Muscles operate eccentrically to either dissipate energy for decelerating the body or to store elastic recoil energy in preparation for a shortening (concentric) contraction. The muscle forces produced during this lengthening behavior can be extremely high, despite the requisite low energetic cost. Traditionally, these high-force eccentric contractions have been associated with a muscle damage response. This clinical commentary explores the ability of the muscle-tendon system to adapt to progressively increasing eccentric muscle forces and the resultant structural and functional outcomes. Damage to the muscle-tendon is not an obligatory response. Rather, the muscle can hypertrophy and a change in the spring characteristics of muscle can enhance power; the tendon also adapts so as to tolerate higher tensions. Both basic and clinical findings are discussed. Specifically, we explore the nature of the structural changes and how these adaptations may help prevent musculoskeletal injury, improve sport performance, and overcome musculoskeletal impairments.

Key Words: muscle action, plyometrics, strength

The greatest magnitude forces in muscle occur when an external force exceeds that produced by the muscle and the muscle lengthens, producing an eccentric contraction and negative work.\(^ {95,115} \) (Because work is force × displacement, it is a product of 2 vectors. When distance is in the opposite direction of the force generated, work is “negative.”) Because the muscle’s force can be maximized when contracting eccentrically, damage to the contractile and cytoskeletal components of the muscle fiber itself,\(^ {64,66} \) weakness,\(^ {61} \) and a perception of soreness\(^ {12,13,43,135} \) often occur. It is curious that muscle, structured to absorb and perform mechanical work during eccentric lengthening, sustains muscle damage while performing a task it appears ideally suited to accomplish. However, muscle damage need not be an obligatory response following high-force eccentric contractions. In fact, the ability to produce high forces with eccentric contractions should perhaps more properly be perceived as a protective muscle adaptation and a stimulus for beneficial muscle (and tendon) responses, rather than as a common cause of damage.\(^ {21,64,115,173,177} \) Many have called for the use of chronic eccentric exercise in the preventative care or rehabilitation of patients.\(^ {49,86,110,111,115,116,140,146} \)

In this commentary we explore how muscles adapt both structurally and functionally to chronic high-force eccentric lengthening contractions and how this adaptation may help (1) to prevent musculoskeletal injury, (2) to improve sport performance, and (3) to overcome musculoskeletal impairments.
ECCENTRIC CONTRACTIONS: MUSCLES OPERATING AS SHOCKS OR SPRINGS

Muscles act like shock-absorbing structures and springs when they absorb mechanical work while eccentrically lengthening. The forces resulting from these eccentric muscle contractions produce negative work. Locomotor muscles function as shock absorbers during the descent of inclines or when decelerating the body segment (e.g., going from stand to sit) and are ubiquitous in many other normal movements such as walking, jogging, maneuvering around obstacles, or regaining balance. In fact, during normal locomotion, muscles are collectively doing near equal amounts of positive (shortening) and negative (lengthening) work. While the energy that is absorbed during the muscle and tendon stretch is often dissipated as heat, elastic strain energy can also be stored and recovered if an immediate shortening concentric contraction follows. When muscles are activated eccentrically immediately prior to shortening, they no longer act as shock absorbers; rather, they perform more like springs (Figure 1).

During a stretch-shorten contraction (SCC), muscles are actively lengthened prior to a subsequent shortening phase. The stretched components of the muscle-tendon unit store elastic recoil potential energy (or elastic strain energy), a portion of which may be subsequently recovered. The storage and recovery of elastic strain energy during a SCC is an important determinant of performance, as the energy stored during a lengthening cycle can substantially amplify force and power production in the subsequent

FIGURE 1. When an active muscle is lengthened during an eccentric contraction, it behaves, in the simplest sense, like a shock absorber in series with a spring. In hiking downhill (top panel), when the velocity of lengthening is relatively slow, the energy that stretches the active muscle is lost as heat. In this example, the knee extensors behave like a shock absorber as the knee moves from extension to flexion (the piston moves from the bottom of the cylinder to the top). In contrast, when mammals (including humans) run (lower panel), the knee and hip extensors are rapidly stretched; the absorbed energy is not immediately lost as heat, but is temporarily stored as elastic recoil potential (strain) energy. In this example, these muscles behave like a spring that can store (the elongated spring representing the hip and knee extensors when strained) and recover energy from stride to stride. The time course of stretch and recovery of elastic recoil energy is dependent on both the magnitude of the forces involved as well as the elasticity (spring stiffness) of the muscle. Reprinted with permission from Lindstedt et al.
shortening cycle. Some studies, however, report that the restitution of elastic strain energy does not provide the increased power output, rather, an increased activation of the muscle enhances shortening work. In all likelihood, the increased power of shortening is a combination of both. The ability to recover elastic strain energy is apparently energetically so advantageous that the most economical stride frequency in running may be set by this key property alone. Apart from the role of tendons and collagen in energy storage, the muscle itself stores and recovers elastic strain energy, as elastic strain energy can occur in the absence of tendons. In a sense, because the muscle is composed of both muscle fibers and tendinous materials, all of these structures must be collectively “tuned” to the spring properties for the muscle-tendon system to store and recover elastic strain energy during locomotion.

**ECCENTRICS IN MUSCLE INJURY: POSSIBLE PREVENTATIVE MECHANISMS**

Muscle is a highly mutable tissue in that both its structure and function adapt to the demands placed on it. Like all biological tissues, modifications to the relative level of physical stress to muscle produce predictable results. One classic example of muscle responding to a high physical stress dosage with either an injury or a beneficial adaptation is high-force eccentric activity. For example, if naive to hiking downhill (eccentric lengthening contractions), one can experience devastating delayed onset muscle soreness (DOMS) after an initial hike. There is clear evidence linking DOMS with muscle damage and inflammation, suggesting that the muscle cell itself has been injured. Likewise, structural damage to the contractile and cytoskeletal elements of the muscle fiber, as well as impairment of the excitation-contraction coupling process, are coupled to reduced force-producing abilities. If one hikes downhill repeatedly, however, after relatively few hikes there is no soreness or muscle damage whatsoever, even with the same intensity exercise stimulus. Hence, the chronic use of eccentric contractions, in this case downhill hiking, results in a pronounced decrease in muscle soreness without any harmful effects if previously exposed. The changes within the muscle responsible for this acute adaptation are largely unknown. There are, however, suggestions that muscles adapt acutely to eccentric exercise by changing optimal length (ie, becoming more compliant via the addition of sarcomeres in series, allowing muscle fibers to operate at longer lengths while avoiding the descending limb of the length-tension curve) or that groups of the more fragile, stress-susceptible fibers are reduced in number after the first bout while stronger fibers survive and provide a protective effect. It has also been suggested that the acute effect lies outside the muscle and is mediated at a motor unit level (recruitment of surviving motor units) or at the neuromuscular junction. One key finding is that even light eccentric training protocols that result in little to no muscle damage are sufficient to bring about this protection. While the exact nature of the acute adaptation remains unclear, chronic exposure to eccentric muscle activity results in an active spring structure(s) adaptation (ie, the muscle stiffens) that occurs independent of the increases in both the muscle size and strength.

To investigate the impact of chronic high-force eccentric training on muscle-tendon stiffness (ie, spring properties), we used an eccentric resistance exercise regimen that was progressively and gradually ramped up over 3 weeks to nearly 500 negative watts. After 8 weeks, we noted the expected muscle size and strength increases. Additionally, we also explored how this training impacted the apparent muscle spring stiffness. We had subjects jump in a hopping motion (jump height was set to 107% of subject height) in place at a frequency that was reported by the subject to be the most “comfortable.” Farley et al determined that at this preferred hopping frequency in humans (2.2 hops per second), the body behaved like a simple spring mass system, with deviations from this frequency reducing the storage and recovery of elastic energy. We have also noted that this comfortable frequency is the most economical, as the cost per jump doubles when the subjects are forced to jump at half this frequency. Following eccentric training, every one of the subjects selected a higher hopping frequency than they did prior to training; the 12% mean overall increase was significant, as none of the control subjects (those exercising on a traditional concentric bike) changed their jumping frequency (Figure 2).

Reich et al used a model of rats walking down a steep (36%) decline with an additional load of 15% of body weight, to eccentrically load rat locomotor muscles, to determine if this apparent increased stiffness resulted from changes in the muscle’s contractile properties, eg, stiffness. (All tissues within the musculo-skeletal system exhibit stiffness. Young’s modulus is the measure of the stiffness of a material [E = stress/strain]. Stress is calculated by force/area and strain by extension/original length. Reich calculated both the Young’s modulus of the muscle, which increased greater than 30% with eccentric training, and active-lengthening [eccentric] force production. The latter is reported here as active muscle stiffness, the force produced with a ramped stretch of 1.5% of the resting muscle length on a muscle 100
seem to confirm those of others103,120,144 in demon-
strating that muscle stiffness changes in response to
chronic eccentric use (Figure 2). These in vitro
measurements of active muscle stiffness excluded the
peripheral nerve and any tendinous attachments; hence, only muscle stiffness was recorded. Thus, we
conclude that the apparent increases in muscle stiff-
ness, which explains the elastic-stiffness diversity
across vertebrate muscle.36 Titin has multiple roles in
striated muscle, ranging from sarcomere assembly to
mechanical roles such as providing the forces needed
to maintain proper sarcomere integrity during con-
tractions58,83 (for reviews see Granier and Labelt69
and Gregorio et al17). In addition, the differential
expression of titin isoforms is thought to play a
dynamic role in active force production.37,163 Because
of titin’s structural properties, its most significant role
may be as the muscle spring. First, as a muscle-
stiffening spring, it may play a key role in the
protective effect that occurs following eccentric exer-
ence.140 Supporting this idea is the fact that novel
high-force eccentric contractions damage the
cytoskeleton,64 by including titin failure, and a bout
of eccentric exercise results in diminished titin con-
tent.168 As well, recent evidence suggests that small
heat shock proteins that protect the cytoskeleton
structures (eg, titin) increase dramatically after re-
peated eccentric bouts.68

If titin is functioning as a locomotor spring, then it
should be tuned to the frequency of muscle use. We
tested this hypothesis by examining titin isoform
expression in muscles that are used cyclically at
different frequencies. Because stride frequency varies
predictably with body size among mammals, by exam-
in ing the titin expressed in different-sized animals, we
predicted shifts in titin isoform expression as a
function of body size. Titin expression analyzed with
SDS-PAGE in animals ranging in size from a shrew to
an elephant116,147 shows a predictable shift from the
most compliant (largest) isoforms in the elephant to
the stiffest (and smallest) isoforms in the shrew.
These results suggest a strong link between stride
frequency and titin “stiffness.” While these results do
not prove that titin is the muscle spring, they suggest
that titin may be a significant and potentially tuned
contributor to the muscle-tendon spring. If titin is
functioning as a locomotor spring, then titin should
adapt in response to changes in physiological de-
mand due to exercise or disease. This notion has
recently been reinforced as titin isoform expression
has been reported as an adaptable property of
striated muscle.17

**WHAT IS THE SPRING STRUCTURE IN MUSCLE
AND IS IT ADAPTABLE?**

The elastic property of vertebrate myofibrils is
thought to be due in large part to the enormous
cytoskeletal protein (2.5-3.7 MDA) filament
titin,126,144 which spans an entire half-sarcomere from
Z-disc to M-line. Titin functions as serially linked
springs that develop tension when stretched.117-119
There are multiple titin isoforms that vary in size and
stiffness, which explains the elastic-stiffness diversity
across vertebrate muscle.36 Titin has multiple roles in
striated muscle, ranging from sarcomere assembly to
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**ECCENTRIC CONTRACTIONS: STRUCTURAL AND
FUNCTIONAL CHANGES TO LOCOMOTOR MUSCLE
THAT ENHANCE SPORT ACTIVITIES**

One of the primary goals for strength and condi-
tioning coaches is to enhance the muscular force
production of an athlete, as power output (force x
velocity) often defines success in sport.171 The perva-
sive role of eccentric muscular force enhancement
prior to a power activity (eg, during a SSC) may be
the most substantial during high-power sport activities
such as running,31,35 sprinting,40,60,129 hopping,40,115
and jumping.22,115,153 The importance of the SSC in
almost all sport activities (possible exceptions being
bicycling and swimming) cannot be overstated. For
example, during a baseball pitch or a high jump, a
series of eccentric contractions in both the lower and upper extremities precedes concentric contractions. During the windup, cocking, and late cocking phases of a throwing motion, the trunk and lower extremities, coupled with the internal rotators of the shoulder, store elastic strain energy via eccentric lengthening prior to transitioning to the accelerating concentric shortening phase (Figure 3). Because SSC activities are ubiquitous in sport, plyometric exercises are popular training paradigms that have improved sport-related activities: upper-body ball put, vertical jump, and throwing. Perhaps, if the magnitude of the force (as well as the elastic strain energy) during the eccentric phase can be maximized via training, power can also be maximized during the concentric phase.

We tested this hypothesis with a group of basketball players, examining the effects of high-force eccentric training on muscle power output. After 6 weeks of high-force eccentric training in 1 subject group as compared to a weight-training control group, there was a significant increase in vertical jump. While both groups had identical initial vertical jump heights at the start of the study, every one of the subjects in the eccentric-training group increased the vertical jump, with an overall mean increase of approximately 8% (5 cm) (Figure 2). Thus, high-force eccentric training can evoke gains in muscle power and size, possibly resulting in part from significant increases in the muscle spring stiffness.

Muscle strength and power improvements seem to be a function of the muscle’s ability to produce high forces. Therefore, because much greater force (2 to 3 times greater) can be produced eccentrically than either isometrically or concentrically, eccentric training has the capability of “overloading” the muscle to a greater extent and enhancing muscle mass, strength, and power, when compared to concentric exercise (Figure 4).

**ECCENTRIC EXERCISE IN PREVENTING MUSCULOSKELETAL INJURY AND IMPAIRMENT**

**Sarcopenia**

The progressive loss of muscle mass with aging, sarcopenia, is a significant public health problem. Decreases in muscle mass begin to occur as early as 25 years of age and progress to the point where by the age of 80 years, one half of the skeletal muscle has been lost. Both cross-sectional and longitudinal data have established that muscle strength also declines by approximately 15% per decade in the sixth and seventh decades and by about 30% per decade thereafter.

**FIGURE 3.** The sequential activated prestretching of muscle-tendon structures prior to the high-power acceleration phase of the throwing motion. (A) During the early cocking phase of the baseball pitch, the right leg is positioned to prestretch the knee extensors, hip extensors, and hip rotators (hip musculature not depicted) prior to ballistic shortening of knee and hip muscle-tendon structures. With muscle-tendon lengthening, high eccentric muscle forces (potential energy) can be converted into high muscle power outputs during the concentric-shortening phase. (B) Still in early cocking, the knee and hip extends, the torso begins to rotate to lengthen the abdominal muscles and the serratus anterior of the right scapula. (C) During the late cocking phase, a prestretch of the pectoralis, serratus anterior, and subscapularis is in preparation for the acceleration phase. Iliopsoas is also prestretched to transfer stability to the spine.
Resistance weight training for the elderly can counteract sarcopenia as strength, power, and muscle mass increases are possible.1,9,62,63,89,94 The unique aspect of eccentric resistance training is that much greater forces, hence greater overload to the muscle, are possible as compared to traditional resistance weight training. In addition to the production of much higher forces, eccentric contractions have another unique attribute: the metabolic cost is greatly reduced.1,2,26 This high-force, low-cost suite of attributes makes it ideal for energetically impaired patient populations. Thus, with high-force eccentric training, significant increases in muscle mass89,109,110,115 and strength73,84,88,92,100,109-111 have been reported. In elderly subjects (mean age, 78 years) suffering the consequences of sarcopenia, we have reported a large increase in isometric leg strength and significant increases in whole muscle mass (6%) and vastus lateralis muscle fiber cross-sectional area (60%) following 11 weeks of high-force eccentric ergometry109 (Figure 4).

Muscle-Tendon Injuries

When forces within a muscle are used to decelerate a limb or body segment, the entire musculotendinous system participates in dissipating, or temporarily storing, the energy. If the forces needed for deceleration exceed that of the musculotendinous system, injury to the muscle, myotendinous unit, the tendon itself, and the osteotendinous insertion may occur.

For example, muscle strain injuries, especially to the hamstring musculature, are quite common in sports requiring explosive running such as football, track and field, and soccer.67,184 Strain injuries to the adductor group, an especially common injury in hockey players,155 occurs in injured weakened muscle following ballistic high-force eccentric contractions.104,113 Athletes with a history of recurring hamstring and adductor muscle injuries have greater impairment of their eccentric strength (2-fold) as compared to concentric strength, suggesting that improvements in the former may minimize the risk of injury.116,122 Others have suggested that eccentric resistance exercise may prevent injury to the muscle-tendon unit by improving the muscle’s ability to absorb more energy before failing.66,132 The exact mechanism of this adaptation is not defined. It is apparent, however, that if the tissue failure force threshold increases and the attenuation of loads is enhanced, a protective effect can occur. While others propose that an increase in muscle spring stiffness might prevent a strain injury, others89,146 postulate the opposite (i.e., that an increased compliance of sarcomeres in series might mitigate muscle strain injuries). The adaptation of the muscle-tendon system to eccentric physical activity is also associated with changes to the myotendinous junction: increased size (hypertrophy), fibroblastic activity, and production of collagen and ground substance.21,120,180,183

Osteopenia

The magnitude of the increase in bone mass, like that in muscle mass and strength, seems to be a function of the magnitude of muscle forces and other loads to bone.73,170 Specifically, the strength and density of bone is likely influenced by local strain of bone, which can occur with muscle exerting high forces on bone during resistance exercise.38,106 Therefore, it is not resistance training per se, but the high forces and intensities possible with resistance training that promote increases in hip bone mineral density.26,73,170 The suggestion that eccentric training, because it produces the highest muscle forces on bone during resistance exercise, should also result in the greatest bone adaptation is alluring.

Following 18 weeks of maximal effort, eccentric exercise on 1 leg and concentric exercise on the other leg (using a leg dynamometer), twelve 20- to 23-year-old women significantly increased midfemur bone mineral density by 3.9% following the eccentric training (a nonsignificant increase of 1.1% was noted in the concentrically trained leg).73 This finding suggests that eccentric resistance to leg muscles provides a greater osteogenic stimulus than concentric resistance. Further, it suggests that the greater eccentric peak forces elicited from the eccentric group were the stimulus for this bone response, as
the total resistance work over the 18 weeks was equivalent to that of the concentric training group. While the preliminary results are promising, they are in no way conclusive. Further investigation into the osteogenic potential of high-force eccentric exercise is warranted.

**Fall Risk in the Elderly**

Falls are the leading cause of accidental deaths among the elderly and many of these falls occur on stairs, where accidents during stair descent outnumber those of stair ascent by more than 3 to 1. Eccentric muscle contractions, in contrast to concentric contractions, are relied upon almost exclusively to successfully descend stairs. Despite the fact that the absolute eccentric force-producing abilities are preserved in the aged. This reduced ability of older adults to exert controlled steady forces during submaximal eccentric contractions has been suggested as the key factor contributing to the much greater frequency of falls during stair descent as compared with stair ascent. In our previous work, chronic exposure (11 weeks) to high-force eccentric leg ergometry in high fall-risk elderly individuals improved stair descent performance (20%) and balance (7%) and significantly decreased the risk of falling (Figure 5).

**ECCENTRIC CONTRACTIONS IN THE MANAGEMENT OF MUSCULOSKELETAL IMPAIRMENTS**

**Tendinoses**

Chronic tendon disorders often result from intensive repetitive activities, which are predominantly eccentric in nature. Due to higher-than-normal eccentric muscle forces transmitted via the tendon, the ability of the tendon to repair itself becomes impaired and the tendon deteriorates. This degenerative process, known commonly as tendinosis, at the Achilles, rotator cuff, lateral and medial elbow, posterior tibial, digital flexor, and patellar tendons, is associated with an abnormal angiofibroblastic healing response.

Ironically, some have suggested that the very type of muscle activity (eccentric) that was in part responsible for the tendinosis should be emphasized in rehabilitation. Ample evidence supports the notion that the tendon, like the muscle, can adapt favorably to physical stress, including that of high eccentric loads. Specifically, tendons become stronger as fibroblast (tenoblast) activity increases and an appropriate collage reaction accelerates. Macroscopic changes include a hypertrophied tendon, while microscopic adaptations are characterized by a thickening of the collagen fibers and fibrils and an increase in tropocollagen cross-links. The tendon fibers then align themselves optimally to manage the high stress levels transmitted from the muscle to the tendon.

The primary impairments associated with tendinosis are pain and weakness, especially in the eccentric-strength component, which can take up to a year to resolve. Hence, there is both anecdotal and experimental evidence that eccentric-resistance exercises are beneficial in the rehabilitation of tendinoses. Patients with the diagnosis of chronic (18 months) Achilles tendinosis, who were managed unsuccessfully with a traditional physical therapy regimen, have responded favorably to high-force eccentric exercises, as reported by Alfredson. Fifteen recreational running athletes (12 males; 3 females; mean age, 44 years) with Achilles tendon pain and decreased eccentric and concentric calf strength underwent an eccentric-resistance exercise program of progressively increasing loads. The eccentric-resistance group was compared to a similar control group (11 men; 4 women; mean age, 40) of patients with recalcitrant Achilles tendon pain treated with rest, nonsteroidal anti-inflammatory drugs.
FIGURE 6. High calf muscle-tendon force training progression for patients with chronic Achilles tendinoses. (A) From an upright body position and standing bilaterally with all bodyweight on the forefoot, the involved ankle is lifted in a plantar-flexion position by the noninjured leg. (B) The involved calf muscle is loaded eccentrically as the ankle (only the involved side) is moved into dorsiflexion with the knee extended. (C) The eccentric calf muscle is loaded with the knee flexed. (D) Muscle-tendon forces are increased by adding weights into the exercise (either free weights, a weighted backpack, or with an exercise machine). Modified from Alfredson et al.6
(NSAID), orthotics, and physical therapy, which included an ordinary training program. The high-force eccentric exercise program consisted of calf raises twice a day, 7 days a week, for 3 sets of 15 repetitions. The subjects performed the concentric part of the exercise bilaterally (raising both heels), while using the impaired side only to do the eccentric lowering phase in a slow, controlled fashion. Once the exercises were possible with little or no discomfort, they were instructed to add resistance by using additional weight (Figure 6). After 12 weeks, all subjects in the eccentric-training program returned to preinjury levels of running activity, whereas subjects in the conventional resistance exercises group (that did not include high-force eccentric exercises) ultimately required surgery. These unambiguous findings may be interpreted with some skepticism, but clearly they suggest a clinical trend that high-force eccentric loading can be beneficial. Alfredson’s results are also strengthened by a 2-year follow-up, where 14 of the 15 runners in the high-force exercise group were still running pain free, while 1 went on to surgery. Similar findings have also been reported when using eccentric as part of the resistance exercise program in patients with tendinoses at the knee and elbow.30,48,91
While the specific mechanisms as to why eccentric loading seems to optimize the rehabilitation of tendinoses have not been elucidated, it is implied that high muscle-tendon forces (eccentric) delivered in a controlled environment (rehabilitation setting) are needed for an optimal tendon adaptation. Again the irony presents itself in that the eccentric component is implicated in the initial injury (acute or chronic), yet high-force eccentric exercises are needed to maximize recovery. It is apparent, however, that the force generated during a concentric-eccentric exercise, or typical strengthening program, is not stimulating these beneficial tendon adaptations. The high forces produced eccentrically, while causing injury to tissues naïve to such forces, induce a beneficial tissue remodeling response when exposed to such forces chronically and progressively. That is, a program based on eccentric overload appears to be a suitable resistance exercise to elicit a remodeling response that meets the demands of functional and sport activities. These high eccentric muscle forces are only produced when an external force exceeds that of the muscle. To induce these high-magnitude forces, an external load capable of exceeding maximal isometric muscle force is required (Figure 7).

JOINT AND LIGAMENT INJURIES: PREVENTION AND MANAGEMENT CONSIDERATIONS RELATED TO ECCENTRIC MUSCLE CONTRACTIONS

The high forces resulting from eccentric muscle activity can assist either in stabilizing or disrupting a joint. When a passive ligamentous restraint is disrupted, as in an anterior cruciate ligament (ACL) injury, muscle activity (particularly the eccentric component) is the only remaining way to prevent excessive translation of the joint. Ironically, these high eccentric muscle forces can also, however, amplify this unintended excessive motion in an unstable joint.45
The best-established method of stabilizing a ligament-impaired joint during a potentially destabilizing activity is to recruit a powerful muscular synergist to restrain the joint. At the knee, the hamstring’s eccentric activity provides a posterior pull on the tibia to help offset the anterior force of the quadriceps.154 In addition to their role as tibiofemoral stabilizers, the hamstrings are activated eccentrically prior to the initial contact of the limb.
such as cutting, stopping, and landing maneuvers. Prior to initial contact during higher-level activities, string activity can also be observed in healthy subjects reported hamstring weakness following ACL injury. It has been suggested as the reason that few studies have been undertaken (walking, jogging, stepping, and hopping). This exaggerated, suboptimal response in-creases contact force and shock (joint compression ping). This exaggerated, suboptimal response in-creases contact force and shock (joint compression ping). This exaggerated, suboptimal response in-creases contact force and shock (joint compression ping).

Decelerating the forward progress of the leg in preparation for contact. Prior to initial contact during gait, both the medial and lateral hamstrings are activated earlier in subjects who are ACL deficient as compared to control subjects. This protective hamstring activity can also be observed in healthy subjects prior to initial contact during higher-level activities, such as cutting, stopping, and landing maneuvers. In fact, some have suggested that gender-related differences in muscular ability to decrease tibial translation explain, in part, the higher incidence of ACL injuries in women. Specifically, patients with ACL deficiency often have quadriceps muscles that are incapable of producing comparable eccentric forces to uninjured limbs. Quadriceps impairs the ability to appropriately absorb shock at the knee via submaximal eccentric contractions. While the consensus is that eccentric muscle re-training is essential, the question as to the mode and optimal dosage of eccentric exercise has not been answered. Certainly for the return of muscle mass, strength, and for muscle spring adaptations, chronic high-force eccentric exercise for 6 to 12 weeks is a potent option. Submaximal eccentric muscle-loading regimes may also be ideally suited to help overcome the force-attenuating and SSC impairments noted in these patients, however, this too remains untested.

CONCLUSION

The traditional thinking that eccentric contractions result in an obligatory damage response may be overstated. While the high forces produced in muscles working eccentrically can certainly cause damage and injury, muscle and tendon appear very capable of adapting to such high forces if the muscle experiences this stimulus progressively and repeat-edly. The adaptive mechanisms are not uniformly defined, but it is apparent that muscle can increase in size and strength and its spring quality can change following chronic exposure to eccentric contractions. The muscle-tendon structure also responds favorably to an eccentric-resistance exercise protocol. These adaptations, which need to be explored further in well-defined, basic, randomized epidemiological studies, play a part in (1) the enhancement of high-power sport activities, (2) the prevention, and (3) the
rehabilitation of sport injuries and non-sport musculoskeletal impairments, especially those that afflict the elderly. Despite the dearth of studies comparing traditional strength training to exclusively eccentric training, the beneficial effects of the high negative-work exercise regimes are apparent. In this paper we have explored the potential to capitalize on the ability to perform eccentric contractions (1) chronically (due to the low energetic cost), even with the frail elderly, and (2) with extremely high muscle forces (in excess of the maximum isometric force), which is only possible during eccentric, not isometric nor concentric, contractions. If an exercise is designed to simply recover, eccentrically, the forces generated concentrically, then that exercise does not take advantage of the unique high force-producing properties of eccentric contractions.

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