayed on a computer screen. Such purpose-built eccentric ergometers are particularly valuable in research and clinical settings because they permit precise control of eccentric loading and enable isolation of eccentric muscle actions.

Studies using eccentric stepping ergometers in older adults have demonstrated significant improvements in functional mobility, muscle strength, and muscle size^{46,55,78,79}, although improvements in static balance have not been consistently observed⁵⁵. When compared to conventional resistance training, motorized eccentric training has often produced superior outcomes. For example, Kim et al.⁴⁶ reported greater improvements in physical function, including gait speed (17% vs. 4%) and stair-climbing performance (14% vs. 3%), as well as greater increases in muscle strength and power assessed by isokinetic knee-extension tests (strength: 16% vs. 4%; power: 9% vs. 5%) following an eight-week eccentric stepping intervention in adults over 65 years of age.

Performing daily activities that emphasize eccentric contractions, such as descending stairs and walking downhill, has also emerged as a practical and accessible training strategy for older adults⁸⁰. One of the primary goals of these interventions is to increase participation

in eccentric exercise by utilizing activities that can be easily incorporated into everyday life. From a practical perspective, downhill stair walking (DSW) may be one of the most accessible forms of eccentric exercise because it requires no specialized equipment and can be performed at little or no cost where stair access is available.

The effectiveness of DSW has been investigated in comparison to ascending stair walking (ASW)^{44,80,81}. In a study of older women with obesity, Chen et al.⁴⁴ reported that DSW produced greater health benefits than ASW despite eliciting lower ratings of perceived exertion. Although both interventions resulted in similar reductions in body mass and body fat, DSW was more effective in improving cardiovascular health, as reflected by greater reductions in resting heart rate (-10% vs. -4%) and systolic blood pressure (-9% vs. -3%). Improvements in insulin sensitivity were also observed following DSW, including a 12% reduction in OGTT responses, whereas no significant changes were evident after ASW. Similarly, DSW produced greater improvements in blood lipid profiles, including a 13% reduction in LDL cholesterol.

The mechanisms underlying these favourable metabolic adaptations remain to be fully elucidated. However, additional analyses from the same study revealed substantially greater increases in circulating adiponectin ($+127\%$), a regulator of carbohydrate and lipid metabolism and endothelial function, and apelin ($+23\%$), an adipokine involved in cardiovascular regulation and fluid homeostasis, following DSW compared to ASW⁸². These findings suggest that eccentric exercise may induce unique endocrine and metabolic adaptations.

Further support for the efficacy of DSW comes from evidence demonstrating a greater reduction (-21%) in a biomarker associated with fibrosis and muscle atrophy linked to sarcopenia⁸². In addition, DSW elicited larger improvements in maximal voluntary isometric strength (34% vs. 15%) and several measures of functional fitness compared to ASW, with the greatest improvement observed in the 30-s chair-stand test (42%). Bone mineral density increased only following DSW (6%), which has been attributed to the greater mechanical loading experienced by the lower-limb muscles and bones during stair descent compared to stair ascent⁴⁴.

Bodyweight resistance exercises can be performed without specialized equipment and are not limited by time or space. This modality allows for an emphasis on eccentric contractions by prolonging the lowering phase of movements such as squats while minimizing load during the concentric phase. In bodyweight resistance exercises, such as bodyweight squats, muscle activity levels in older adults correspond to approximately 20–30% of their maximal voluntary contraction strength. To highlight eccentric contractions, the eccentric phase in these exercises is typically performed over three to five seconds^{83,84}. Katsura et al.⁸⁴ reported that eccentric-focused bodyweight resistance training improved maximal voluntary contrac-

tion (MVC) by 13%, chair stand performance over 30 s by 17%, TUG performance by 18%, sit-and-reach flexibility by 7%, 6-meter walking speed by 10%, and balance by 17% following 10 weeks of training performed twice a week. These findings suggest that bodyweight eccentric exercise training is effective in preventing falls and maintaining muscle and physical function, which are essential for independence and quality of life in older adults, ultimately extending their health span.

Collectively, these findings highlight the important role of eccentric contractions in exercise interventions for older adults. Low-load and eccentric-biased exercise modalities can improve muscle strength, physical function, metabolic health, cardiovascular health, and bone health while imposing relatively low physiological strain. Such characteristics make these interventions particularly attractive for promoting healthy ageing and reducing the risk of falls, frailty, and fall-related injuries.

Implementation and prescription of eccentric exercise

Because eccentric contractions potentially induce muscle damage, the prescription of eccentric exercise in clinical practice was discouraged for many years. For older adults, the temporary loss of muscle strength and impairment of proprioceptive function following unaccustomed eccentric exercise may compromise safety during daily activities by increasing the risk of falls and related injuries⁷⁷). In addition, unpleasant symptoms such as muscle soreness and stiffness may reduce exercise tolerance and adherence, particularly among previously inactive individuals. Therefore, minimizing muscle damage is a critical consideration when prescribing eccentric exercise for older adults. If substantial muscle damage occurs, recovery may be delayed, prolonged, or less efficient in aged muscle⁸⁵). However, as discussed previously, a gradual progression of exercise load can markedly reduce these adverse effects [Fig. 4].

Despite these concerns, eccentric exercise interventions have gained increasing acceptance owing to growing evidence demonstrating that substantial physiological and functional benefits can be achieved without inducing clinically significant muscle damage. For example, Chen et al.⁴⁴) successfully introduced descending stair-walking exercise to older women with obesity by progressively increasing the exercise volume over time. Importantly, no evidence of muscle damage or exercise-related injuries was reported during the intervention. Similarly, other studies have shown that when eccentric training intensity is increased gradually, positive outcomes can be achieved without signs of muscle damage, even in very frail older adults^{47,49}). Furthermore, LaStayo et al.⁵⁴) reported that the gradual introduction and progression of eccentric training loads resulted in substantial strength gains in older adults without adverse changes in serum CK activity, tumour necrosis factor- α (TNF- α) concentration, or other clinical

markers of muscle damage.

Current evidence suggests that submaximal eccentric exercise is sufficient to elicit significant functional and health-related benefits. Although many early studies employed moderate- to high-intensity eccentric contractions, more recent investigations have demonstrated positive outcomes using relatively low training intensities. For example, Johnson et al.⁷⁸) reported significant improvements in physical function after older adults completed an 8-week programme on a commercially available eccentric stepping ergometer (Eccentron®) at intensities ranging from 20% to 50% of maximal eccentric strength. Similarly, Kay et al.⁵⁵) observed substantial improvements in mobility, eccentric strength, and vastus lateralis muscle thickness following six weeks of twice-weekly training on an eccentric recumbent stepper performed at approximately 50% of maximal voluntary contraction.

With regard to exercise volume, the duration of multi-joint eccentric training sessions has varied considerably across studies, ranging from three to 30 minutes per session^{48,54,55,77,78}). Studies involving older adults have demonstrated that programmes beginning with relatively short exercise durations (3 to 5 min per session) and progressing gradually to approximately 10 min per session can produce meaningful improvements in physical function and mobility^{55,78}). When higher training loads are used, four 5-min bouts per session appear to be as effective as a continuous 20-min bout while inducing less fatigue⁷⁵).

Most eccentric exercise interventions have employed training frequencies of two or three sessions per week. However, evidence indicates that meaningful improvements in muscle strength and functional capacity can also be achieved with only one eccentric exercise session per week^{49,86}). Future research should further investigate the effects of different training frequencies in older adults to optimize exercise prescription⁷⁶). Such work is particularly relevant given that only a small proportion of older adults report a preference for exercising three times per week⁸⁷). Moreover, research in young adults has shown that a multi-joint eccentric training programme performed three times per week provided no additional benefits over once-weekly training when total training volume was matched⁸⁸). Sato et al.⁸⁹) showed that a 3-s maximal voluntary eccentric contraction of the elbow flexors performed daily for five days a week for four weeks increased maximal voluntary isometric ($10.2 \pm 6.4\%$), concentric ($12.8 \pm 9.6\%$), and eccentric contraction torque ($12.2 \pm 7.8\%$), but these were not achieved by maximal isometric or concentric contraction in the same volume. This indicates that eccentric contraction produces more potent effects than isometric or concentric contraction on neuromuscular adaptation.

Collectively, these findings indicate that eccentric exercise can be safely and effectively prescribed for older adults when appropriate progression principles are followed. Starting with low-to-moderate intensities and vol-

umes and gradually increasing the training stimulus appears to maximize the benefits of eccentric exercise while minimizing the risk of muscle damage, excessive fatigue, and poor adherence.

Recommendations

The balance between the potential risks and substantial benefits of eccentric exercise underscores the need for evidence-based guidelines for eccentric exercise prescription to maximize both safety and effectiveness. Exercise programmes should be individualized according to an individual's health status, physical function, fitness level, and training goals, with careful consideration given to exercise technique, intensity, volume, progression, and recovery. Appropriate progression is particularly important when introducing eccentric exercise to older adults, as gradual increases in training load can minimize the risk of muscle damage while maximizing functional adaptations.

Supervision by qualified exercise professionals and the use of appropriate equipment are essential to ensure the safe implementation of eccentric exercise programmes in older adults and to minimize the risk of injury and adverse events. Although eccentric exercise programmes can target all major muscle groups, particular emphasis should be placed on strengthening the lower limbs. Lower-limb muscle strength and function are critical determinants of mobility, postural stability, physical independence, and overall quality of life in older adults. Therefore, improv-

ing the strength and function of the hip, knee, and ankle musculature should be considered a primary objective of eccentric exercise interventions designed for ageing populations.

To enhance adherence to exercise programmes, behavioural strategies, social support, and environmental modifications should be incorporated into intervention design to promote long-term participation and sustainability. Such strategies may include goal setting, progress monitoring, group-based exercise opportunities, and ongoing encouragement from healthcare professionals, family members, and peers. In addition, collaboration among community organizations, healthcare providers, exercise professionals, and policymakers is essential to facilitate the dissemination and implementation of eccentric exercise programmes across a variety of settings and to increase access for a broader segment of the older adult population.

Overall, current evidence indicates that eccentric exercise represents a safe, feasible, and highly effective intervention for improving muscle strength, functional capacity, metabolic health, and overall well-being in older adults when appropriately prescribed and supervised. General recommendations for implementing eccentric exercise interventions in apparently healthy older adults are summarized in Table 1.

It is important to note that eccentric exercise has been successfully used in the management and rehabilitation of patients with a range of chronic diseases, including chron-

Table 1. General recommendations before, during and after implementing eccentric exercise training.

Before	Medical check	Medical examination or health screening questionnaire to inform any diseases (e.g., metabolic disorders, degenerative joint and muscle disease, or osteoarthritis) and medications
		Pain check (e.g., knee or other joint pain)
		Presence of history or fear of falling
	Physical fitness assessment	Physical activity status assessment using functional fitness tests for older adults (e.g., STS, TUG, 6min walk test) and muscle strength measurements
	Exercise prescription	Prescription of personalized exercise intervention based on equipment availability, participant's health, fitness level, exercise preference and individual needs
During	Safety concerns	Close supervision by experienced clinicians or exercise professionals
		Particular attention to participant safety (e.g., use of equipment, participant position, movement execution, presence of pain or discomfort)
	Initial exposure	Implementation of initial familiarization phase beginning with very low eccentric load to confer repeated bout effect
	Training design	Careful and progressive ramping of eccentric loads considering Frequency, Intensity, Time, and Type (F.I.T.T Principles)
	Follow-up	Monitoring of perceived exertion rate (RPE) during each exercise session
After	Exercise adherence	Assessment of self-reported musculoskeletal pain (DOMS) using visual analogue scale throughout exercise program
		Continuous encouragement, feedback and verbal communication to ensure participant motivation and exercise compliance
	Effect check	Measurement of training-induced adaptations according to individual goals (fatigue, pain, mobility, strength, ...) after exercise intervention period

ic obstructive pulmonary disease⁹⁰), multiple sclerosis⁹¹), metabolic dysfunction-associated fatty liver disease⁹²), stroke⁹³), diabetes⁹⁴), and cancer⁹⁵). As illustrated in Fig. 5, eccentric exercise can be effectively incorporated into rehabilitation programmes for many chronic conditions. When prescribing eccentric exercise for patients with chronic diseases, the recommendations outlined in Table 1 should be followed.

Mechanisms underpinning effects of eccentric exercise training

The mechanisms underlying the apparently superior effects of eccentric exercise training on muscle function, physical performance, and health-related outcomes, compared to concentric exercise training or other exercise modalities, are not yet fully understood. Several potential mechanisms have been proposed, although many remain speculative [Fig. 7].

With respect to improvements in muscle function, eccentric contractions may induce unique neural adaptations, including enhanced neural drive from the central nervous system and improved motor unit recruitment strategies. In addition, eccentric loading appears to stimulate adaptations in the muscle–tendon unit, including increases in tendon stiffness and mechanical efficiency, which may contribute to improvements in muscle strength, power, and functional performance. At the muscular level, the high forces generated during eccentric contractions create substantial mechanical strain within and between muscle fibres. The shear stress arising between recruited and non-recruited fibres may activate mechanosensitive structures, such as integrins located on the muscle cell membrane. Activation of these mechanotransduction pathways is thought to stimulate intracellular

signalling cascades involved in muscle protein synthesis, ultimately promoting muscle hypertrophy and strength gains.

It is now well established that skeletal muscle releases a variety of signalling molecules, known as myokines, in response to exercise. Likewise, other organs and tissues release biologically active factors during physical activity, collectively referred to as “exerkines.” These molecules play important roles in mediating communication among skeletal muscle, adipose tissue, liver, bone, cardiovascular system, and the brain. It is possible that eccentric exercise induces a distinct or greater release of specific myokines and exerkines compared to concentric exercise or other training modalities. Such responses may partially explain the favourable effects of eccentric exercise on insulin sensitivity, glucose regulation, lipid metabolism, cardiovascular health, and cognitive function that have been reported in several intervention studies.

Emerging evidence also suggests that eccentric exercise may influence systemic inflammation, mitochondrial function, and metabolic regulation through endocrine and paracrine signalling pathways. However, the extent to which these mechanisms differ from those elicited by other forms of exercise remains unclear. Further research is therefore needed to identify the specific molecular and cellular pathways responsible for the unique adaptations associated with eccentric exercise training and to determine how these pathways contribute to improvements in muscle function, metabolic health, and healthy ageing.

A better understanding of these mechanisms will not only advance knowledge of exercise physiology, but may also facilitate the development of more targeted and effective eccentric exercise interventions for older adults and clinical populations.

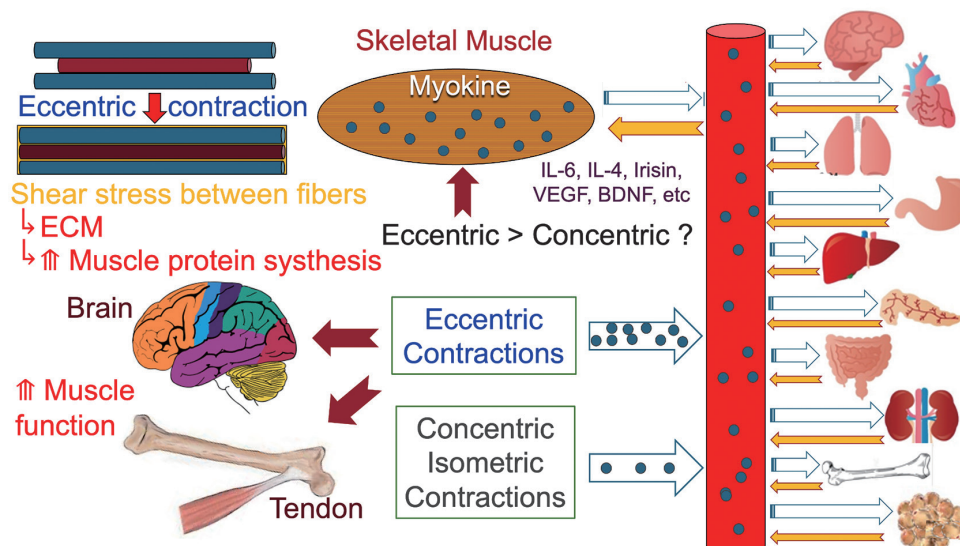


Fig. 7 Possible mechanisms of effects of eccentric exercise training. Blue dots show myokines. White arrows show possible effects of myokines on organs, and orange arrows show possible release of “exerkines” from organs.

Conclusion

Eccentric exercise, characterized by active muscle lengthening under load, offers several unique physiological and functional advantages. Owing to its ability to generate high muscle forces at relatively low metabolic and cardiovascular cost, eccentric exercise is particularly well suited to older adults, individuals with limited exercise capacity, and those with chronic health conditions. A growing body of evidence demonstrates that eccentric exercise training is highly effective for improving muscle strength, power, and mass, all of which are essential for maintaining mobility, physical function, and independence with ageing.

In addition to its musculoskeletal benefits, eccentric exercise training has been shown to enhance balance, functional performance, and metabolic health, while reducing the risk of falls and fall-related injuries. When appropriately prescribed using a gradual progression of training intensity and volume, eccentric exercise can be implemented safely with minimal risk of muscle damage and high levels of participant adherence. These characteristics make eccentric exercise a practical and accessible intervention for promoting healthy ageing.

Although the beneficial effects of eccentric exercise are increasingly well documented, the physiological and molecular mechanisms underlying these adaptations remain incompletely understood. Future research should further investigate the mechanisms by which eccentric exercise influences neuromuscular, metabolic, cardiovascular, and cognitive function, and determine how these responses differ from those elicited by isometric, concentric, and aerobic exercise modalities.

Overall, eccentric exercise represents a safe, feasible, and highly effective strategy for preserving muscle function, enhancing physical performance, and improving health outcomes across the lifespan. Its broader implementation in exercise, rehabilitation, and public health settings has considerable potential to extend health span, maintain independence, and improve quality of life in ageing populations.

Conflicts of Interest

The authors have no relevant financial or non-financial conflict of interest to disclose.

Author Contributions

Both authors contributed to the manuscript conception and design. The drafts of the manuscript were written by the authors and revised with discussion. The authors read and approved the final version of the manuscript.

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