Degeneration of articular cartilage can have a devastating effect on an individual’s ability to participate in physically demanding activities. Although osteoarthritis (OA) of the knee is the most common cause of disability among older adults in the United States, its occurrence is not limited to the elderly, it is not a natural consequence of the aging process, and it is not a condition that necessarily worsens over time. OA can be regarded as a state of altered physiology that is potentially amenable to control, and reversal of the process might even be possible. The purpose of this article is to review the critical role that quadriceps strength appears to play in protecting the articular cartilage of the knee from excessive impact loading.

The composition of articular cartilage is 75–85% water, which is contained within a meshwork of hydrophilic molecules configured in a manner that resembles an aggregation of coiled wire and bottle brushes. Under a compressive load, articular cartilage behaves in a manner similar to that of a water-filled sponge, in which water is displaced to adjacent noncompressed areas and is drawn back to its original location when the compressive force is removed. Because cartilage is avascular, water translocation that results from cyclic compressive loading plays an essential role in the delivery of nutrients and removal of metabolites. Excessive loading, either a single force application of great magnitude or repetitive application of high forces, can damage the microstructural elements that give articular cartilage its resilient quality. Although damaged articular cartilage exhibits an increase in water content (as a result of the development of water-filled pockets within the damaged meshwork of microstructural elements), its ability to dissipate compressive force is compromised. Eventually, the joint surface softens, loses its smooth texture, becomes fibrillated, and develops clefts and crevices.

Magnetic resonance imaging (MRI) has dramatically increased awareness of articular-cartilage pathology associated with knee-ligament injuries. Microfractures of the trabeculae of subchondral bone, which produce the appearance of an MRI “bone bruise,” are believed to heal with callus formation that decreases the compliance of subchondral bone (i.e., increases its stiffness) and concentrates force on the overlying hyaline cartilage. Complete elimination of articular-surface loading (through immobilization or restriction of weight-bearing activity) might seem logical for facilitating healing, but the absence of mechanical stimulation results in chondrocyte death. In fact, an appropriate level of cyclic compressive loading actually stimulates chondrocyte synthesis of the microstructural elements of articular cartilage. Thus, creating an optimal healing environment within articular cartilage entails careful assessment of loading tolerance. Progressive introduction of rehabilitative activities that will enhance neuromuscular dissipation of impact loads is essential to protect against potentially injurious forces.
Importance of Quadriceps Strength

The quadriceps muscle group plays an important role in preventing knee injury by restraining excessive varus or valgus knee displacement. Another extremely important role is eccentric control of knee flexion during functional activities, which attenuates the vertical component of ground-reaction force. By increasing the range of knee flexion that occurs immediately after foot contact with the ground, controlled eccentric lengthening of the quadriceps decreases the magnitude of the force impulse that would otherwise be transmitted to the articular surfaces of the knee. Prospective research findings have demonstrated that isokinetic quadriceps strength (ratio of concentric peak torque to body weight) is a strong predictor of radiographic evidence of knee OA, which has identified quadriceps weakness as a probable primary risk factor for joint degeneration.3

Loss of quadriceps strength is associated with a variety of acute knee injuries and overuse syndromes. Preinjury quadriceps strength is often exceedingly difficult to restore, particularly in patients who have an anterior cruciate ligament (ACL) deficiency or who have undergone surgical ACL reconstruction.4-10 There is clearly a widespread awareness of the importance of hamstrings strength in restraining anterior tibial translation in ACL-deficient and ACL-reconstructed patients, but there does not seem to be a high level of awareness of the importance of quadriceps strength. Isometric and isokinetic quadriceps strength in ACL-reconstructed patients have been shown to be significantly correlated with the amount of knee flexion observed during the stance phase of gait.8,10 Thus, persistent quadriceps weakness might perpetuate an abnormal gait pattern, which could have adverse long-term consequences.

Arthrogenous Muscle Inhibition

Arthrogenous muscle inhibition (AMI) is the inability to fully activate a muscle during an effort to produce a maximum voluntary contraction (MVC). Swelling of the knee-joint capsule (either pathologic or artificially produced by injection of fluid) has been clearly shown to decrease the ability to voluntarily activate the quadriceps, but AMI can also exist in the absence of swelling or pain.3,4,7,11 There is strong evidence that AMI is caused by abnormal afferent input from joint mechanoreceptors, which causes inhibitory interneurons in the spinal cord to release a neurotransmitter (gamma amino butyric acid) that decreases the excitability of the motor-neuron pool activating the quadriceps.11,12

Researchers have identified the presence of quadriceps AMI through several different methods: comparison of isometric muscle force produced by superimposition of neuromuscular stimulation (NMES) during MVC with that produced by MVC without NMES,4,7,10,12,13 decreased amplitude of the Hoffman reflex (an electrically induced muscle response that is similar to the patellar-tendon-tap reflex response),14 and decreased amplitude or decreased frequency of surface-electromyography signal during isometric MVC.6,11 Because isokinetic peak-torque generation is clearly reduced in the presence of AMI, comparison of quadriceps peak-torque values of an injured extremity with those of an uninjured extremity can provide indirect evidence that the condition exists.

Isokinetic Evaluation of Quadriceps Performance

Although some researchers have reported evidence of impaired fast-twitch-muscle performance capabilities that have been attributed to AMI, the preponderance of relevant research findings strongly suggests that slow-twitch motor units are more profoundly affected by AMI. Individuals with quadriceps AMI have been observed to increase concentric performance at 180º/s with training, whereas torque-generation capabilities remained impaired at lower isokinetic velocities (<90º/s) and with isometric testing.5,7 Furthermore, pre- and postsurgical isokinetic strength assessments of ACL-reconstructed patients have demonstrated greater bilateral deficits at 60º/s than at 120º/s.5

The effect that movement velocity appears to have on isokinetic evidence of AMI is illustrated by the data in Table 1 and the corresponding isokinetic torque curves presented in Figure 1. The patient was a 48-year-old physically active man who had experienced bilateral knee pain for several years and progressively increasing pain in his left knee over the preceding 6 months. He was diagnosed as having bilateral knee OA, with the left knee more severely affected than
the right knee. Before arthroscopic debridement of the left knee, a presurgical isokinetic strength assessment failed to reveal any meaningful differences between extremities in concentric quadriceps performance at 300º/s (<10%). Large performance deficits in quadriceps peak torque, total work, and average power were evident at 60º/s (≥30%), and the deficits observed at 180º/s were approximately half the magnitude of those observed at 60º/s (~15%). The trend for increasing magnitude of bilateral differences at lower testing velocities illustrated by this case is typical for patients with ACL injury or unilateral knee OA.

Isokinetic testing is less prevalent today than in previous years, largely because of widespread acceptance of the idea that open-chain test results lack relevance to closed-chain lower extremity function. Many clinicians who still use isokinetic knee testing to evaluate patient status do not test at a velocity below 180º/s because of the concern that low-velocity open-chain quadriceps resistance might induce potentially injurious ACL strain. Test-velocity selection might also be influenced by the idea that testing should be performed at the highest possible velocity in order to replicate the rate of joint displacement associated with sport-specific movements as closely as possible. Although these considerations might be appropriate in certain situations, failure to test at a relatively low isokinetic velocity could prevent the true magnitude of the quadriceps performance deficit from being identified.

Sport-specific knee-joint motions often exceed the velocity at which slow-twitch motor units can contract, but the eccentric-impact-attenuation function of the quadriceps produces deceleration of knee flexion through a velocity spectrum that eventually allows for slow-twitch recruitment. Although fast-twitch fibers generate greater absolute force, slow-twitch fibers generate relatively greater force for a given amount of deformation (greater stiffness). Because slow-twitch fibers exhibit twice the stiffness of fast-twitch fibers, they almost certainly play an important role in eccentric deceleration of joint motion.

Given that both quadriceps weakness and excessive body weight have been identified as risk factors for developing knee OA, the quadriceps peak torque-

### Table 1. Concentric Quadriceps Performance Deficits of the Involved Extremity on Tests at 60º/s, 180º/s, and 300º/s

<table>
<thead>
<tr>
<th>Velocity (º/s)</th>
<th>60º/s, 5 repetitions</th>
<th>180º/s, 10 repetitions</th>
<th>300º/s, 15 repetitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak torque</td>
<td>35.0%</td>
<td>17.8%</td>
<td>2.9%</td>
</tr>
<tr>
<td>Total work</td>
<td>28.9%</td>
<td>15.3%</td>
<td>7.0%</td>
</tr>
<tr>
<td>Average power</td>
<td>30.2%</td>
<td>12.8%</td>
<td>5.1%</td>
</tr>
<tr>
<td>Average deficit</td>
<td>31.4%</td>
<td>15.3%</td>
<td>5.0%</td>
</tr>
</tbody>
</table>

![Concentric quadriceps torque curves](image)

**Figure 1** Concentric quadriceps torque curves (peak-torque repetition) for the uninvolved extremity (solid line) and involved extremity (dashed line) of a 48-year-old patient diagnosed with bilateral knee osteoarthritis (significantly greater symptoms in the involved extremity).
to–body weight ratio (QPT:BW) is a potentially important indicator of the ability to attenuate impact loads. Slemenda et al.\(^3\) reported that the concentric QPT:BW at 60º/s was approximately 20% lower in individuals with radiographic evidence of knee OA than in those without such evidence. Unfortunately, no clear threshold values for QPT:BW have been established to identify relative risk categories. Many clinicians consider a 60º/s concentric QPT:BW value of 0.90–1.00 to represent an excellent level of quadriceps strength for a young athlete, regardless of gender. Although strength is typically observed to decline with age, many senior adults are capable of achieving strength levels that approach those of young athletes. A 60º/s concentric QPT:BW value of 0.70–0.80 probably represents a strength goal that is attainable by most patients, regardless of gender or age. The patient whose isokinetic test results appear in Table 1 and Figure 1 demonstrated 60º/s concentric QPT:BW values of 0.40 for the involved extremity and 0.62 for the extremity that was designated as uninvolved (on the basis of lesser symptom intensity).

### Management of Arthrogenous Muscle Inhibition

AMI obviously presents a major obstacle to restoration of optimal quadriceps strength. Quadriceps responsiveness in the presence of AMI has been increased by four distinctively different interventions: joint anesthesia, administration of NMES during MVC, transcutaneous electrical stimulation (TENS), and cryotherapy. Shakespeare et al.\(^{11}\) demonstrated that the integrated surface-electromyography signal from the quadriceps was maintained at a near-normal level when the knee joint was anesthetized (blockage of all joint afference) immediately after a meniscectomy, but joint analgesia (blockage of pain sensation) did not prevent the quadriceps surface-electromyography signal from being profoundly reduced. Because quadriceps AMI is less evident when all neural input from the knee joint to the spinal cord is blocked, abnormal joint-mechanoreceptor afference is almost certainly the cause of AMI. This research finding clearly advances our understanding of AMI, but repetitive intra-articular injection of anesthetic medication is not a viable clinical method of suppressing AMI during rehabilitation.

Snyder-Mackler et al.\(^8,9\) have presented evidence that high-intensity NMES during MVC can produce greater quadriceps strength gains than those achieved by volitional exercise alone in patients with AMI. Thus, NMES of sufficient intensity can directly generate alpha-motoneuron impulses that cannot be voluntarily produced by descending motor commands. The primary limitation of this clinical procedure is patient reluctance to tolerate the high NMES intensity level that is necessary to overcome AMI. Patient motivation is clearly an important factor influencing recovery of quadriceps strength after injury.\(^{16}\)

Recent work by Hopkins et al.\(^{14}\) has demonstrated that both cryotherapy and TENS can counteract quadriceps AMI created by an artificial knee-joint effusion. Cold-induced lowering of nerve-conduction velocity decreases the frequency of afferent-impulse inputs to the spinal cord, which probably alters neural-signal processing with the central nervous system. Conversely, TENS probably reduces AMI by increasing the volume of spinal-cord inputs from large afferent nerves. These findings advance our understanding of the mechanism by which AMI is produced, but there is currently no research evidence concerning the long-term benefits that might be derived from using either cryotherapy or TENS to restore quadriceps strength.
Summary
Although a direct relationship between quadriceps AMI and knee OA has not yet been clearly established, quadriceps strength probably plays an extremely important role in protecting articular cartilage from excessive impulse loading during athletic activities. Either low-velocity isokinetic testing or low-velocity isometric testing is necessary to identify the full extent to which quadriceps AMI might affect an individual’s ability to voluntarily produce a maximum contraction. Failure to identify impaired quadriceps function might have serious long-term consequences. If articular-cartilage deterioration in the knee can be arrested or reversed, optimal quadriceps strength is probably an essential factor.

References

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