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REVIEW

Update on rehabilitation following ACL reconstruction

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Abstract: As anterior cruciate ligament (ACL) reconstruction has evolved to less invasive, more anatomical approaches, rehabilitation of the injured athlete has likewise become more progressive and innovative, with a sound understanding of graft and fixation strength and biologic healing-remodeling constraints. This review discusses these innovations including specific considerations before surgery, when planning rehabilitation timetables, and the importance of reestablishing nonimpaired active and passive knee range of motion and biarticular musculotendinous extensibility in positions of function. Concepts of self-efficacy or confidence and reestablishing the "athlete role" are also addressed. Since ACL injury and reinjury are largely related to the influence of structure-form-function on dynamic knee joint stability, the interrelationships between sensorimotor, neuromuscular, and conventional resistance training are also discussed. Although pivot shift "giving way" relates to function loss following ACL injury, anterior translational laxity often does not. Although there is growing evidence that progressive eccentric training may benefit the patient following ACL reconstruction, there is less evidence supporting the use of functional ACL knee braces. Of considerable importance is selecting and achieving a criteria-based progression to sports-specific training, reestablishing osseous homeostasis and improved bone density, blending open and closed kinetic chain exercises at the appropriate time period, and appreciating the influence of the trunk, upper extremities, and sports equipment use on knee loads. We believe that knee dysfunction and functional recovery should be considered from a local, regional, and global perspective. These concepts are consolidated into our approach to prepare patients for return to play including field testing and maintenance training.
Keywords: knee, arthroscopy, neuromuscular reeducation, sport-specific training

Introduction

When a patient is referred for rehabilitation, the clinician needs to consider their age (chronological and physiological), activity level, athletic activity history, and future participation expectations, in addition to knowing the graft type and how it was fixed in bone tunnels or sockets. We should also have a complete knowledge of their general health, injury history, and the presence of any comorbidities. Obtaining a thorough understanding of the index anterior cruciate ligament (ACL) injury mechanism can be especially important in developing functional exercise progressions. By necessity, the knee surgeon must place a considerable part of their attention on what they observe through an arthroscope, while the rehabilitation clinician attempts to improve reconstructed joint function. Both, however, ultimately serve the patient best by "looking through the telescope" regarding where they have been and where

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they would like to go, including a more global or whole body appraisal to help prevent future knee injuries. As the rehabilitation and orthopedic surgery communities know all too well, a patient's functional capability is ever changing. It is not only influenced by training, injury, and surgery but also by aging, lifestyle choices, and general health. Our job is to be as aggressive as we can in restoring function while still maintaining an optimal tissue healing environment. First, we must do no harm; second, we must understand the function that the patient will need to perform before designing the rehabilitation-conditioning plan (form follows function); and third, we must prepare them for the long-term (life), not solely for the next athletic season.

Preoperative or nonoperative physical therapy

Keays et al[1] compared 12 subjects with chronic unilateral ACL deficiency following a home-based physical therapy program consisting of open and closed kinetic chain exercises, dynamic quadriceps-hamstring coactivation, calf muscle strengthening, small arc plyometrics, single-leg balance activities, lower extremity stretching, and patient education with a matched-group of subjects who did not receive training before surgery, and an uninjured control group matched for age, gender, and activity level. At 6 weeks after program initiation, the exercise group had significantly improved isokinetic knee extensor strength, improved single-leg standing balance, fewer knee "giving way" episodes, improved agility, and improved subjective performance. They suggested that all patients with ACL deficiency should participate in preoperative physical therapy before ACL reconstruction to maximize dynamic knee-stabilizing potential.

Hurd et al[2] suggested that traditional rehabilitation protocols such as resistance training, cardiovascular exercise, and agility drills do not improve dynamic knee stabilization. Of 345 highly active subjects who participated in a screening exam at a mean 6 weeks (range 1–28 weeks) after an index unilateral ACL injury, 199 subjects were classified as noncopers and 146 subjects were classified as potential copers. At 10-year follow-up, 63 of 88 (71.6%) potential copers successfully returned to preinjury activities without surgery, and 25 had not undergone ACL reconstruction. They concluded that an early screening exam consisting of unilateral hop tests (single-leg hop for distance, triple crossover hop, straight triple hop, timed 6-m hop) with a goal of ≥80% bilateral performance, self-assessment surveys (Knee Outcome Survey Activities of Daily Living Scale, and Global Rating) with goals of ≥80% and ≥60% scores, respectively, and the number of knee "giving way" episodes (goal of ≤1 episode) were effective for prospectively identifying patients with good nonoperative care potential after ACL injury. However, of the subjects who eventually returned to sports, 36 of 63 (57.1%) eventually underwent ACL reconstruction. Because of this finding, Hurd et al[2] emphasized that the average person with an ACL injury requires surgery to enable return to high-level activities. Patients who desire to resume high-level activities were counseled against nonoperative care because they would be more likely to sustain a meniscal tear or articular cartilage lesion during a repeat knee "giving way" episode.[2]

Hartigan et al[3] studied the effects of preoperative perturbation training on 19 subjects with acute unilateral ACL deficiency who had been classified as noncopers. Subjects were randomly assigned into perturbation or strength training groups. The perturbation group received specialized neuromuscular training and quadriceps strength training, whereas the strength group only received quadriceps strength training. Both groups received 10 sessions. At 6 months post-ACL reconstruction, both groups had improved quadriceps strength. Only the perturbation group, however, had more symmetrical knee range of motion when walking.[3] Participation in a presurgical exercise program may help ensure full active knee range of motion, increase the strength and responsiveness of dynamic knee-stabilizing musculature, and help screen for patients who might benefit from a nonoperative treatment plan.

Less invasive surgery reduces acute care and increases rehabilitation timetable decisions

Arthroscopy has lead to less invasive ACL reconstruction methods and fewer knee range of motion and weight bearing restrictions during postoperative recovery. Discharge planning from supervised rehabilitation should be initiated during the first postoperative week as the communication network between patient (or parent for minors), athletic trainer and/or strength coach, and team coach begins to develop. Early "acute care" rehabilitation (0–4 weeks) generally focuses on surgical wound care, decreasing postsurgical pain and effusion, reestablishing involved lower extremity nonimpaired (preinjury level) active knee range of motion (particularly extension), and return to activities of daily living without the need of assistive devices or postoperative braces. This is an excellent time to improve integrated core-lower extremity strength and endurance with plank and bridge type movements with and

Figure 1 Lateral plank with hip abduction.

without leg lifts (Figure 1).[4] Exercises performed during this time period should focus more on developing efficient neural activation pathways than on increasing muscular hypertrophy.[5] This is particularly true for reestablishing quadriceps femoris neuromuscular activation often with the assistance of electrical muscle stimulation and biofeedback techniques.

Important milestones to achieve between weeks 0–2 include: 1, full knee extension and 2, sufficient quadriceps control to enable comfortable walking on all surfaces without an assistive device or postoperative knee brace. Important milestones to be achieved between weeks 0–4 include: 1, full knee flexion (occasionally with limits until 12 weeks following posterior horn meniscal repair) and 2, rehabilitation clinician perception of effective involved lower extremity dynamic knee stability during single-leg stance with three-dimensional (3D) balance and perturbation challenges. Important milestones to be progressively achieved between weeks 5–26 include reestablishing: 1, normal biarticular muscle group extensibility; 2, involved lower extremity strength and power approximating 80%–90% of the noninvolved lower extremity (both with isolated isokinetic knee extensor and flexor tests and with single-leg press); and 3, rehabilitation clinician perception of effective involved lower extremity dynamic knee stability during multidimensional single-leg jump landings with 3D balance and perturbation challenges (Table 1). To achieve this, we focus on proximal stability before distal mobility, consider movement quality a higher priority than the resistance progression or the number of repetitions that can be successfully performed and confirm appropriate muscle strength, endurance, and length with consideration for intersegmental (hip, knee, and ankle) neuromuscular contributions. During these progressions, it is important to stay within the safe "envelope of function" combining loading frequency, rates, and magnitudes that facilitate the desired physiological response while not adversely loading the healing graft construct.[6]

Since ACL injury is often associated with bone bruising, collateral ligament injuries, meniscal repair and/or articular cartilage restoration procedures, progressions often need to be adjusted for each patient. As rehabilitation progresses, the focus shifts from treating local impairments to treating more regional and global or "whole body" functional limitations.

Before progressing to sport-specific training (knee surgeon and rehabilitation clinician agreed), criteria such as $<15\%$ side-to-side single-leg hop power differences should be confirmed.[7] Although nonimpaired active knee flexion and biarticular hip and knee muscle group extensibility are

Table 1 ACL rehabilitation phases and approximate timetable

	Phase	Approximate timetable
Progressively improve self-efficacy and confidence and decrease kinesiophobia	Early acute care Reestablish independent activity of daily living function Sensorimotor training bias	0–4 wk
	Progressive transition from "patient" to "athlete" role Reestablish strength, power, and endurance Blend resistance and neuromuscular training	5–26 wk
	Sport-specific training Neuromuscular training bias	27–36 wk
	Return to play decision-making Multifaceted, more to the total picture than meets the eye! Progress through: 1, highly controlled functional activities to individual tasks performed on the playing field with oversight by the clinician; 2, individual workouts with oversight by the coach and clinician; 3, workouts with two or three teammates with oversight by the coach and clinician; 4, return to unrestricted practice with full team; 5, release to competition.	37–52 wk

usually achieved over the initial postsurgical weeks, these goals should be revisited before the more intense plyometric jumping of sport-specific training is initiated (27–36 weeks). Hip and knee stiffness may compensate for poor quadriceps femoris strength. Decreased biarticular muscle extensibility can be associated with quadriceps femoris inhibition, leading to patellofemoral joint dysfunction, and other lower extremity kinetic chain symptoms. Sport-specific training gradually transitions into return to play consideration (37–52 weeks). Return to play decision-making, however, represents a progression from the highly protected and rigidly controlled exercises in the clinic to less protected, less controlled sport, position, and style of play-specific activities that closely simulate those to which the athlete will be returning. This decision-making progression may take 4–6 weeks (and sometimes longer) (Table 1).

Nonimpaired knee range of motion and biarticular muscle extensibility

Reestablishing nonimpaired passive and active involved lower extremity hip, knee, and ankle motion, and biarticular muscle extensibility is essential and should be achieved as quickly as possible with appreciation for healing ACL graft constraints and concomitant surgical procedures. Hip and knee muscle extensibility or perceived stiffness by the patient should be evaluated with them in prone (right side – hamstring stretch; left side – quadriceps stretch) (Figure 2) and supine (right side – modified Thomas stretch; left side – piriformis stretch) (Figure 3) positions that simulate functional positions during fast walking, running, or jumping.[8] Decreased extensibility of the involved lower extremity muscles that function through the hip and attach to the pelvis, such as the rectus femoris, tensor fascia lata, large gluteal muscles, small hip external rotators, hip adductors, and hamstrings, can be associated with compensatory overuse and related maladaptive compensations.

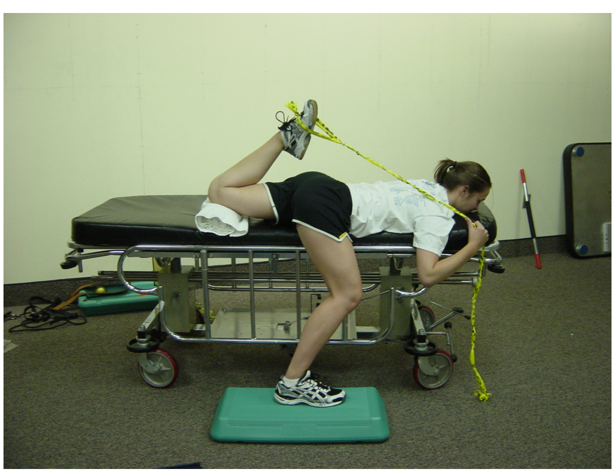

Figure 2 Prone quadriceps stretch (left side) and hamstring stretch (right side).

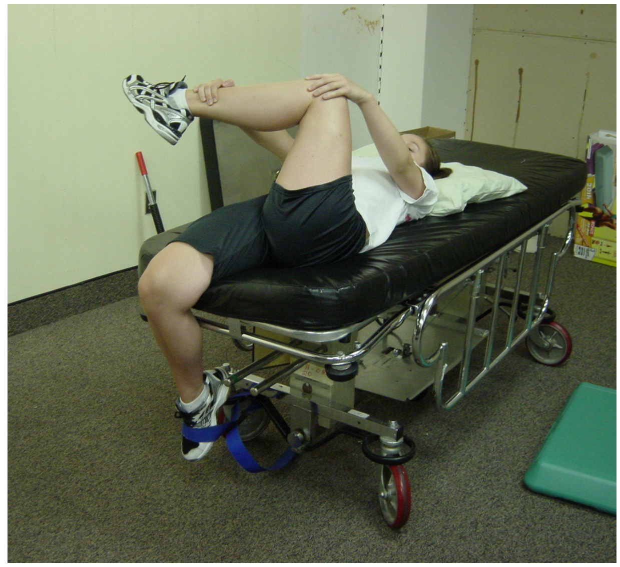

Figure 3 Supine modified Thomas stretch (right side) and piriformis stretch (left side).

Self-efficacy, confidence, and reestablishing the "athlete role"

Patients who perform functional exercises that simulate athletic movements early during rehabilitation may be more likely to successfully return to sports following ACL reconstruction.[9,10] Functional exercises simulate the weight-bearing and nonweight-bearing components of specific daily activities in a manner that replicates 3D lower extremity function within the joint ranges and velocities, which facilitate the desired physiological response (improved neuromuscular function and connective tissue integrity).[11] Since they more closely simulate athletic movements and movement subcomponents than conventional resistance training exercises, functional exercises are more likely to improve patient self-efficacy and confidence and more quickly help them reestablish the "athlete role" as they progress toward sport-specific training.[9,10] The reduced postoperative acute care period has enabled rehabilitation clinicians to initiate progressive functional exercises earlier to better facilitate patient function, increase confidence and self-efficacy, and decrease kinesiophobia.[9,10,12,13] Appropriately selected conventional resistance training exercises, however, are essential to reestablishing adequate levels of involved lower extremity strength, power, and endurance, as well as to eliminate or at least minimize the effects of quadriceps femoris muscle group weakness or inhibition.

Structure, form, function, and dynamic knee joint stability

Form or posture both at rest and during movement, function, and structural adaptations are intimately related. From an engineering or architectural perspective, structure is a relatively permanent concept.[14] However, in biological systems, structure, although slower to change than function, is constantly being altered via the specific adaptations that occur with the imposed demands of regular activity and exercise (neuromuscular network efficiency, muscle size, bone density, cardiovascular and pulmonary capacities, etc). Following ACL reconstruction, rehabilitation clinicians need to do more than simply help the patient restore pain-free passive and active knee range of motion, strength, power, and endurance. We must also teach them and verify that they use acceptable form and technique through widely varying movements including double-leg and single-leg jump take-offs and landings, sudden or spontaneous running directional changes, and stops. Proper form includes having the center of mass positioned within a stable base of support and with coordinated trunk and upper extremity movements with minimal extraneous side-to-side lateral trunk flexion or upper extremity flailing to accommodate for deficient lower extremity strength or faulty alignment. The ability to control the upper extremities and trunk is essential to protecting the ACL-reconstructed knee.[4,15–17] Chaudhari et al[17] have shown how upper extremity position while carrying a ball or another sports implement can significantly change knee loading patterns and increase loading magnitude during single-leg landings.

Routine presentation and maintenance of an "athletic ready position" with slight to moderate hip and knee flexion and ankle dorsiflexion with the mean centers of plantar pressure aligned near the middle of each foot rather than over the heels or toes is essential to prevent knee reinjury (Figure 4). During jump landings, the head should be erect with the eyes looking forward and the body center of mass should be lowered via controlled hip and knee flexion (not increased trunk flexion with concomitant hip and knee extension) within an approximately shoulder-width base of support. The postural alignment strategy that the patient uses during athletic movements is a potentially modifiable knee injury risk factor. Patients should learn appropriate athletic movement technique in a methodical slow-to-fast progression, first developing consistent alignment before progressing to high-speed, high-intensity performance. A well-designed neuromuscular training program can help decrease this risk.[18] The educational goal is to develop the patient's capacity to instantaneously use proper form or immediately execute biomechanical corrections without cueing 100% of the time. In our opinion, adequate dynamic knee joint stability and decreased noncontact injury risk can only be reasonably assured through repeated observations that verify appropriate technique under conditions similar to actual athletic performance.

Figure 4 The "athletic ready position".

Conventional resistance, sensorimotor, and neuromuscular training

Input to the somatosensory system can be subdivided into tactile and proprioceptive senses arising from peripheral receptors in the skin and musculotendinous and capsuloligamentous tissues.[19] The somatosensory system (peripheral afferent mechanism related to postural control) provides information about trunk, thigh, leg, and foot orientation through the hip, knee, and ankle joints in relationship to one another and to the supporting surface. Proprioception encompasses the sensation of joint movement (kinesthesia) and joint position (static joint position sense) to mediate neuromuscular control.[19] We believe, however, that tests or activities designed to specifically measure isolated proprioception, such as the time required to detect passive knee movement or the capacity to replicate a specific knee joint angle, have little or no relationship to function. In contrast, exercises that develop the interaction between sensory cues and motor responses as they relate to specific sports activities can improve proprioception while also developing strength, power, balance, and endurance.

Sensorimotor training is a form of neuromuscular training during which the patient stands on an unstable surface to facilitate ligament-muscular reflex arc excitability.[20,21] Gruber and Gollhofer[22] reported that sensorimotor training helps "open up" or enhances "afferent system drive". Sensorimotor training may help regulate muscle spindle sensitivity and adjust dynamic knee stiffness when joint forces increase (eg, during sports movements).[23] However, for sensorimotor training to increase knee joint dynamic stiffness and hamstring reflex activation, Gruber et al[24] reported that the ankle joint needed to be relatively fixed. Reduced ACL injury incidence has been reported following sensorimotor training among soccer players.[25] Other studies, however, have reported no knee injury incidence differences following sensorimotor training alone.[26–28] Combining sensorimotor and conventional resistance training may be more effective if sensorimotor training is started first, particularly if the patient is beginning from a relatively low conditioning level. In comparing the effects of these training interventions on postural stability, maximum isometric force production, and squat-jump and drop-jump performance, Bruhn et al[29] reported that both training modes increased the rate of leg press force development, maximum isometric force, and improved jump performance. However, only the resistance training group displayed statistically significant increases. They concluded that conventional strength training with high loads improved motor neuron efferent drive mechanical efficiency, whereas sensorimotor training enhanced afferent input to the central nervous system.

Conventional resistance training to improve lower extremity strength, power, or endurance is highly effective for improving athletic performance.[29,30] Neuromuscular training focuses more on improving activation timing and sequencing and the responsiveness that facilitates dynamic knee stiffness and stability. Neuromuscular training also attempts to ensure appropriately balanced contributions from each lower extremity joint (hip, knee, ankle) using the postures and alignments needed to prevent knee injury or reinjury during functionally relevant sports movements. Risberg et al[31] designed a neuromuscular training program for patients following ACL reconstruction consisting of balance exercises, dynamic joint stability exercises, plyometric exercises, agility drills, and other sports-specific exercises. Patients were randomly assigned to either a neuromuscular training or to a conventional strength training group. At 6-month follow-up, the neuromuscular training group had significantly improved Cincinnati knee scores and visual analog scale global knee function scores compared with the conventional strength training group. Both groups, however, displayed similar improvements in strength, balance, proprioception, and hop tests.

The term neuromuscular training has become increasingly used in application to knee injury prevention, post-ACL reconstruction rehabilitation, and sport-specific training. It may include a wide variety of interventions including core strengthening, balance training, jump technique training, plyometric exercises, agility drills, and sudden, unexpected support surface perturbations.[2,31–36] Any exercise that facilitates spontaneous neuromuscular responses during sudden joint position changes can be described as neuromuscular training. Development of appropriately timed, unconscious efferent responses to afferent signals can improve dynamic knee stability.

Feed forward processing is the concept that fast movements can be controlled by events that the neuromuscular system has previously encountered.[37] High repetition exercises can convert motor programs from the conscious to unconscious realm enhancing lower extremity neuromuscular control. Since reflex activation in response to environmental stimuli cannot occur quickly enough to prevent knee injury or reinjury, developing an efficient "preset or preactivation sense" is vital. Neuromuscular training helps develop finely tuned motor programs and activation sequences that occur before and during stressful knee joint loading. There has been an increased recognition that to prevent athletic knee injury or reinjury, dynamic knee joint stability needs to be improved through enhanced neuromuscular control mechanisms.[37–39]

Regardless of the specific exercises used, we have found that most reports on neuromuscular training for knee injury or reinjury prevention emphasize proper postural alignment, particularly during single-leg jump landings.[7,17,36] Additionally, most reports emphasize the need to reestablish balanced intersegmental neuromuscular contributions throughout the lower extremity and core and to efficiently incorporate the stretch-shortening cycle into functionally relevant athletic movements. Our findings suggest that neuromuscular training performed in the presence of faulty technique or postural alignment is of limited value and may increase knee injury or reinjury risk.

Knee joint laxity

The loss of function experienced by patients after ACL rupture is highly variable and often does not directly relate to the magnitude of measured anterior knee joint laxity.[40] The presence of a positive pivot shift test, however, displays a significant association with functional disability[41] and is an indicator of the eventual need for surgery.[42] Following ACL reconstruction, the orthopedic surgeon and rehabilitation clinician should not become obsessed with anterior tibial translational laxity measurements. Routine reevaluation at key time periods, such as when the patient transitions from acute care to more advanced functional exercises and when they transition from advanced functional exercises to sport-specific training, should suffice for most patients. Time is better spent evaluating the patient as they perform movements that they must become proficient with and the safety of the technique and alignment used when performing those movements.

The power of progressive eccentrics

Hortobagyi et al[43] suggested that training specifically to improve eccentric loading capability may be more effective than concentric-only training for removing neuromuscular inhibition and creating more uniform motor neuron activation patterns. Therapeutic exercises that emphasize eccentric gluteus maximus, quadriceps femoris, and gastrocnemius-soleus activation can improve lower extremity muscular shock absorption, prevent knee reinjury, enhance athletic performance, help heal lower extremity musculotendinous injuries, increase bone mineral density, and decrease fall risk.[44] Gerber et al[45] studied 40 patients at 15-weeks post-ACL reconstruction using either a bone-patellar tendon-bone or hamstring autograft, randomly assigning them either to a standard rehabilitation group or to a group that performed a 12-week progressive resistance, eccentric exercise program. At 1-year follow-up, magnetic resonance imaging-determined muscle volume of quadriceps femoris (23.3% ± 14.1% vs 13.4% ± 10.3%) and gluteus maximus (20.6% ± 12.9% vs 11.6% ± 10.4%) increased significantly more at the involved lower extremity of the eccentric exercise group compared with that of the standard rehabilitation group. Involved lower extremity knee extensor isokinetic strength and single-leg hop distance were also greater in the eccentric exercise group. Maximal-effort, eccentric strength training has long been associated with improved athletic performance; however, accumulated microscopic muscle fiber damage and delayed-onset muscle soreness have raised concerns regarding its use as a rehabilitation form. Progressive, submaximal loads can be used without excessive soreness, benefiting patients following ACL reconstruction, particularly when combined with functionally relevant movements.

Functional ACL knee braces and sleeves

We operationally define functional ACL knee braces as custom or "off-the-shelf" braces designed specifically to control knee motion after ACL reconstruction during the performance of athletic maneuvers. Knee sleeves are defined as simple slide-on garments (eg, neoprene sleeves) designed to improve knee proprioception, and with the addition of collateral hinges, to improve medial-lateral knee stability. An important component of the decision-making process regarding functional ACL knee brace use is the status of secondary capsuloligamentous stabilizers, such as the collateral ligaments and menisci. Dysfunction or laxity of these structures may increase the need for prescribing a functional brace or sleeve.

In our experience, patients who display hyperelastic, collateral ligament characteristics warrant particular attention to improve midrange dynamic knee joint stability, maintain appropriate biomechanical alignment during single lower extremity jump landings (avoiding excessive knee extension, flexion, or valgus-varus), and develop coordinated dynamic lower extremity stiffness. Beighton Scale[46] tests can help identify patients with hyperelastic traits. We believe that these patients may particularly benefit from the proprioceptive attributes of functional knee brace or sleeve use over the first postoperative year beginning with sport-specific training, in addition to any motion control benefits that they may also provide.

Functional knee brace prescription is not without possible negative consequences. In a 3D lower-extremity kinematic and electromyography study of treadmill running with or without functional knee brace use, Theoret and Lamontagne[47] reported that the braced condition decreased active knee range of motion, increased hamstring activation, and decreased quadriceps femoris activation. In a randomized, controlled clinical trial, Birmingham et al[48] compared the postoperative outcomes of 150 patients who underwent ACL reconstruction using a 4-strand hamstring tendon autograft. Before surgery, half the group received an "off-the-shelf" functional knee brace and the other half of the group received a simple neoprene sleeve. At 6-, 12-, and 24-months postsurgery, they reported no significant group differences for the ACL Quality-of-Life Questionnaire, KT-1000 arthrometer side-to-side difference, forward hop symmetry index, and

Tegner activity scale. Based on these findings, they concluded that patient outcomes did not differ whether a functional knee brace or a neoprene sleeve was used. However, they did not control for patient self-efficacy, confidence or kinesiophobia levels. Conceivably, the simple knee sleeve group may have had a greater percentage of subjects with high self-efficacy and confidence and lower kinesiophobia. This potentially could have improved their outcome compared with the functional knee brace group.

In reviewing 12 randomized controlled trials, Wright and Fetzer[49] reported no evidence that knee pain, range of motion, ACL graft stability, or protection from subsequent injury were influenced by functional knee brace use. In a review of 70 randomized controlled trials regarding ACL injury treatment and rehabilitation, Andersson et al[50] reported that postoperative functional knee brace use did not affect patient outcomes following ACL reconstruction. If the decision is made to prescribe a functional knee brace following ACL reconstruction, a less expensive knee sleeve (to improve proprioception) or a hinged knee sleeve (to improve proprioception and provide medial-lateral support) may suffice. Improved valgus-varus knee stability from a hinged knee sleeve alone may be sufficient to significantly reduce the knee reinjury risk. Future research should consider how patient psychobehavioral characteristics and the presence of hyperelastic collateral ligaments might influence knee brace outcome study findings.

Osseous homeostasis and bone density

Proximal tibia and distal femur bone mineral density does not return to premorbid levels following ACL injury or after reconstruction.[51,52] Tunnel or socket region bone quality is essential to ACL graft fixation. Following ACL reconstruction, patients should begin progressive weight bearing as soon as it is safely possible. Impact loads during nonhabitual or unexpected accelerating and decelerating directional change movements produce the stimulation needed for osteogenesis.[53–55] Bone strain rate might be more important than magnitude.[56] Progressive intensity 60-minute sessions of slow-to-fast stepping, walking, foot stamping, lateral jumping, running, countermovement jumping, jumping without countermovement, and drop jumping can improve lower extremity bone density.[53,54,57] Exercise-induced osteogenic responses increase with adequate rest between sessions, and it is better to add extra sessions than to prolong individual session duration.[58] Vertical impact load acceleration varies from 0.3–1.0 g for walking, 1.1–2.4 g for stepping or stamping, 2.5–3.8 g for jogging, 3.9–5.3 g for running and moderate-intensity jumping, and 5.4–9.2 g for drop jumping (1 g = the acceleration of gravity, 9.81 m/s^2). Compared with walking, accelerations are approximately four times greater during running, five times greater during jumping, and six times greater during drop jumping.[54] Exercises that generate low vertical impact load acceleration <2.4 g, such as walking and stair climbing, are unlikely to increase lower extremity bone mineral density in healthy, younger individuals, but they may be useful for strengthening weakened bone in patients with chronic conditions, revision cases, older patients, or patients who have experienced prolonged immobilization, disuse, and restricted weight bearing.[57]

Lower extremity neuromuscular activation can also produce an osteogenic effect.[53,57] Using a rat model, Warner et al[55] showed how novel bone strains from aquatic exercise increased cortical and cancellous bone mineral density. This suggests that progressively increasing weight-bearing loads may not be the only loading factor to be considered to increase lower extremity bone mineral density. When weight bearing must be restricted, aquatic exercise can provide another way to increase bone mineral density. To optimize osteogenic responses, however, patients need to ingest adequate levels of dietary calcium, phosphorous, and vitamin D.[59,60]

Open and closed kinetic chain exercises

Open kinetic chain or nonweight-bearing exercises can provide superior isolated muscle or muscle group recruitment and ease of strength measurement.[61] Closed kinetic chain or weight-bearing exercises can provide superior integrated lower extremity neuromuscular recruitment and ease of composite strength or power measurement. The prescriptive use of both open and closed kinetic chain exercises enables patients to develop the dynamic lower extremity stability and neuromuscular control needed to protect the healing ACL graft.[62] Combining resisted open kinetic chain knee flexion with hip extension in prone or standing positions helps reestablish hamstring strength through end-range active knee flexion. Manual loading at the distal leg during knee flexion can provide movement guidance feedback and progressive resistance. Seated knee extension exercises with high distal loads may increase ACL strain, tibiofemoral joint shear, and patellofemoral joint compression near end-range knee extension.[63,64] Andersson et al[50] in a review of 70 randomized controlled trials on ACL injuries with special reference to the choice of surgical techniques and rehabilitation reported that closed kinetic chain exercises produced less pain and knee joint laxity while achieving superior subjective outcomes compared with open kinetic chain exercises. Since the seated knee extension exercise has a unique capacity for developing isolated quadriceps femoris function, however, more proximally placed loads, extension limits to approximately 45°, and active movements through full range without resistance can reduce these concerns while still providing some exercise benefit.

Criteria-based progression to sports-specific training

Once patients have met a specific criteria verifying the adequate restoration of involved lower extremity strength, power, endurance, and perceived function, Myer et al[7] suggested that involved and noninvolved lower extremity vertical ground reaction force comparisons be made during repeated, 10 second duration, maximal effort single-leg vertical hops. Technological advances have decreased the expense, improved the user "friendliness," and increased the portability of force plate measurement equipment making it easier for clinics to obtain this information. Power decay at the involved lower extremity can identify patients in need of further rehabilitation before advancing them to more intense sport-specific training. In addition to quantitative biomechanical analysis, qualitative movement posture and alignment analysis during routine activities of daily living and during functionally relevant athletic tasks can provide valuable information about patient knee loading readiness and their confidence or self-efficacy.[9,10,12,13] We believe that increased self-efficacy and confidence and decreased kinesiophobia suggests a greater patient willingness to "use" the involved lower extremity. Perceived function surveys that more closely relate to actual sport-specific movement and athletic function performance capability are greatly needed. A variety of multidirectional single-leg hop tests should be used and evaluated for time, distance, and movement quality. A minimum of three tests should be performed and >90% bilateral equivalence is desired.[65]

Progressive plyometric training has a direct carryover to improved sprint and agility timing, and improved countermovement jump performance with reduced ground contact time.[66] Effective management of the transition from the highly controlled rehabilitation environment to progressively less restricted sport-specific training is essential to a successful patient outcome. To better achieve this, we have developed a "functional camp" consisting of eight weekly sessions of approximately 90 minutes per session (discussed in detail in the "What we do" section of this review). Successful completion of this camp is followed by field testing with rigidly timed rest periods with quantitative and qualitative evaluations of safe athletic performance capability, prescriptively designed to match the sport and position played by the patient. We believe that criterion-based return to sport evaluations should be specific to the sport, to the position played, and to the style of play. To increase validity, the evaluation should be performed with central and peripheral fatigue as an essential element to better determine performance during a "worst case" scenario.[67,68] Environmental conditions including heat, humidity, playing surface and attire, fatigue, and the influence of frustration or anxiety on decision-making are essential elements to simulate when establishing a patient's return to play readiness. In our opinion, all sports-minded patients who undergo ACL reconstruction can benefit from this type of evaluation.

Local treatments for more regional or global problems are incomplete

Solely "knee-centric" rehabilitation plans may not adequately address all of the issues that lead to the index ACL injury; therefore, they are less likely to prevent reinjury. Regional interventions through the entire lower extremity and core and global interventions throughout the entire body (including the trunk and upper extremities) may be needed to adequately address the confluence of factors that contributed to the index ACL injury, particularly among patients who have sustained a noncontact injury. Local treatments for global problems are insufficient.

What we do

The hip and knee joints have the largest muscle groups in the body functioning through them. The ball and socket hip joint makes it considerably more stable despite its superior mobility.[69] Optimizing neuromuscular function at the hip[36,70,71] and the core[15,16,71] is essential to prevent knee injury or reinjury. The knee functions primarily in the sagittal plane. In contrast, the hip joint truly has 3-dimensions of large range, sagittal (flexion-extension), frontal (abduction-adduction), and transverse (internal-external rotation) plane movement capability. In the presence of impaired quadriceps femoris function, exercises following ACL reconstruction can usually be more aggressive with progressive intensity frontal plane movements (making greater use of the hips) than with sagittal plane movements, provided that appropriate lower extremity alignment is present and excessive or poorly controlled genu valgus or varus movements do not occur. When a hamstring autograft (semitendinous, gracilis) is used for ACL reconstruction, rehabilitation clinicians should confirm appropriate frontal plane knee alignment during exercise performance. The surgical harvest of these dynamic medial knee stabilizers for ACL graft use increases the risk of dynamic valgus malalignment during the early postsurgical period. The lateral step-up and medicine ball press movement performed on a 10.1 to 30.5 cm in step (Figure 5) can help determine if a patient has adequate combined hip and quadriceps femoris strength to begin more advanced exercises. As quadriceps femoris function is improved with this exercise, the patient can gradually advance to more intense, primarily sagittal plane movements.

We have found that the single leg press exercise is a useful method to determine composite single lower extremity strength. Side-to-side comparison of six progressive resistance sets performed with each lower extremity independently for 12, 12, 10, 10, 8, and 8 repetitions can help determine the patient's capacity for safely handling 1 g loads before progressing to the multiple g's associated with higher impact activities. The noninvolved lower extremity goes first with progressively increasing resistance that gets as heavy as possible while maintaining appropriate technique. As a "rule of thumb, at the involved lower extremity, the patient should start with about 50% of the loads used with the noninvolved lower extremity. Less resistance (approximately 25%–30%) may be needed, if the patient was deconditioned before surgery, if rehabilitation was delayed, if they underwent revision surgery, or if they have undergone an articular cartilage restoration procedure located in a weight bearing region. Following posterior horn meniscal repair, end-range knee flexion may need to be restricted for 6–12 weeks. To better activate the gastrocnemius in a manner that simulates vertical jumping neuromuscular function, the center of plantar force should move closer to the forefoot at the end of each repetition.[72,73] When the patient can complete each exercise set successfully with quality movements, resistance is increased with each set for the next session. If they complete all of the exercise set repetition goals except for the last two sets, they should modify future sessions based on the following rule. If at least six repetitions were completed, the same resistance should be used during the next session. If they successfully perform <6 quality repetitions, they should decrease the resistance in each set for the next session. It should not take long for the noninvolved lower extremity to plateau with this progression, whereas the involved lower extremity should display quicker and prolonged gains. We have patients perform the single-leg press once or twice weekly so that they have time to recover before functional training. When approximately 80%–90% bilateral equivalence is achieved with the last 2 sets, they are generally ready to begin progressive hop or jump training. Although approximately 80%–90% bilateral equivalence with isokinetic knee extensor testing is recommended,[7] it generally lacks information regarding eccentric function, and unless adaptors are added to the test device, it does not provide information regarding the composite hip-knee-ankle extensor function needed for hopping and jumping. Even when 80%–90% bilateral equivalence is identified with single-leg pressing, it is essential to confirm appropriate frontal plane hip and knee alignment during nonimpact or low-impact exercises (single-leg squats, lunges, step ups, etc) before advancing to greater impact loads (hopping, jumping, bounding, etc). Before jumping exercises are initiated, the patient's footwear should be evaluated for motion control characteristics and medial-longitudinal arch support. This is especially important during single-leg jump landing activities as excessive, prolonged, or sudden subtalar joint eversion and foot pronation may contribute to faulty frontal

Figure 5 Lateral step-up with medicine ball press.

Figure 6 Matrix exercise.

Figure 8 Matrix exercise with Bosu ball and medicine ball.

and transverse plane lower extremity control.[74] When an orthotic is needed, a good pair of over the counter arch supports will generally suffice.

The Matrix exercise helps to develop multidirectional neuromuscular responsiveness throughout both lower extremities with the rehabilitation clinician continually evaluating movement quality (Figure 6). A metronome is used to guide timing and cadence, a weighted vest can be used to increase vertical loads; an adjustable step (stabile) (Figure 7) or Bosu ball (nonstabile) (Figure 8)

Figure 7 Matrix exercise with step, medicine ball, and weighted vest.

Figure 9 Forward lunge-trunk rotation with weighted vest and medicine ball.

Figure 10 Lateral step-up with weighted vest and volleyball press.

can be used to increase the motor control challenge, and a variety of sports equipment such as boxing gloves, balls, sticks, racquets, or dumbbells can increase trunk, upper extremity, and lower extremity integration requirements. Proficiency with Matrix exercises, lateral lunge with trunk rotation, forward lunge with trunk rotation (Figure 9), lateral elevated stepping (Figure 10), heading a stability ball during single-leg stance on a Bosu ball (Figure 11), and Woggler walking (Figure 12) are low-impact methods of developing integrated hip-knee-ankle function before progressing to hopping and jumping (Figure 13). As with the Matrix exercise, a weighted vest can be used to progressively increase vertical loads, but never at the expense of faulty technique, poor alignment, or otherwise reduced movement quality. Long-axis trunk-lower extremity rotation on the Ground Force 360 device (Center of Rotational Exercise, Inc., Clearwater, FL, USA) (Figure 14) uses pro-

Figure 11 Single leg balance on Bosu ball while heading a stability ball.

Figure 12 Diagonal Woggler walking under a high positioned tape.

Figure 13 Blindfolded lateral single leg hop and stabilization over a low positioned tape.

Figure 14 Long-axis rotation with progressive concentric and eccentric resistance on the Ground Force 360 Device.

gressive speed, concentric and eccentric resistances, and range of motion to simulate athletic movement challenges. The Ground Force 360 device provides a unique environment to train composite trunk, core, and lower extremity neuromuscular control, while the rehabilitation clinician monitors postural alignment and movement coordination. The rehabilitation clinician must remember that ultimately the reconstructed knee should be able to safely withstand repetitive loads in excess of 5 times the force of gravity during single-leg jump landings.[54]

Field testing criteria and returning to play

Return to play decision-making requires careful consideration of biological, psychobehavioral, and biomechanical readiness because each of these factors can contribute to the success or failure of ACL reconstruction and rehabilitation. There is generally more to the total picture than meets the eye! Return to play decision-making is too large a goal to perform in only 1 step following successful rehabilitation. Just as immediate acute care goals should focus on functional milestones such as reestablishing normal, pain-free active knee range of motion, and quadriceps femoris control during walking gait, return to play decision-making should likewise consist of a series of progressive goals that need to be achieved before release to unrestricted, competitive play. There should be a gradual progression from the highly protected and controlled exercises performed in the clinic to the less protected and controlled, more functionally specific, and relevant activities of the sport, position, and style of play to which the patient will be returning. What used to be a "simple thumbs up" or "thumbs down" subjective opinion regarding the potential readiness for a patient to safely return to sports has been replaced by a more gradual decision-making progression that may take 4–6 weeks (and sometimes longer) (Table 1). More often than not, the patient is not ready to return to unrestricted sport participation even when they strongly believe that they are! The development of valid, criterion-based assessments to determine readiness for sport-specific training and eventual return to sports is greatly needed and is a fertile area of research.[7] After the decision is made to allow them to return to unrestricted practice activities, they should be required to successfully complete 1 or 2 weeks of unrestricted, organized practice sessions without any problems before being allowed to return to competition.

Maintenance training

Even after successfully returning to competition, the patient should continue maintenance neuromuscular conditioning, particularly of the involved lower extremity knee and ankle extensors, for as long as they are athletically active, as the index injury may have somewhat long-term, even permanent osseous[51,52] and neurophysiological[75,76] effects. In addition to periodically revisiting single-leg press capability, they should perform regular, preseason and in-season neuromuscular training exercises that focus on appropriate jump landing technique, neuromuscular responsiveness, and appropriately balanced hip, knee, and ankle contributions to performance.

Summary

Patient participation in a presurgical exercise program can help ensure full active knee range of motion, increase the strength and responsiveness of dynamic knee-stabilizing musculature, and identify individuals who might benefit from a nonoperative treatment plan. Less invasive surgery has increased rehabilitation progression timetable decision-making. As rehabilitation progresses, the focus shifts from treating local impairments to treating more regional and global functional limitations. Greater attention to involved lower extremity eccentric strength may greatly enhance patient function following ACL reconstruction. In addition to restoring involved lower extremity strength and power within 80%–90% of the noninvolved lower extremity before sport-specific training, it is essential to reestablish the athlete role, increasing self-efficacy and confidence. Following repetitive training to optimize feed-forward neuromuscular preactivation timing, appropriate sport-specific movement form and technique should be verified. Return to play decision-making should consider biological, psychobehavioral, and biomechanical readiness in a graded progression. Since ACL injury may have somewhat permanent effects, even following surgical reconstruction, neuromuscular maintenance training is recommended to ensure continued, long-term, dynamic knee-stabilizing capabilities.

Disclosure

The authors report no conflicts of interest in this work.

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