Eccentric Exercise in Rehabilitation: Safety, Feasibility and Application

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Key Words: Eccentric, Rehabilitation, Muscle, Function, Patients

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ABSTRACT

This non-exhaustive, mini review reports on the application of eccentric exercise in various rehabilitation populations. The two defining properties of eccentric muscle contractions, a potential for high muscle force production at an energy cost that is uniquely low, are revisited and formatted as exercise countermeasures to muscle atrophy, weakness and deficits in physical function. Following a dual phase implementation, eccentric exercise that induces rehabilitation benefits without muscle damage, thereby making it both safe and feasible in rehabilitation, is described. Clinical considerations, algorithms of exercise progression and suggested modes of eccentric exercise are presented.
INTRODUCTION

Lengthening (eccentric) muscle contractions have received much less experimental attention than either isometric or shortening (concentric) contractions, especially in rehabilitation populations. However, they have had an interesting and at times curious, research history. Our current understanding of muscle energetics is often and appropriately traced to A.V. Hill and his brilliant students Bassett (9). One of Hill's students, W.O. Fenn focused on muscle energetics in general and the energy "cost" of doing work in particular. What is now known as the "Fenn Effect" is a recognition that the energy cost of muscle contraction is roughly equal to the cost of force production plus the additional cost of the work produced. In other words, the energy required for force production in skeletal muscle is increased when muscles shorten while contracting and doing positive work (91). However, Fenn (28) also made an observation that received far less attention, namely that if a muscle is stretched while contracting the energy liberated by the muscle is reduced. We could call this a "Negative Fenn Effect" which led none other than Hill himself to speculate that the identical chemical reactions that consume ATP in shortening contractions could be reversed when muscles are subjected to mechanical stretch ("negative work") during lengthening contractions, functionally generating ATP (49, 50). While this "ATP generation" concept has been long ago debunked, these early experiments first established that the energy cost of isometric force production is: 1) increased if work is done by the muscle and 2) reduced if work is done on the muscle (eccentrically-induced negative work). Thus, these early studies established that the energy cost to produce identical magnitude and duration of force is least during eccentric contractions.

In addition to their low energy cost of force production, eccentric contractions also generate the highest forces. Nearly a century and a half ago, and long before the contributions of A.V. Hill, Adolf Ficksee Fick (29) published a paper which first: 1) introduced the term "isometric" to denote a muscle contraction in which no change in length occurs and 2) documented that if a muscle were stretched during a contraction it could produce increased force. The enhancement of force production during stretch in muscle has remained a curious observation with uncertain mechanistic explanations, even with the introduction of the sliding filament theory (52, 53). Recently, the magnitude and cause of this stretch enhancement in force is receiving increased attention (22, 46). In fact, the behavior of muscle during stretch has generated a new addition to the sliding filament model of muscle contraction where force enhancement is generated by the "engagement" of passive structural elements (e.g., titin) upon activation (44, 83). While there remains some debate regarding causation, there is no debate that skeletal muscle can produce far greater force if stretched while activated, i.e. during an eccentric contraction, than it can during either an isometric or concentric contraction.

Thus, the two defining properties of eccentric muscle contractions have been known for nearly a century: 1) force production is uniquely high and 2) energy cost to produce the force is uniquely low (70, 71, 92). Over 40 years ago, the observation was made by Komi and Buskirk (58) that, because of these defining properties, eccentric exercise has the greatest potential for muscle training or "conditioning". Indeed, high force and low cost constitute ideal characteristics for resistance exercise interventions designed for rehabilitation populations. Many frail or otherwise exercise-limited
individuals (e.g., those suffering from chronic cardiac or obstructive pulmonary diseases, cancer, metabolic, neurologic or postoperative conditions) are impaired in their abilities to produce sufficient muscle force to preserve their muscle mass and function, and/or they lack the energy capacity to do so. Even modest exercise interventions may be beyond their capabilities. Without sufficient load on their muscles, they enter a downward spiral of muscle wasting, often resulting in life-threatening falls. Thus, interventions for these individuals are needed that can produce high force, but do so with minimal energetic cost.

Despite their alluring characteristics, eccentric contractions of muscle have been viewed more as an anomaly rather than a potential life-enhancing intervention. The reason stems from another association with eccentric contractions, muscle damage. Eccentric muscle contractions became so linked with delayed onset muscle soreness (6, 21) they are now the primary experimental tool for causing and studying muscle damage. A quick Pubmed search coupling ‘eccentric’ with ‘injury or damage’ yields over 1000 citations, but less than 50 if coupled with ‘rehabilitation or beneficial’. This association has become so strong that eccentric contractions are often viewed as inevitably linked to muscle damage. Perhaps because of the very high forces that can be generated eccentrically, it is not surprising that they can cause muscle damage (6). Indeed, there has been a persistent idea that damage is a necessary prerequisite for any muscle remodeling (21, 26, 30, 102). If always true, this would be a very unfortunate constraint for rehabilitation, because those individuals who could benefit most from increased muscle strength are often those with the greatest vulnerability to any inflammatory response (36, 112).

Evidence is now mounting that muscle damage is neither inevitable nor necessary for muscle rehabilitation. First, evidence exists that eccentric exercise training can be safely and effectively used in rehabilitation (17, 19, 34, 62). The single key in avoiding any adverse muscle response of damage or injury to the muscle is dose. When high eccentric forces are generated in muscle naive to eccentric contractions, damage is almost inevitable. However, if the magnitude and duration of the force production is increased gradually over time no symptoms of damage, inflammation or even soreness are present (61, 65). Second, the beneficial muscle structure and function responses can occur completely independent of any observable symptoms of muscle inflammation or injury (30). Thus, employing high-force eccentric contractions to promote muscle rehabilitation, with no detectable damage, has great potential (51).

In this mini-review we discuss the use of chronic eccentric training as a resistance exercise intervention for rehabilitation populations. The rehabilitation focus is directed to adults or older adults with comorbid disease conditions and/or recovering from surgery and joint injury. The groups described are diagnostically diverse, though the common impairments of muscle atrophy and weakness underlie (in-part) their deficits in physical function.
SAFETY AND FEASIBILITY IN REHABILITATION POPULATIONS

Diverse samples of individuals in rehabilitation programs have demonstrated the ability to safely progress negative work over a course of many weeks of eccentric exercise training (17, 32, 33, 61, 62, 69, 75, 76, 97). Importantly, to safely progress negative work a segue from an adaptation phase to a phase that utilizes higher doses of eccentrically-induced negative work is required to avoid unnecessary muscle damage and negate the possibility of adverse responses, which includes profound pain, weakness and at worst exertional rhabdomyolysis (101). In contrast, eccentric exercise implemented chronically to reverse tendinopathies is often designed to induce a pain response as part of the therapeutic regimen (note: this approach is covered in detail in the previous paper in this mini-review by Kjaer and will not be covered here). Moreover, in older adults and populations plagued by disease and/or recovering from surgery, a phased-in progression of non-painful, nor injurious eccentric exercise has been shown to be universally feasible since the relative exertion required to perform increasing amounts of negative work is low. Additionally, older adults’ peak heart rate, systolic blood pressure, cardiac index and expired ventilation are lower during eccentric bouts of exercise of equivalent volume to concentric exercise (59, 110). Consequently, high levels of adherence and compliance with eccentric exercise have been reported (75, 79, 90).

Older Adults

Older adults in rehabilitation settings, including individuals characterized as frail, can partake in eccentric exercise without signs or symptoms of muscle or joint injury. Older adults living with diseases that result in atrophy, fatigue and weakness can progressively load their locomotor muscles eccentrically without inducing classic damage responses such as increases in creatine kinase and/or inflammatory markers along with decrements in force production (17, 60, 75). Negative work increases of ~2-10 fold (17, 33, 35, 61, 62, 75) over a course of 10-12 weeks are attainable with this population and may underlie the promotion of growth factors and molecular changes consistent with a positive muscle response to resistance exercise (60, 75, 81, 115). Further, since the perceived exertion required to produce these high levels of negative work are only “somewhat hard” older adults appear more willing to attend a high fraction (>90%) of the 2-3x/week eccentric rehabilitation over a course of 6-12 weeks. Meticulous attention to proper positioning, alignment and form is necessary to avoid undue stress on the ankle, knee and hip joints during eccentric exercise, especially in those with osteopenia and or osteoarthritis. After each session of eccentric exercise older adults may experience an acute bout of leg fatigue so a short rest period may be warranted before moving on to any other exercise modes.

Adults with Cardiopulmonary Disorders

Individuals with coronary artery, chronic heart failure or chronic obstructive pulmonary disease typically have cardiac and/or ventilatory restrictions that can constrain exercising in rehabilitation programs. In principle, eccentric exercise can be an attractive
and feasible alternative to resistance exercise for patients with limited cardiopulmonary
exercise tolerance. When exercising eccentrically, adults and older adults with minimal
left ventricular dysfunction and no exertional ischemia can produce fourfold greater
muscular stress and induce improvement in the distance walked in six minutes without
overstressing the cardiovascular system, i.e., at cardiovascular and metabolic levels
similar to those observed during concentric exercise (11, 79). Similarly, those with severe
chronic airway obstruction, e.g., forced expiratory volume <50% predicted, have
achieved non-damaging high negative work levels during eccentric exercise
with tolerable levels of leg fatigue and dyspnea compared to concentric ergometry
exercise (97). Standard cardiopulmonary rehabilitation exercise monitoring precautions
should be employed during eccentric exercise with this population.

**Older Adults Who Have Survived Cancer**

Survivors of cancer, and its treatment, often experience a reduced quality of life
due in part to impaired muscular abilities and deficits in mobility. Many older adults who
survive, and are considered anabolically-impaired, can still feasibly exercise using
eccentric contractions. Older (average age of 75 years) adult survivors of breast, prostate
or colorectal cancer participated in 34 out of 36 eccentric exercise sessions over 12 weeks
and increased their negative work >3 fold without a muscle injury response (62). Despite
hormone-related muscle function deficits, survivors of prostate cancer on androgen
deprivation therapy are able to exercise adequately to derive benefits in strength, mobility
and fatigue levels in an eccentric exercise rehabilitation program (40). There has not yet
been any reported exacerbation of cancer-related fatigue following eccentric exercise,
though this should be monitored closely especially immediately following an exercise
bout. Further, any cancer related treatments that might impair an older adults’ immune
response or amplify catabolic processes will require close attention and care so as to not
amplify these adverse responses to treatment.

**Adults with Metabolic Conditions**

Adults with type 2 diabetes can experience an acceleration of muscle loss
especially when coupled with increasing age (84). Loss of muscle strength is also greater
in older adults with diabetes relative to their peers (85) and this is in part, likely related to
the increased fall risk seen in this population (77, 103, 111). Exercise aimed at improving
muscle mass and strength in persons with diabetes is now regularly recommended (1, 2,
105). While a single exposure to eccentric resistance exercise specifically has been
associated with increased insulin resistance (7, 55, 86), and a parallel skeletal muscle
damage response, more recent evidence (37) suggests that elevated glucose and insulin
responses to an oral glucose tolerance test in healthy young women after an initial bout of
eccentric exercise is attenuated after a repeated eccentric bout, and after chronic exposure
to eccentric training (86) with skeletal muscle accounting for nearly 80% of glucose
uptake, it is important to exercise locomotor muscle in metabolically impaired
populations without worsening insulin resistance. Chronic and progressive exposure to
eccentric exercise results in significant improvements in leg lean mass, strength, and
mobility without adversely impacting insulin sensitivity in overweight, physically
inactive postmenopausal women with impaired glucose tolerance (74), and has been shown to enhance insulin sensitivity and decrease glycosylated hemoglobin by 10.6% in young sedentary women (86). Further, in healthy sedentary adults (mean age 48 years), chronic exposure (8 weeks, 3-5X/wk) to downhill hiking, a predominantly eccentric exercise modality, has also been shown to be similarly metabolically beneficial to concentric exercise (uphill hiking) (20, 114). Importantly, these metabolic improvements were accompanied by decreases in two typical markers of muscle injury, high-sensitivity C-reactive protein and serum creatine kinase. Because adults with diabetes often suffer from diabetes related micro and macrovascular complications including cardiovascular disease, retinopathy, peripheral neuropathy, and peripheral vascular disease, eccentric resistance exercise presents a viable alternative or adjunct to more traditional resistance or aerobic exercise in this population. Eccentric exercise in particular because of its lower energetic cost and perceived exertion is safe and feasible for those with diabetes (73, 75). If, however, the goal of rehabilitation is to utilize more energy during rehabilitation and decrease weight and BMI the lower metabolic cost of eccentric exercise may not be an ideal intervention and should be coupled with aerobic exercise (75). To maximize safety, techniques to minimize valsalva should be employed and visual foot inspections should be regularly performed. Glycemic responses to resistance training, especially hypoglycemia should be monitored closely, as should changes in diabetes medications.

**Adults and Children with Neurologic Conditions**

Individuals with central or peripheral nervous system deficits not only experience peripheral muscle atrophy but also a constrained, or lack of, neural drive to the muscle. The combined effect of these deficits may greatly restrict the force production ability of skeletal muscle and therefore impair mobility. It has been suggested that this loss of muscle function is obligate to central nervous system conditions, however, recent research using concentric or eccentric training suggests otherwise (14, 16, 27, 39, 56, 78, 106). Preliminary evidence in a limited number of central nervous system disorders suggests that eccentric training is a safe and feasible means of providing resistance exercise (17, 42, 94). For example, no sustained increase in markers of muscle damage or loss of isometric force production was noted during a 12-week high intensity eccentric training program in mild to moderately impaired older adults with Parkinson disease (17). Further, older adults following a stroke can improve leg muscle power with both standard and eccentric resistance training, however, greater cross-education effects have been noted in the non-paretic (untrained) legs only following high-intensity eccentric rehabilitation. This suggests that eccentric training may be inducing central neural adaptations (14). One concern regarding eccentric contractions in persons with upper motor neuron lesions is the potential to increase spastic muscle responses due to lengthening of muscle in the context of hyperactive stretch reflexes. To our knowledge, few studies have addressed this issue experimentally, however, a recent study in children who exercised eccentrically has attenuated this concern. In children with cerebral palsy and upper limb spasticity, eccentric strength training, resulted in increased torque throughout range of motion as well as reductions in EMG measured co-contractions (94).
Resistance training in the context of peripheral nervous system and neuromuscular disorders has historically been more controversial. Unfortunately, the specific effects of eccentric training cannot be determined from these studies since the descriptions of the resistance training interventions suggest a combination of concentric and eccentric contractions. Certainly more research is needed to understand the effects of eccentric training in these disorders.

**Adults Following Orthopaedic Knee Surgery or Joint Injury**

The early postoperative period following both anterior cruciate ligament reconstruction and total knee arthroplasty is the typical period for amplified muscle (e.g., the quadriceps) atrophy and weakness. Establishing the safety and feasibility is of utmost importance to any intervention applied after these surgical procedures. Foremost is the need to retain the stability afforded by the ligament reconstruction by closely monitoring the intensity of the resistance exercise and any adverse joint responses. Pain, knee effusion, injury recurrence, and instability rates are important metrics underlying knee joint safety following knee surgery. If the eccentric rehabilitation is judiciously implemented and progressed as outlined in the series of papers by Gerber (32, 33, 35) and reviewed by Lepley (68) the knee stability is not compromised following anterior cruciate ligament reconstruction in those with either patellar tendon or semitendinosus-gracilis grafts (32). No differences in any of the above mentioned safety measures have been noted following 12 weeks of rehabilitation with eccentric exercise as the resistance mode versus accelerated rehabilitation with standard resistance exercise initiated three weeks after surgery (32). The successful progression of negative work over a course of many weeks of rehabilitation suggests eccentric exercise is also feasible. Eccentric exercise three weeks after total knee arthroplasty surgery also does not adversely impact joint or muscle responses despite a five-fold increase in negative work over six weeks (76). Similar findings have been noted when implementing eccentric exercise many months following operative and non-operative eccentric rehabilitation for musculoskeletal knee joint injuries (38). Clearly, any adverse joint responses such as an increase in knee joint swelling or a loss of knee joint range of motion would be an indication to discontinue eccentric exercise. What has been reported to date suggests that knee swelling can be avoided and knee range of motion increases with eccentric exercise after surgery (15, 38, 64, 76). Therefore the early, safe and feasible implementation of eccentric exercise as part of knee rehabilitation should be considered safe, and the reported >85% adherence is added evidence of its feasibility.

**ECCENTRIC REHABILITATION: MUSCLE AND PHYSICAL FUNCTION OUTCOMES**

Given the safety and feasibility of eccentric exercise, and the high-force, low-cost nature of negative work, the application of eccentric resistance exercise as a strength training intervention to counteract sarcopenia and postoperative muscle atrophy in rehabilitation populations is alluring. Sarcopenia has historically been defined as a loss of muscle mass, though more contemporary and clinically applicable definitions include the loss of muscle strength and mobility.
Numerous gaps in our mechanistic understanding following chronic eccentric training exist, however, proposed mechanisms attempting to explain preserved eccentric force capacity in older individuals, how force enhancement following active muscle lengthening occurs, and changes underlying a protective repeated bout effect, may also be appropriate explanations for changes following eccentric rehabilitation. While classic hypertrophic signaling responses to resistance training may explain in-part how enhanced function follows eccentric training, these typical responses do not account for all of the changes. Several other neurologic, mechanical and/or cellular adaptations have been proposed (98). Examples of such are: heightened quadriceps stretch reflex activity in adults surviving a stroke, and an enhanced neural drive, with eccentric training (25); a higher contribution of synergistic muscle and cross-educational effects associated with central neural adaptations (14, 87); a mechanical stress-dependent increase in the proportion of attached cross bridges with eccentric activity (45, 66); and a change in the muscle cells use of passive elements like titin (67, 80), and elastic elements transmitting force outside the cell such as the tendon (95, 96).

These proposed mechanisms of adaptation will not be particularly helpful for the clinician in designing eccentric rehabilitation protocols, though they do highlight the need for more basic understanding of how the following changes occur. Here below we briefly review the impact of eccentric rehabilitation trials aimed at halting or reversing sarcopenia and postoperative atrophy in rehabilitation populations.

**Muscle Size**

Muscle hypertrophic responses following eccentric resistance exercise, measured at the fiber and whole muscle level, are mixed. Hypertrophy following eccentric exercise in older adults is greater (90) or equivalent (82, 90, 93) to that following standard resistance exercise. Other structural changes synonymous with positive responses following resistance exercise can occur. For example, increased vastus lateralis thickness (90) and decreased depots of leg intramuscular fat (75, 81, 82) have been demonstrated in older adults.

Following total knee arthroplasty (15, 64, 76) or when aging is coupled with disease, e.g., cardiopulmonary, cancer, diabetes, or Parkinson Disease, a more predictable increase in muscle size occurs (18, 63, 75, 107). The greatest changes in leg muscle cross sectional area or volume have been reported in adults following anterior cruciate ligament reconstruction (12, 32, 33, 35). Importantly from a rehabilitation perspective, these changes can occur when eccentric exercise is initiated three weeks after surgery and continued for 12 weeks. This may be due to the fact that this rehabilitation population is typically younger and less impacted by impaired muscle growth responses that hinder older-diseased rehabilitation populations. The increase in the volume of the quadriceps and gluteus maximus muscles has been observed to be twice that following the standard accelerated ligament reconstruction rehabilitation program (33). Additionally, these greater muscle responses can be maintained and coupled with functional strength and hopping improvements nine months following eccentric rehabilitation (32). Similarly, greater increases in quadriceps muscle volume have been noted in older adults one to four years after their total knee arthroplasty surgery (64), and in older adults with Parkinson...
disease (18) when eccentric resistance exercise is incorporated in a rehabilitation program compared to standard resistance exercise.

Additionally, older adults characterized as anabolically-impaired, such as survivors of cancer (63) or postmenopausal women with impaired glucose tolerance (74), can grow muscle following eccentric exercise when compared to standard care approaches. The magnitude of improvement, however, is less than in those who are not anabolically impaired. Rehabilitation with eccentric exercise for those in their 5th decade demonstrates mixed muscle hypertrophy responses. Adults with type 2 diabetes mellitus demonstrated hypertrophy with a program that combined aerobic and eccentric resistance exercise versus aerobic exercise only (75). Alternatively, those with stable coronary artery disease, however, did not change their quadriceps muscle fiber area with eccentric exercise (107). Since no studies with rehabilitation populations have compared work- and intensity-matched bouts of isolated eccentric and concentric exercise the suggestion that contraction type significantly influences hypertrophic signaling and adaptation is still not clear.

Muscle Function

Muscle strength and power enhancements appear to be more predictable than changes in muscle size after a course of rehabilitation with eccentric exercise, even when there is no differential increase in muscle size noted in older adults who exercise eccentrically versus concentrically (61, 82, 107). At times, strength improvements following eccentric exercise in older adults may be superior-to (90) or equivalent-to (93) improvements noted in a concentric or high velocity training groups (69). These strength improvements occur with all contraction types, though some studies characterize the strength enhancement as muscle contraction type specific (38, 93). Eccentric exercise training may also assist older adults in tasks that require control of submaximal muscle forces (61, 82, 90). This may be especially important for older adults at high risk of falling who have been observed to have poorer control of submaximal eccentric muscle forces (88, 89).

Older adults enrolled in cardiopulmonary (79, 97, 107) or post-operative knee (64, 76) rehabilitation can improve muscle strength with eccentric exercise. Further, those exercising eccentrically following a diagnosis of cancer (40, 62, 63), Parkinson disease (17, 18), polymyositis (41), osteoarthritis (38) or a metabolic impairment (74) all demonstrate eccentric resistance exercise training effects manifested as improved strength and/or power.

Clinically important and statistically significant increases in strength and strength-related variables have also been noted in non-elderly adult rehabilitation populations. Adults in rehabilitation following anterior cruciate ligament reconstruction (12, 32, 33, 35) highlight the potential for a rapid restoration of strength following eccentric exercise. Smaller strength enhancements have been noted in: individuals with isolated insufficiency of their posterior cruciate ligament of the knee (72), those with multiple sclerosis (42) and children with cerebral palsy (94).
Physical Function

Improvements in muscle size and strength provide evidence of the physiologic efficacy of eccentric exercise, however, such effects are of little relevance if they do not also produce enhancements in physical function, here defined as the “the ability to move around” (10) and “the ability to perform daily activities” (109). Underlying the physical function deficits are ubiquitous impairments in muscle structure and function (e.g., composition and strength).

This link between muscle strength and mobility performance drives the need for resistance exercise as part of a rehabilitation program in needy adult and older adult populations (64, 98, 108). Muscles do nearly equal amounts of positive and negative work during normal gait and locomotion (13, 43), and many precarious high fall risk tasks like descending stairs rely almost exclusively on eccentric muscle contractions. Therefore, it is not surprising that all previous eccentric exercise trials that monitored mobility levels in rehabilitation populations have demonstrated improvements in a wide variety of physical function tasks requiring both eccentric and concentric contractions. The greatest eccentric exercise effects on mobility to date have appeared in individuals following knee surgery (38, 64, 76) or in those with the most to gain (18, 63, 75, 100, 110). Fewer studies using eccentric rehabilitation have documented abilities to perform daily activities, though improvements in self-reported quality of life have been noted in total knee arthroplasty recipients and older individuals with Parkinson disease (19, 32, 64).

Thus, rehabilitation interventions targeting eccentric muscle contractions can benefit older adults requiring rehabilitation, not only to improve their mobility, but also to avoid falls, which can improve confidence when moving about. Additionally, even for those not at a high fall-risk, the increased reserve of muscle mass, strength/power and mobility resulting from eccentric muscle activity will serve as a physical function “safety factor”.

ECCENTRIC REHABILITATION: APPLICATION

Progression of Eccentric Exercise

In order to expose patient populations to higher muscle forces using eccentric muscle activity, a progressive ramping of negative work is required. An eccentric exposure-adaptation phase must be implemented initially to avoid unnecessary muscle damage. If a patient’s locomotor muscle does not first experience lower eccentric forces and a low volume of negative work during an eccentric exposure-adaptation phase the patient typically may experience high levels of muscle damage and consequently will not adhere to the resistance exercise program, nor be capable of experiencing the eventual positive aspects of higher eccentric muscle forces. By exposing the muscle to lower doses of negative work initially, an adaptive repeated bout effect is expected. The mechanisms surrounding this adaptation are multifactorial (47, 48) and beyond the purpose of this mini-review, however, this should not undermine the significant need for this adaptation.
to occur prior to higher dose eccentric loading. When exposing rehabilitation populations
to lower doses of negative work during this adaptation transient, low levels of delayed
onset muscle soreness are acceptable. Following the eccentric exposure-adaptation phase
the muscle is better prepared to experience the higher forces that are characteristic of a
progressive eccentric-negative work phase.

During the progressive eccentric-negative work phase the goal is for the
rehabilitating participant to progressively resist a higher load for prolonged periods.
Eventually the exercise load being resisted should exceed the participant’s isometric
maximum load, i.e., the load should now exceed that which can be moved concentrically.
The benefit of eccentric resistance exercise from a muscle strengthening perspective is
likely greatest when the exercise load is greater than that which can simply be recovered
eccentrically following a concentric component of the exercise (99). In general the
expectation is that the loading goal during the progressive eccentric-negative work phase
should exceed an isometric maximum load, and the eccentric exercise duration should be
performed for up to 20-30 minutes per session, 2-3 times per week for 6-12 weeks. With
the use of eccentric ergometry muscle force output with eccentric contractions have been
demonstrated to be up to 1.5x maximum isometric force (31). Coupling this with
previous studies (3-5, 8, 54, 57, 104, 113) comparing eccentric and concentric force,
torque and work, it is not unreasonable to estimate the total negative work possible per
week could be ~20-40% greater that standard resistance exercise despite similar relative
training intensities. This load and ultimate volume of negative work may be best achieved
using an eccentric ergometer delivery mode and progressing the intensity using the a
perceived exertion scale (59).

Modes of Eccentric Exercise

In order to implement and experience the muscle and physical function training
benefit during the progressive eccentric-negative work phase, external assistance will be
required to move the exercise load concentrically prior to resisting the load eccentrically.
In most rehabilitation applications, a motorized ergometer delivers the load to the
individual, requiring the exercise participant to repeatedly absorb energy and perform
negative work only. Ergometers for both the lower (61, 79, 100) and upper extremities
(23, 24) have been described in detail and can be fabricated using motors and controllers.
Commercial ergometers (BTE, Inc., Hanover MD) are currently available for
rehabilitation purposes.

Alternatively, eccentric exercise can be implemented with traditional resistance
exercise equipment, or using body mass alone. The application of these modes of
eccentric resistance requires two extremities to perform the concentric movement
followed by one extremity performing the eccentric action.
Finally, it is possible to capture the potential benefits of eccentric exercise using an individual’s body mass during functional activities (e.g., hiking downhill) or when performing eccentrically-biased movement patterns (e.g., Tai Chi). The eccentric loading stems from the individual’s body mass and the activities or movement patterns are designed to progressively transfer more of an individual’s body mass over a single leg in an eccentric fashion. With downhill hiking the knee and hip extensors are performing negative work with each decelerating step. Traditional movement exercise like Tai Chi allows individuals to progress the exercise eccentrically when the hip and knee flexion range of movement is increased and/or the speed in which the movements are performed is slowed. Further, functional weight bearing activities like moving from standing to sitting can be employed as an eccentric activity.

SUMMARY

Interventions geared toward individuals following surgery, or older adults with comorbid clinical pathologies on a progressive downward decline toward mobility limitations and/or frailty (e.g., hip fracture, postoperative, pneumonia), are needed. These interventions are especially important when muscle mass reserves and quality are low, mobility impairments are high, and physical independence is dwindling. Although pharmacologic approaches are being investigated as alternative methods to increase or attenuate declines in muscle, few if any, countermeasures are superior to resistance exercise. The safety, feasibility and potential clinical benefits of eccentric resistance exercise training regimens for rehabilitation populations are becoming more apparent. In this regard, the further development of parameters to optimize intensity, duration, and modes of eccentric training may lead to significant enhancements in muscle size, strength, physical function and quality of life for elderly, diseased, or chronically injured individuals.

Acknowledgments:

Fernando Frajacomo’s contribution is supported via scholarship program for doctoral candidates. Process number BEX-7126123, CAPES foundation, Ministry of Education of Brazil, Brasilia-DF 70040-020, Brazil. Current Address: Fernando Tadeu Trevisan Frajacomo, Visitor Scholar, Department of Physical therapy, University of Utah, Salt Lake City, Utah.
References


12. Brasileiro JS, Pinto OM, Avila MA, and Salvini TF. Functional and morphological changes in the quadriceps muscle induced by eccentric training after ACL reconstruction. Revista brasileira de fisioterapia (Sao Carlos (Sao Paulo, Brazil)) 15: 284-290, 2011.


Laroche D, Joussain C, Espagnac C, Morisset C, Tordi N, Gremaux V, and Casillas JM. Is It Possible to Individualize Intensity of Eccentric Cycling Exercise From Perceived Exertion on Concentric Test? *Archives of physical medicine and rehabilitation* 2012.


LaStayo PC, Ewy GA, Pierotti DD, Johns RK, and Lindstedt S. The positive effects of negative work: increased muscle strength and decreased fall risk in a frail


69. Leszczak TJ, Olson JM, Stafford J, and Brezzo RD. Early Adaptations to Eccentric and High Velocity Training on Strength and Functional Performance in Community Dwelling Older Adults. *Journal of strength and conditioning research / National Strength & Conditioning Association* 2012.


75. Marcus RL, Smith S, Morrell G, Addison O, Dibble LE, Wahoff-Stice D, and Lastayo PC. Comparison of combined aerobic and high-force eccentric resistance


77. Maurer MS, Burcham J, and Cheng H. Diabetes mellitus is associated with an increased risk of falls in elderly residents of a long-term care facility. The journals of gerontology Series A, Biological sciences and medical sciences 60: 1157-1162, 2005.


**Figure Legend**

Figure 1. Eccentric rehabilitation applications for individuals with a variety of age and/or medical-related conditions; all of which share muscle atrophy, weakness and physical dysfunction as common impairments.

Figure 2. Sample eccentric workload progression over 12 weeks. Negative work (left hand vertical axis and full white line) and perceived exertion (right hand vertical axis and bars). Note the distinction (vertical stippled line) between the initial, exposure-adaptation phase where work and perceived exertion remain relatively stable, and the progressive eccentric negative work phase where work and perceived exertion increase in parallel to a point where perceived exertion levels of “somewhat hard” are reached and remain stable while work continues to increase.

Figure 3. Eccentric-negative work progression algorithm for temporary pain (VAS= visual analog scale), adverse reactions or missed sessions.

Table 1. Example of progression of total volume of eccentric work on eccentric ergometer over 12 weeks. Duration could be substituted with sets and repetitions of different eccentric exercises.
Eccentric Rehabilitation Applications

- Cardio-pulmonary Disease
- Frailty
- Diabetes
- Cancer
- Neurologic Disease
- Knee Surgery Injury
- Atrophy
- Physical Dysfunction
- Weakness
Exposure-Adaptation Phase

Progressive Eccentric-Negative Work Phase

Negative Work

Perceived Exertion

Program Duration (weeks)
Eccentric-Negative Work Progression

Program Initiated: 3x/wk

1-2 consecutive sessions missed or Minimal leg/joint pain (0-4 on VAS) → Continue progressive work program

3 consecutive sessions missed or Moderate leg/joint pain (5-7 on VAS) → Maintain total volume from last completed session

4 or more consecutive sessions missed or Minimal leg/joint pain (8-10 on VAS) → Stop Exercise and re-evaluate source of pain. If clinically appropriate to reinitiate exercise revert back to total volume at the beginning of the last week that was completed
<table>
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<tr>
<th></th>
<th>Exposure-Adaptation Phase (weeks 1-2)</th>
<th>Progressive Eccentric-Negative Work Phase (weeks 3-12)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency</strong></td>
<td>2-3 x/week</td>
<td>2-3 x/week</td>
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<tr>
<td><strong>Duration</strong></td>
<td>5-8 minutes/session</td>
<td>10-12 minutes/session – week 3-4</td>
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<td></td>
<td></td>
<td>14-16 minutes/session – week 5-6</td>
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<td></td>
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<td>18-20 minutes/session – week 7-12</td>
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<tr>
<td><strong>Intensity</strong></td>
<td>“very light”</td>
<td>“fairly light” – week 3-5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“somewhat hard” – week 6-12</td>
</tr>
</tbody>
</table>