Journal of Athletic Training 1999;34(2):177–193

www.nata.org/jat

Rehabilitation After Anterior Cruciate Ligament Reconstruction in the Female Athlete

Kevin E. Wilk, PT*†; Christopher Arrigo, MS, PT, ATC‡; James R. Andrews, MD†§||; William G. Clancy, Jr, MD§||

* HealthSouth Rehabilitation, Birmingham, AL; † American Sports Medicine Institute, Birmingham, AL; ‡ HealthSouth Rehabilitation, Arlington, TX; § University of Alabama at Birmingham, Birmingham, AL; || Alabama Sports Medicine and Orthopaedic Center, Birmingham, AL

Objective: To discuss the rehabilitation program after anterior cruciate ligament (ACL) reconstruction in the female athlete. In addition, we will discuss 8 unique characteristics identified in the female athlete and specific training drills to address and correct the potentially deleterious effects of these unique characteristics.

Background: The female athlete appears to be more susceptible to noncontact ACL injuries than the male athlete. There seem to be many differences between the female and male athlete that may contribute to the increased injury rate in the female athlete. These variations include anatomical and neuromuscular considerations and differences.

Description: Based on the unique characteristics of the female athlete and the anatomical and neuromuscular dissimilarities, a specially designed rehabilitation program has been established for the female athlete after ACL surgery.

Clinical Advantages: The rehabilitation drills discussed in this article challenge the neuromuscular system through proprioception, kinesthesia, dynamic joint stability, neuromuscular control, and perturbation training activities. Improving the female athlete's neuromuscular system will, we believe, expedite the injured athlete's recovery after ACL injury or surgery. Although the concepts discussed are part of a postoperative rehabilitation program after ACL surgery, these concepts may also be implemented as a preventive program to assist in reducing the incidence of ACL injuries in the female athlete.

Key Words: neuromuscular control, perturbation training, dynamic stability

Anterior cruciate ligament (ACL) injuries are the most common severe ligamentous injuries incurred by athletes. The typical mechanism of injury is deceleration with twisting, pivoting, or a change of direction. In our clinical experience, at least 60% of all ACL injuries sustained by athletes are due to a noncontact mechanism of injury. The female athlete appears to be more susceptible to noncontact ACL injuries than her male counterpart.[1–5]

An increasing number of female athletes seem to be sustaining ACL injuries. Malone et al[1] reported that collegiate female basketball players were 8 times more likely to sustain ACL injuries compared with collegiate male basketball players. During the 1989–1990 intercollegiate basketball season, the NCAA Injury Surveillance System reported that female athletes injured their ACLs 7 to 8 times more frequently than male athletes.[2] Lindenfeld et al[3] reported that the injury rate for ACL injuries in female soccer players was 6 times greater than that of male soccer players. Other sports in which the female athlete appears to be more susceptible to ACL injuries include volleyball and gymnastics.[4,5] Ferretti et al[4] reported a 4-fold higher incidence of serious knee ligament injuries in female versus male elite volleyball players. Chandy and Grana,[5] in a 3-year study, reported that female athletes were 4.6 times more likely to sustain a season-ending knee injury than male athletes. Specifically, female athletes in jumping sports had significantly more severe knee injuries.

Understanding the reasons for this increased injury rate is vital to the development of a postoperative rehabilitation program, and even more importantly, a preventive training program to decrease the incidence of severe ligamentous injury. According to our injury data, including high school and college athletes in all competitive and recreational sports, the female high school athlete appears to have a 1 in 100 chance of sustaining an ACL injury, whereas the male high school athlete appears to have a 1 in 500 chance of sustaining an ACL injury. The collegiate male athlete appears to exhibit a 1 in 50 chance, while the collegiate female athlete appears to have a 1 in 10 chance (K. E. Wilk et al, unpublished data, 1998).

Thus, with the increasing number of females participating in athletics and an increasing number of ACL injuries occurring, a specific postoperative rehabilitation program for the female athlete after ACL surgery is useful. In this article, we will discuss the rehabilitation program after ACL surgery. Additionally, specific exercises to address the unique characteristics

Address correspondence to Kevin E. Wilk, PT, HealthSouth Sports Medicine Center, 1201 11th Ave. South, #100, Birmingham, AL 35205.

of the female athlete will be discussed, along with suggestions regarding specific drills.

UNIQUE CHARACTERISTICS OF THE FEMALE ATHLETE

There are numerous sex differences that contribute to the increased rate of ACL injuries in the female athlete. These sex differences are both anatomical and neuromuscular (Table 1). The female usually exhibits a wider pelvis, increased flexibility, less-developed thigh musculature, increased genu valgum, and increased external tibial torsion when compared with the male. Although these differences are anatomical, suggesting structural variations in the body, several of these anatomical differences may be affected by specially designed training drills. Discussions with many patients who have torn their ACLs and review of videotapes documenting ACL injury reveal that a frequent mechanism for sustaining an ACL injury is a valgus stress with rotation at the knee joint. This mechanism of ACL injury is especially common when the athlete lands from a jump. Thus, preventive and rehabilitative training drills should be developed to control the valgus moment at the knee joints through hip and ankle movement strategies. Also, the female athlete exhibits increased flexibility and genu recurvatum. Therefore, the female athlete must be trained to control knee extension and hyperextension through quadriceps and hamstring muscle coactivation.

Specific neuromuscular and muscular performance differences exist between female and male athletes. Several authors have documented that females exhibit significantly less muscular strength than males.[6–8] Hakkinen[7] examined the force-production characteristics of the leg extensors and trunk flexors and extensors in male and female basketball players. The male players demonstrated greater absolute maximal strength values in all 3 muscle groups when compared with the females, even when the force values were related to body weight.

Explosive force production of the leg musculature is an important neuromuscular characteristic among athletes. Electromechanical response time refers to the interval between a stimulus and a change in electrical activity in skeletal muscle and the delay between the change in electrical activity and actual force generation by the muscle.[9] Females appear to generate muscular force at a slower rate than males. Komi and Karlsson[10] reported that female subjects required about twice as much time as males to attain 70% of a maximal voluntary contraction. Bell and Jacobs[11] demonstrated a shorter electromechanical response time in males compared with females. Several investigations[12,13] have documented similar results. Bell and Jacobs[11] postulated that the shorter electromechanical response time in males is due to stiffer muscles. The elastic component in males' muscles is more resistant to stretching than in females due to inherent flexibility differences, thereby shortening the electromechanical delay.[14] This finding has significant rehabilitation and training implications. A critical component to dynamic joint stability is the time required to generate muscular torque once the protective muscle contraction has been initiated. The time interval required to reach maximum muscular capacity appears to be an important parameter in injury prevention.[15–17] Therefore, it would appear that the enhancement of dynamic joint stability in the female athlete depends in part on neuromuscular response times. High-speed muscle training seems to be an important way to address this parameter.

Furthermore, it appears that muscular fatigue significantly affects the rate of force development and muscle contraction velocity.[18–20] Hakkinen and Komi[20] examined the effects of fatigue produced by a maintained isometric contraction of the knee extensors at 50% of a maximum effort in 14 males. The continual contraction caused a significant increase in integrated electromyogram (EMG) activity and a decrease in mean power. Additionally, the investigators noted that fatigue occurred in the contractile element of the muscle and that the muscle spindle sensitivity was increased during fatigue loading. Zhou et al[18] noted a significant increase (147%) in the electromechanical delay of the knee extensors after muscular fatigue. Thus, it appears that muscular endurance training should be an integral component of a well-structured rehabilitation program after ACL injury.

Recently, Huston and Wojtys[21] examined the neuromuscular performance differences between male and female collegiate athletes and nonathletes. Significant findings were numerous; however, a few key points stand out. The order of muscular recruitment to produce dynamic joint stability in response to anterior tibial translation in female athletes was significantly different than that of male athletes or female nonathletes. The male athletes and nonathletes recruited their hamstring and gastrocnemius muscles to resist anterior tibial translation, whereas the female athletes relied more on the quadriceps muscles. Thus, the female athlete appears to exhibit a less effective protective reflex to stabilize the knee joint than either

Table 1. Sex Differences in Females Compared with Males

Anatomical Differences	Muscular and Neuromuscular Differences	Laxity and Range of Motion
Wider pelvis	Diminished muscular force	Greater range of motion
Increased flexibility	Dependence on quadriceps muscle for stability	Genu recurvatum
Less-developed thigh musculature	Longer time to develop force	Increased knee laxity
Narrower femoral notch	Longer electromechanical response time	Increased hip rotation
Smaller ACL		
Increased genu valgum		
Increased external tibial torsion		

the male athlete or the female nonathlete. In fact, using the quadriceps to stabilize the knee joint may render the ligament more susceptible to injury by increasing ACL strain.[22,23] Hewitt et al[24] reported a significant imbalance between the hamstrings and quadriceps muscles in a group of high school volleyball players. The investigators noted that the female athletes' unilateral hamstrings to quadriceps muscle ratio was 47%, while the males' was 67%. The authors stated that the female athletes' unilateral muscle ratio was less efficient in stabilizing the knee joint. Hence, the rehabilitation program must incorporate drills to train the female athlete to better use the knee-flexor musculature in providing dynamic joint stability.

Female athletes also exhibit greater laxity and range of motion than male athletes. Huston and Wojtys[21] have demonstrated that the knees of women exhibit greater laxity than those of men. The female athlete group showed significantly more anterior tibial displacement (4.5 mm) when compared with the male athlete group (3.5 mm). It should also be noted that changes in knee laxity have been reported during the menstrual cycle. Huston and Wojtys[25] reported a statistically significant difference in knee laxity during one menstrual cycle. The greatest laxity was noted on day 1 of the cycle. In addition, females tend to exhibit greater genu recurvatum than males. In a recent study conducted at our center, we compared tibiofemoral displacement measurements in female athletes with significant hyperextension (more than 7°) and female athletes who exhibited less than 5° of hyperextension. We found a tendency, but no statistically significant difference, toward greater total tibiofemoral displacement in individuals who exhibited more hyperextension compared with individuals with only a few degrees of hyperextension (K. E. Wilk et al, unpublished data, 1998). Another protective mechanism in preventing ACL injuries is the ability to actively contract the knee musculature to increase the stiffness of the knee joint. Recently, Wojtys et al[26] reported that male athletes were able to increase knee stiffness by 473%, whereas females were able to increase knee stiffness by only 217%.

The increased incidence of ACL injuries in the female athlete appears to be multifactorial. To our minds, it seems to be caused by a combination of both anatomical and neuromuscular differences. Based on these differences, we have developed 8 key factors to consider when developing an ACL rehabilitation program for the female athlete (Table 2).

CURRENT CONCEPTS IN ACL REHABILITATION

Before discussing the specific factors to consider in the female athlete, we will briefly discuss our philosophy and our current rehabilitation program after ACL reconstruction. Our current rehabilitation program is an adaptation of our previously published program[27,28] and represents an evolution in rehabilitation to a greater emphasis on functional rehabilitation drills and a reflection of the importance of proprioception and neuromuscular control. We currently use 2 ACL rehabilitation programs. The accelerated ACL rehabilitation program is used for competitive or serious recreational athletes. This program is more aggressive and demanding because of the increased demands placed on the knee joint by the athlete. In contrast, the other rehabilitation program is designed for the less-serious recreational athlete. This program is slightly slower than the accelerated program because these patients are generally less conditioned and their lifestyle prohibits any aggressive rehabilitation program.

The female athlete who undergoes an ACL reconstructive procedure is initiated on the accelerated rehabilitation program unless specific circumstances exist (eg, meniscus repair, osteochondral procedures, concomitant lateral collateral ligament or posterior cruciate ligament surgery). Hardin et al[29] have suggested a decelerated rehabilitation program after ACL reconstruction for an adolescent female athlete who exhibits hyperelasticity. While we agree with the authors that overaggressive rehabilitation may result in excessive capsular mobility or graft stretch-out, or both, we strongly support immediate muscular training and early restoration of proprioception and neuromuscular control in the female athlete. We base this point of view on the neuromuscular differences exhibited by the female athlete.

The accelerated 6-phase ACL rehabilitation program outlined in Table 3 is designed to return the athlete to sport as quickly and safely as possible. We use a criterion-based approach, where the patient must accomplish specific objectives before advancing to the next phase of the rehabilitation program. Also, the specific time frames are based on healing constraints. We will briefly discuss the program.

The rehabilitation program begins immediately after the ACL injury. The goals of the preoperative phase are to diminish inflammation, swelling, and pain and to restore normal range of motion. Before surgery, emphasis is placed on

Table 2. Factors to Consider in ACL Rehabilitation of the Female Athlete

Factor	Rehabilitation
Females exhibit a wider pelvis and increased genu valgum	Dynamic control of valgus moment at the knee joint
Female athletes recruit quadriceps muscle to stabilize the knee	Retrain the neuromuscular pattern for the female athlete to use the hamstrings
Females generate muscular force more slowly than males	Train for fast speeds and reaction timing
Jumping athletes lose hip control upon landing	Train hip and trunk control
Less-developed thigh musculature	Train the hip musculature to assist in stabilization
Genu recurvatum and increased knee laxity	Train athlete to control knee extension (stability position)
Exhibit less-effective dynamic stabilization	Enhance neuromuscular control and protective pattern reflexes
Poorer muscular endurance rates	Train female athlete to enhance muscular endurance

Table 3. Accelerated Rehabilitation for ACL PTG* Reconstruction (Isolated)

I. Preoperative Phase
Goals: Diminish inflammation, swelling, and pain
Restore normal range of motion (especially knee extension)
Restore voluntary muscle activation
Provide patient education to prepare patient for surgery
Brace: Elastic wrap or knee sleeve to reduce swelling
Weightbearing: As tolerated with or without crutches
Exercises: Ankle pumps
Passive knee extension to zero
Passive knee flexion to tolerance
Straight-leg raises
Quadriceps setting
Hip abduction and adduction raises
Closed kinetic chain exercises: minisquats, lunges, step-ups
Muscle stimulation: Electrical muscle stimulation to quadriceps during voluntary quadriceps exercises (4 to 6 h/d)
Cryotherapy/elevation: Apply ice 20 min of every hour, elevate leg with knee in full extension (knee must be above heart)
Patient education: Review postoperative rehabilitation program
Review instructional video (optional)
Select appropriate surgical date

II. Immediate Postoperative Phase (Day 1 through Day 7)
Goals: Restore full passive knee extension
Diminish joint swelling and pain
Restore patellar mobility
Gradually improve knee flexion
Reestablish quadriceps control
Restore independent ambulation
Postoperative Day 1:
Brace: EZ Wrap Brace (Professional Products, DeFuniak Springs, FL) or immobilizer applied to knee, locked in full knee extension during ambulation
Weightbearing: 2 crutches, weightbearing as tolerated
Exercises: Ankle pumps
Overpressure into full, passive knee extension
Active and passive knee flexion (90° by day 5)
Straight-leg raises
Quadriceps isometric setting
Hip abduction and adduction
Hamstring stretches
Closed kinetic chain exercises: minisquats, weight shifts
Continuous passive motion: As needed, 0° to 45° to 50° (as tolerated and as directed by physician)
Muscle stimulation: Use muscle stimulator during active muscle exercises (4 to 6 h/d)
Ice and elevation: Ice 20 min of every hour; elevate leg with knee in full extension
Postoperative Days 2 to 3:
Brace: EZ wrap brace and immobilizer locked at zero
Weightbearing: 2 crutches as tolerated
Range of motion: Remove brace, perform range-of-motion exercises 4 to 6 times a day
Exercises: Multiangle isometrics at 90° and 60° (knee extension)
Knee extension 90° to 40°
Patellar mobilization
Overpressure into extension
Ankle pumps
Straight-leg raises (3 directions)
Minisquats and weight shifts
Standing hamstring curls
Quadriceps isometric setting
Muscle stimulation: to quadriceps during exercises (6 h/d)
Continuous passive motion: 0° to 90° as needed

Table 3. Continued

Ice and elevation: Ice 20 min of every hour and elevate leg with knee in full extension
Postoperative Days 4 to 7:
Brace: EZ Wrap/immobilizer
Weightbearing: 2 crutches, weightbearing as tolerated
Range of motion: Remove brace, perform range-of-motion exercises 4 to 6 times per day, knee flexion 90° by day 5, approximately 100° by day 7
Exercise: Continue all exercises as listed in postoperative days 2–4, and progress proprioception and balance drills
Muscle stimulation: Apply to quadriceps during active exercises
Continuous passive motion: 0° to 90° as needed
Ice and elevation: Ice 20 min of every hour and elevate leg with knee in full extension

III. Early Rehabilitation Phase (Week 2 through Week 4)
Goals: Maintain full passive knee extension
Gradually increase knee flexion
Diminish swelling and pain
Muscle training
Restore proprioception
Patellar mobility
Criteria to progress to phase III:
Quadriceps control (ability to perform good quadriceps set and straight-leg raise)
Full passive knee extension
Passive range of motion from 9° to 90°
Good patellar mobility
Minimal joint effusion
Independent ambulation
Week 2:
Brace: Discontinue brace or immobilizer at 2 to 3 wk
Weightbearing: As tolerated (goal is to discontinue crutches at 10 d)
Range of motion: Self-ROM stretching (4 to 8 times a day), emphasis on maintaining full, passive range of motion
KT-2000 test: 6.75-kg anterior-posterior test only
Exercises: Muscle stimulation to quadriceps during quadriceps exercises
Isometric quadriceps sets
Straight-leg raises (4 planes)
Leg press
Knee extension 90° to 40°
Half-squats 0° to 40°
Weight shifts
Front and side lunges
Hamstring curls
Bicycle
Proprioception training
Overpressure into extension
Passive range of motion from 0° to 50°
Patellar mobilization
Well-leg exercises
Progressive resistance exercise program (begin with .45 kg, increase by .45 kg per wk)
Week 3:
Brace: Discontinue
Range of motion: Continue range-of-motion stretching and overpressure into extension
Exercises: Continue all exercises as in wk 2
Passive range-of-motion exercises from 0° to 115°
Bicycle for range-of-motion progression
Pool-walking program (if incision is closed)
Eccentric quadriceps program
Lateral lunges
Lateral step-ups

Table 3. Continued

Front step-ups
Lateral step-overs (cones)
Stair-stepper machine
Progress proprioception and neuromuscular control drills

IV. Intermediate Phase (Week 4 through Week 10)

Goals: Restore full knee range of motion (0° to 125°)
Improve lower extremity strength
Enhance proprioception, balance, and neuromuscular control
Improve muscular endurance
Restore limb confidence and function

Criteria to enter phase IV:
Active range of motion from 0° to 115°
Quadriceps strength 60% of contralateral side (isometric test at 60° of knee flexion)
Unchanged KT bilateral values
Minimal to no joint effusion
No joint line or patellofemoral pain
Brace: no immobilizer or brace; may use knee sleeve (Bauerfeind Comprifix brace, Bauerfeind USA, Kennesaw, GA)
Range of motion: self-ROM 4 to 5 times per day (using the other leg to provide ROM)
KT-2000 Testing
Week 4: 9-kg test
Weeks 6 through 8: 9- and 13.5-kg tests

Week 4:
Progress isometric strengthening program
Leg press
Knee extension from 90° to 40°
Hamstring curls
Hip abduction and adduction
Hip flexion and extension
Lateral step-overs
Lateral lunges
Lateral step-ups
Front step-downs
Wall squats
Vertical squats
Toe calf raises
Biodex stability system (balance, squats, etc)
Proprioception drills
Bicycle
Stair-stepper machine
Pool program (backward running, hip and leg exercises)

Week 6:
Continue all exercises
Pool running (forward) and agility drills
Balance on tilt boards
Progress to balance board throws
KT-2000 test (9- and 13.5-kg tests)

Week 8:
Continue all exercises listed in weeks 4 through 6
Plyometric leg press
Perturbation training
Isokinetic exercises (90° to 40°) (120° to 240°/s)
Walking program
Bicycle for endurance
Stair-stepper machine for endurance
KT-2000 test: 9- and 13.5-kg test

Week 10:
KT-2000 test: (9- and 13.5-kg and manual maximum test)
Isokinetic test: (test concentric knee extension and flexion at 180° and 300°/s)

Table 3. Continued

Exercises: Continue all exercises listed in wks 6, 8, and 10
Plyometric training drills
Continue stretching drills

V. Advanced Activity Phase (Week 10 through Week 16)

Goals: Normalize lower extremity strength
Enhance muscular power and endurance
Improve neuromuscular control
Perform selected sport-specific drills

Criteria to enter phase V:
Active range of motion from 0° to 125° or greater
Quadriceps strength 70% of contralateral side, knee flexor:extensor ratio of 70% to 75%
No change in KT values (comparable with contralateral side, within 2 mm)
No pain or effusion
Satisfactory clinical examination
Satisfactory isokinetic test (values for females at 180 degrees)
Quadriceps bilateral comparison 75%
Hamstrings equal bilateral
Quadriceps peak torque/body weight
Hamstrings/quadriceps ratio 66% to 75%
Hop test (80% of contralateral leg)
Subjective knee scoring (modified Noyes System[30])
80 points or better

Continue all exercises listed in wks 10–12

VI. Return-to-Activity Phase (Week 16 through Week 22)

Goals: Gradual return to full unrestricted sports
Achieve maximal strength and endurance
Normalize neuromuscular control
Progress skill training

Criteria to enter phase VI:
Full range of motion
Unchanged KT-2000 test (within 2.5 mm of opposite side)
Isokinetic test that fulfills criteria
Quadriceps bilateral comparison (80% or greater)
Hamstring bilateral comparison (110% or greater)
Quadriceps torque/body weight ratio (55% or greater)
Hamstrings/quadriceps ratio 70% or greater
Proprioceptive test 100% of contralateral leg
Functional test 85% or greater of contralateral side
Satisfactory clinical examination
Subjective knee scoring (modified Noyes System: 90 points or better)
Tests: KT-2000, isokinetic, and functional tests before return

Exercises: Continue strengthening program
Continue neuromuscular control drills
Continue plyometric drills
Progress running and agility program
Progress sport-specific training

6-month follow-up:
Isokinetic test
KT-2000 test
Functional test

12-month follow-up:
Isokinetic test
KT-2000 test
Functional test

* PTG = patellar tendon graft.

restoring full passive knee extension to decrease postoperative complications such as arthrofibrosis.[30,31] Additionally, muscle-training exercises are performed to prevent muscular atrophy.

The primary goal of the muscle-strengthening exercises is muscle activation. It has been reported that, once an individual has torn the ACL, one of the protective mechanisms is a reflex inhibition of the quadriceps and facilitation of the hamstring muscles.[32,33] This protective reflex mechanism, in the opinion of author KEW, is the primary reason for quadriceps muscle atrophy after ACL injury or surgery. Thus, a critical aspect of the rehabilitation program before and after surgery is reestablishing voluntary muscular activation of the quadriceps muscles. The patient is encouraged to recruit as much of the quadriceps muscle as possible. Often, electrical muscle stimulation or biofeedback, or both, are used to facilitate greater muscle activation.

Additionally, closed and open kinetic chain exercises are performed to activate muscular patterns and to restore proprioception. Specific drills to improve balance, proprioception, kinesthesia, and neuromuscular control are initiated immediately postinjury to prevent deafferentation.[34–36] Another key component of the preoperative phase is patient education and counseling. The patient is instructed in the postoperative program as part of the mental preparation for the surgery and the rehabilitation program. During this preoperative phase, an appropriate date for surgery is determined. We have found a great deal of variability as to when an athlete is ready for surgery. Instead of delaying surgery a set amount of time, the clinician should consider the following preoperative conditions: full range of motion, minimal swelling, active muscle recruitment, and mental preparedness. Shelbourne et al[37] reported that delaying surgery until motion had been restored decreased the incidence of arthrofibrosis. Also, Shelbourne and Foulk[38] have noted that quadriceps muscle strength returned more quickly when surgery was delayed longer than 21 days.

The postoperative rehabilitation program is initiated immediately after surgery. The goals of this phase are listed in Table 3. Patients remain in the hospital after surgery for 23 hours' observation. This overnight stay allows control of the patient's activity level, pain, and swelling and ensures the consistent and accurate start of the prescribed rehabilitation program. A commercial cold wrap is applied to the knee immediately after surgery (Figure 1). Continuous passive motion via machine is initiated from 0° to 45° when the patient goes to the hospital room. Quadriceps muscle contractions and full, passive knee-extension exercises are emphasized during the first week to prevent the development of knee-flexion and patellar contractures. The patient is permitted to weightbear as tolerated with 2 crutches, and the postoperative brace is locked in full knee extension. The patient's knee flexion range of motion is gradually increased. By postoperative day 5, the patient should exhibit 90° of knee flexion and, by day 7, approximately 100°. Additionally, closed kinetic chain functional training is begun during the first week. These drills include minisquats (0° to 45°), weight shifts, balance drills, and proprioceptive training activities. The rehabilitation specialist and the patient perform patellar mobilizations to restore normal patellar mobility. The primary goals of the first week of rehabilitation are restoring full passive knee extension, diminishing swelling and pain, restoring patellar mobility, gradually restoring knee flexion, reestablishing voluntary quadriceps control, and controlling the patient's activity level.

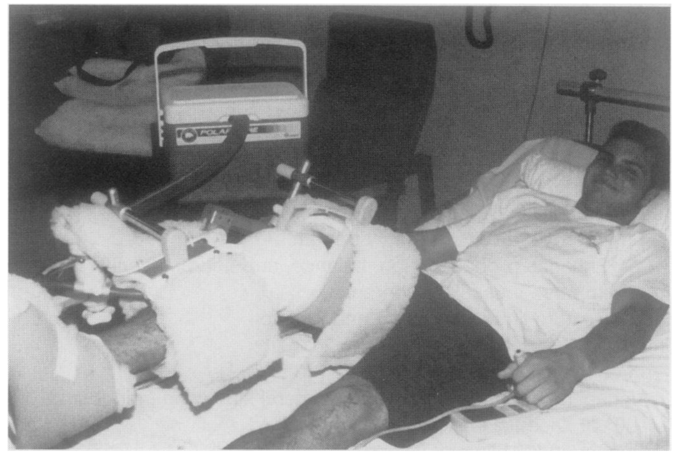

Figure 1. A commercial cold wrap is applied to the knee joint while the patient's knee is placed in a continuous passive motion machine.

The next phase, the early rehabilitative phase, includes weeks 2 through 4. The goals of this specific phase are listed in Table 3. Additionally, the patient must fulfill specific criteria before progressing into phase III. One of the critical goals of this phase is restoring full passive knee extension. Females usually exhibit hyperextension of the knee joint. A rehabilitation dilemma has been whether or not to restore hyperextension in the female's knee after an ACL reconstruction. Rubenstein et al[39] have reported that restoring full hyperextension does not adversely affect ligamentous stability. However, we suggest restoring only approximately 5° of hyperextension in the female athlete through stretching techniques in the training room or clinic (Figure 2). If the athlete exhibits more than 5° of hyperextension in the contralateral knee, the authors prefer

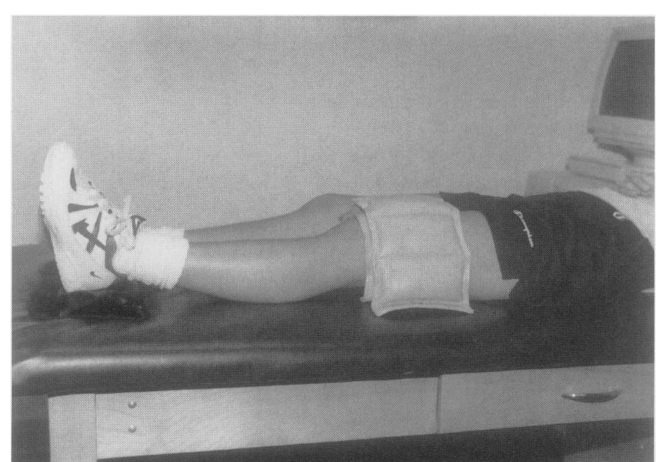

Figure 2. A low-load, long-duration stretching technique to restore the patient's full passive knee extension. Usually a weight of 3.6 to 5.4 kg is used to create the stretch of approximately 10 to 12 minutes.

the athlete to gradually regain the additional hyperextension of the involved knee through functional activities. The purpose of restricting hyperextension is the effect it has on dynamic joint stability. When the knee is in a fully extended or hyperextended position, the knee flexors are at a mechanical disadvantage to be recruited to produce forceful knee flexion (Figure 3). Several studies[40-41] have documented that the hamstring muscles are more efficient at 30° of knee flexion than at 0° or 5° of hyperextension, which is due to moment arms and muscle fiber lengths.

During phase III, the patient's knee flexion is gradually increased. The rate of progression is based on the patient's response to the surgery (eg, joint swelling and pain). If significant joint effusion exists, we progress the knee flexion motion slightly more slowly until the swelling is reduced. The rate of knee flexion motion is progressed based on the patient's ligamentous endfeel. A firm endfeel indicates aggressive stretching and progression of motion. Conversely, a capsular endfeel or one with give to it would suggest the need for a more gradual rate of stretching. Muscle-training drills and exercises are progressed with closed and open chain exercises. Electrical muscle stimulation is applied to the quadriceps to facilitate active quadriceps contraction, to reeducate the muscle, and to prevent muscle inhibition due to pain or swelling.[42-46] It is essential to reestablish muscle activation early in the rehabilitation program to prevent quadriceps atrophy and promote quadriceps muscular training. In addition, drills to enhance proprioception and weight distribution are initiated (Figures 4 and 5). A vital goal during the second week is to train the patient to assume full-body weight on the involved leg. A NeuroCom Balance System (NeuroCom International, Clackamas, OR) is used to assess the percentage of body weight the patient is assuming on the involved leg and to provide biofeedback training. Additionally, selected open kinetic chain exercises are permitted, such as resisted knee flexion (unless a meniscus repair was performed), hip abduction and adduction, and knee-extension exercises from 100° to 40°. Many investigators have reported that ACL strain increases significantly during the last 30° of knee extension.[47-53] Recently, Beynnon et al[54] studied the strain behavior of the anteromedial bundle of the ACL during rehabilitation exercises in vivo. During an open kinetic chain isometric quadriceps contraction at 15° of knee flexion against 30 Nm of torque, the peak strain was 4.4%, whereas at 30° of knee flexion against the same resistance, the peak strain was approximately 2.7%. At 60° of knee flexion, there was no strain on the ACL. Because of the increasing strain on the ACL at terminal extension, we initially restrict active resisted knee extensions to 40°. Placement of the resistance and speed of the exercise can also influence the

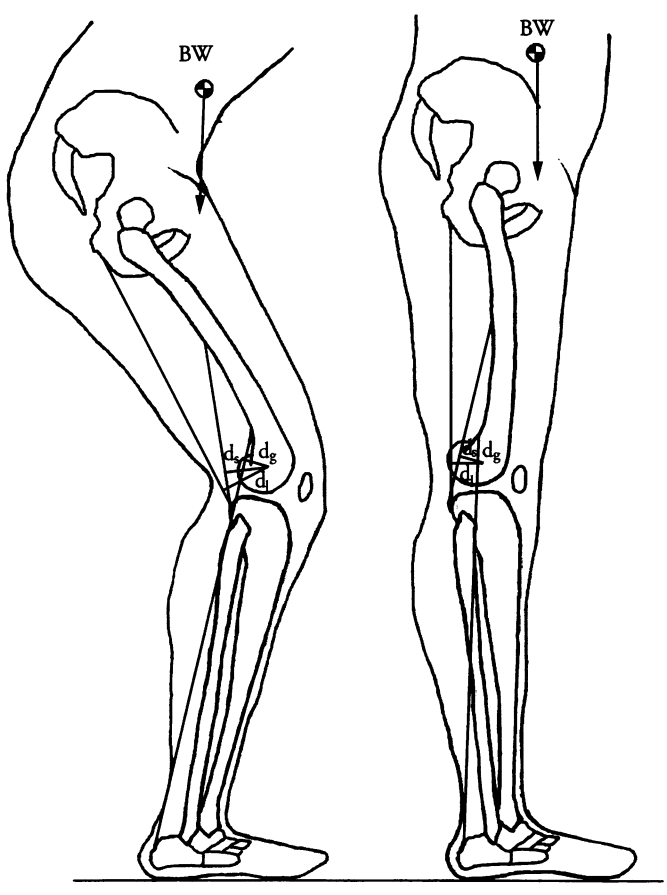

Figure 3. When the knee joint is placed into hyperextension, the flexor muscles (hamstrings and gastrocnemius) are placed at a mechanical disadvantage to stabilize the knee joint. The knee-flexor moment arms with the knee flexed to 30° (A) and hyperextended to 5° (B) are illustrated. The d_s indicates the moment arm for the short head of the biceps femoris; d_l the moment arm for the long head of the biceps femoris; and d_g the moment arm for the gastrocnemius muscle. BW indicates the body-weight effect.

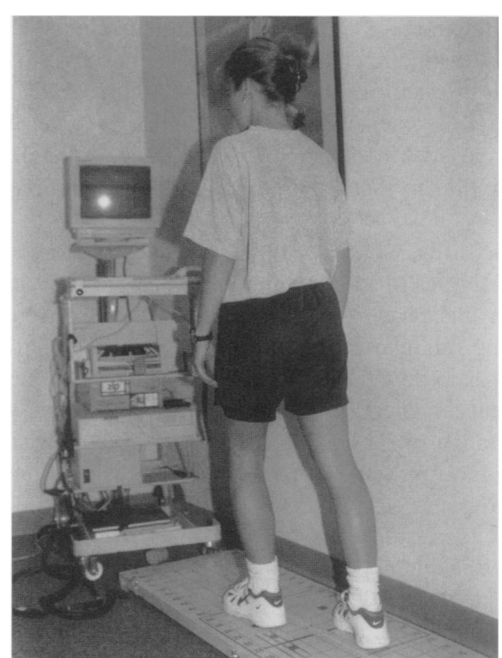

Figure 4. The patient performs weight shifts on a force platform (NeuroCom Balance System) to analyze weight-distribution forces.

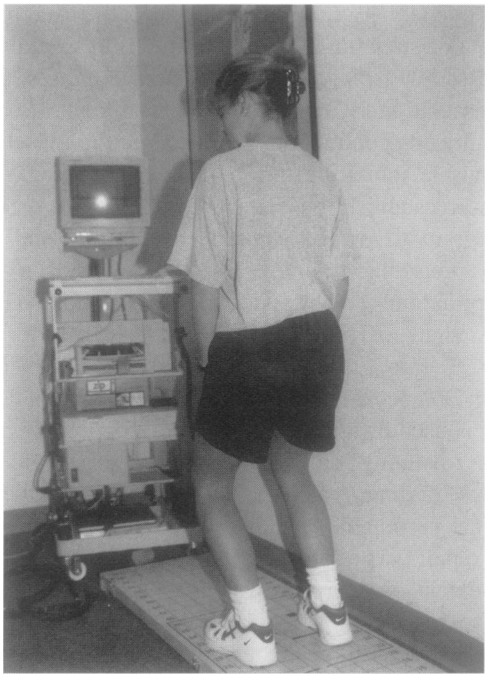

Figure 5. Vertical squats are performed on a force platform to accurately assess weightbearing forces.

magnitude of tibiofemoral shear forces. Wilk and Andrews[55] studied the effects of pad placement during isokinetic exercise in ACL-deficient patients. The investigators noted significantly less tibial displacement when the resistance pad was positioned proximally as compared with the conventional distal pad placement. Furthermore, a greater magnitude of anterior tibial displacement was noted during knee extensions at slower speed (60°/s) compared with faster isokinetic speeds (180°/s and 300°/s). Beynnon et al[54] have documented an ACL strain during closed kinetic chain exercises, such as a vertical squat. They demonstrated the greatest strain on the ACL from 40° of flexion to full extension. The strain behavior of the ACL during a closed kinetic chain exercise (eg, squats) was extremely similar to that during open kinetic chain knee extension.[54]

Exercise drills, which are functional and emphasize weightbearing activities to strengthen the lower extremity, are implemented in this phase. Functional strengthening exercises are used during this phase, including vertical squats, lateral step-ups, front step-downs, lateral lunges, and lateral step-overs. The patient is encouraged to ride a stationary bicycle to facilitate range of motion. Lastly, a pool program is initiated (once the incision has healed adequately) to facilitate proper gait training and to provide a safe environment for other functional exercise drills.[56,57]

The intermediate phase usually is started at week 4 and progresses to week 10. The patient is progressed into this phase based on specific criteria (Table 3); therefore, the actual time frame may vary slightly. The goals of this phase are to restore full motion (0° to 125°); improve lower extremity strength; enhance proprioception, balance, and neuromuscular control; and restore limb confidence and function. The exercises and drills performed in this phase should be functional, effective, and safe. The isotonic strengthening program should be progressed in weight and number of repetitions and sets. During this phase, proprioception and functional exercises are performed to enhance dynamic joint stability. Thus, balance drills such as squats on an unstable platform (eg, the Biodex Stability System [Biodex Corp, Shirley, NY]) (Figure 6) are performed. The pool program is progressed to incorporate forward and backward running, agility drills, and eventually jumping drills in the pool. The lateral lunges and front lunges are advanced from straight planes to multiple planes, and ball catches and throws are incorporated to remove the patient's conscious awareness (Figure 7). Hence, proprioceptive and dynamic stability drills are performed in conjunction with upper extremity skills.

At 10 weeks, isokinetic and knee arthrometer tests are performed to determine muscular performance and static knee stability, respectfully. The muscular performance characteristics of an ACL-reconstructed knee at 10 to 12 weeks postsurgery have been documented by the authors.[58] At this time, the patient typically exhibits a 30% deficit in the quadriceps, as indicated by bilateral peak torque comparisons, and minimal to no deficit demonstrated in the knee-flexor muscle group. Additionally, the patient torque-to-body weight ratio and unilateral muscle ratios are also evaluated. The knee arthrometer score should be comparable with the uninvolved knee (usually within 2 mm).

The advanced activity phase is usually initiated at week 10 and progresses until week 16. The emphasis of the phase is on advanced strengthening drills, neuromuscular control drills,

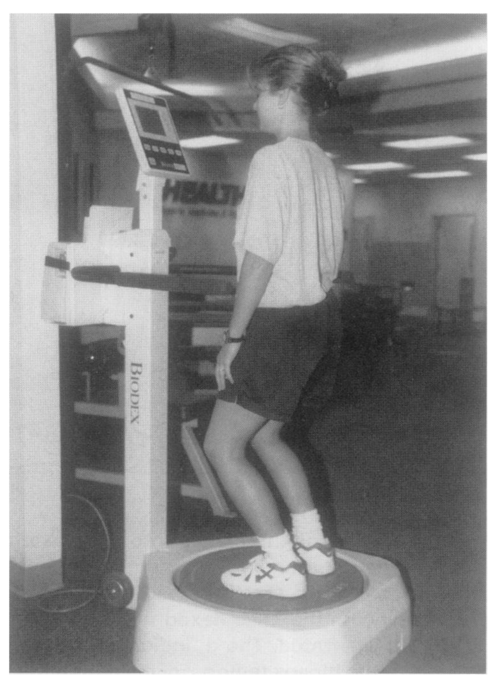

Figure 6. Vertical squats are performed on a Biodex balance system.

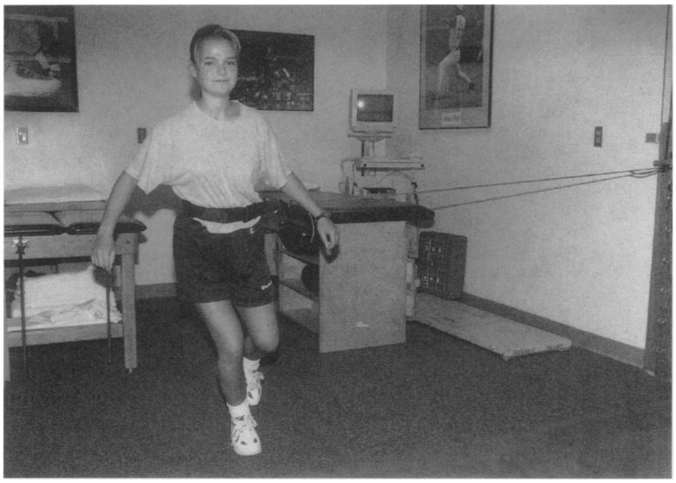

Figure 7. Lateral lunges performed in a single plane of motion. The patient is instructed to lunge, land, and maintain knee flexion to 25° to 30° during the drill.

and early return to sport-specific training drills. Before the patient enters this phase of the rehabilitation program, specific criteria must have been achieved (Table 3). Once these predetermined criteria are achieved, advanced drills can be initiated. During this phase, strengthening exercises are progressed to high-weight, low-repetition sets to emphasize muscular hypertrophy. Plyometric drills are used to enhance dynamic joint stability and neuromuscular control. Additionally, perturbation training is emphasized to enhance neuromuscular control. A running program is also initiated, including agility drills such as side shuffles, cariocas, and backward running. At 14 to 16 weeks postsurgery, a series of tests is performed to determine whether the athlete can gradually return to sport activities (eg, team practice). We routinely perform knee arthrometer, isokinetic,[59,60] proprioceptive, and hop tests.[61–63] In addition, the patient completes a subjective knee function questionnaire. The specific criteria can be found in Table 3. Once these criteria have been met and the clinical examination is satisfactory, the athlete enters the return-to-activity phase.

The return-to-activity phase usually begins at approximately 16 weeks after surgery but can vary based on the patient's rate of progression. During this phase, the patient is strongly encouraged to perform specific strengthening exercises (selected to correct deficits), plyometrics, and neuromuscular control drills and to accelerate sport-specific training drills. Functional motor patterns through skill activities are progressed and closely monitored. Once the patient has achieved normal movement patterns and the criteria have been satisfactorily achieved, the athlete may resume team practice.

SPECIAL CONSIDERATIONS FOR THE FEMALE ATHLETE

We have identified 8 factors that we feel are important to consider when rehabilitating a female athlete after ACL recon-

Table 4. Female ACL Rehabilitation: 8 Special Considerations and Specific Exercise Drills

Hip musculature to stabilize knee
Lateral step-overs (regular, fast, very slow)
Step-overs with ball catches
Step-overs with rotation
Lateral step-ups on foam
Dip walk
Squats (foam) (Balance Master)
Front diagonal lunges onto foam
Retrain neuromuscular pattern hamstring control
Lateral lunges straight
Lateral lunges
Lateral lunges with rotation
Lateral lunges onto foam
Lateral lunges with ball catches
Squats unstable pattern
Lateral lunges jumping
Lateral unstable pattern
Coactivation balance through biofeedback
Slide board
Fitter (Fitter International, Calgary, Alberta, Canada)
Control valgus moment
Front step-downs
Lateral step-ups with Thera-Band (The Hygienic Corporation, Akron, OH)
Tilt board balance throws
Control hyperextension
Plyometric leg press
Plyometric leg press with 4 corners
Plyometric jumps
1 box
2 boxes
4 boxes
2 boxes rotation
2 boxes with catches
Bounding drills
Forward and backward step-over drills
High-speed training, especially hamstrings
Isokinetics
Backward lunging
Shuttle
Lateral lunges (fast jumps)
Resistance tubing for hamstring
Backward running
Neuromuscular reaction
Squats on tilt board
Balance beam with cords
Dip walk with cords
Balance throws
Balance throws perturbations
Lateral lunges with perturbations onto tilt board
Less-developed thigh musculature
Knee-extensor and -flexor strengthening exercises
Squats
Leg press
Wall squats
Bicycling
Poorer muscular endurance
Stair climbing
Bicycling
Weight training (low weights, high repetitions)
Cardiovascular training
Balance drills for longer durations

struction (Tables 2 and 4). These factors take into consideration the unique anatomical and neuromuscular characteristics of the female athlete. We have developed rehabilitation considerations and specific exercises and neuromuscular drills based on each of these 8 characteristics. We will briefly discuss and illustrate these rehabilitation considerations.

Dynamic Control of the Valgus Moment

First, an anatomical characteristic unique to the female athlete is the wider pelvis and increased genu valgum compared with the male athlete. The rehabilitation goal is dynamic control of the valgus moment at the knee joint. We have observed that valgus stress at the knee joint combined with femoral external rotation is a common mechanism of noncontact ACL injuries in the female athlete, especially when landing after a jump (Figure 8). Thus, through specific neuromuscular training drills, the athlete must learn to dynamically control this type of valgus moment. Markolf et al[64] have shown that muscular contraction can decrease both varus and valgus laxity of the knee 3-fold. Specific neuromuscular control drills designed to dynamically control valgus and varus moments at the knee joint include front step-downs, lateral step-ups with resistance, and balance on a tilt board while performing a throw. While performing the front step-down, the athlete is instructed to control the knee to prevent it from going into a valgus position (Figure 9). Lateral step-ups can be performed with a resistance band placed around the knee, forcing the knee into a valgus moment and requiring the athlete to resist that movement (Figure 10). An additional drill to control the valgus moment at the knee is performed with the athlete standing on a tilt board, maintaining a fixed posture, while performing a throw and catch with a ball (Figure 11).

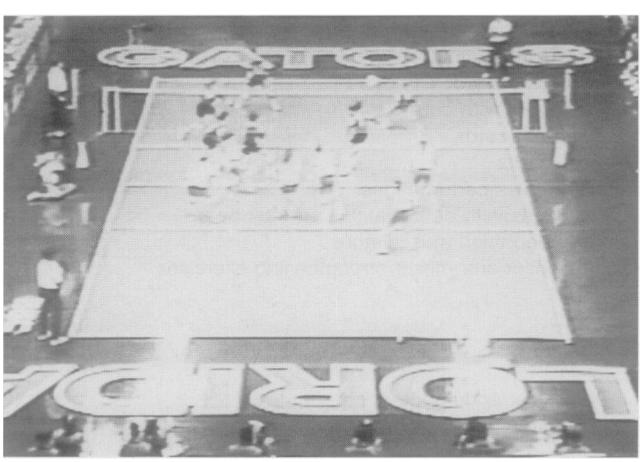

Figure 8. As this female volleyball player (near court, second from left) lands, her knee joint is stressed into a valgus moment as her femur externally rotates. In addition, her body weight is moving backward and laterally. She sustained a complete ACL rupture and an incomplete medial collateral ligament sprain.

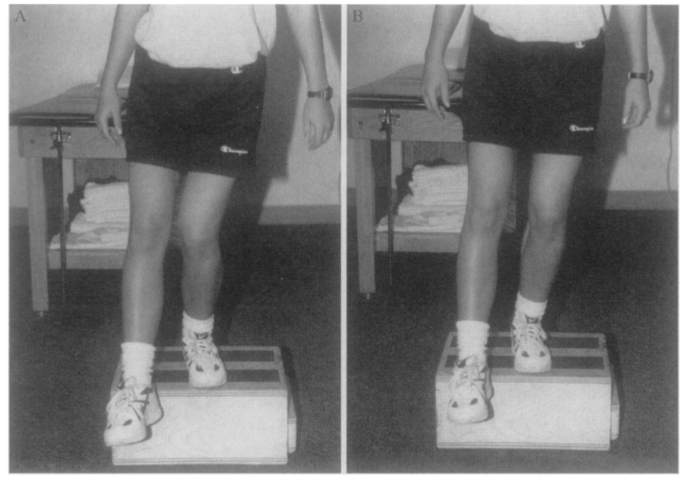

Figure 9. The front step-down exercise. A, This patient allows her knee to move into a valgus moment; this is incorrect or improper movement pattern. B, This patient maintains a proper knee position during the exercise; this knee is facing directly forward.

Muscular Coactivation for Dynamic Stabilization

Next, as discussed previously, the female athlete recruits the quadriceps muscle to stabilize the knee joint instead of the more efficient hamstring muscle group. Therefore, the rehabilitation goal is to train the athlete to use the coactivation pattern of the quadriceps and hamstrings to stabilize the knee joint. Barratta et al[65] noted the increased risk of ligamentous injury in athletes with quadriceps to hamstring muscle strength imbalances and reduced hamstring-quadriceps muscle contraction patterns. They observed an increased coactivation of

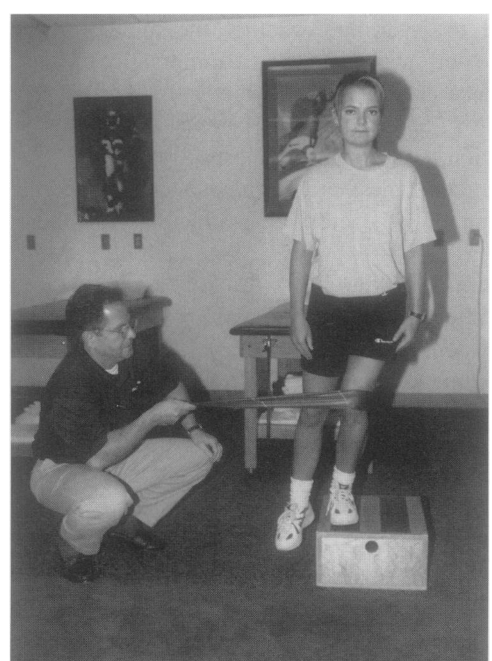

Figure 10. A lateral step-up exercise is performed with resistance tubing applied around the knee to provide resistance in an abducted movement.

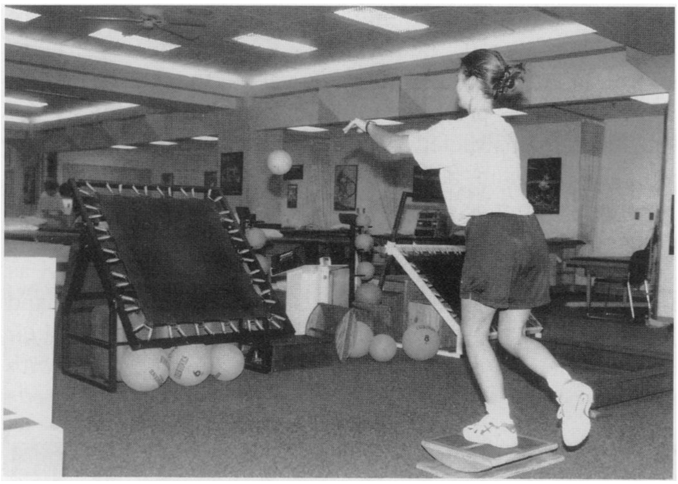

Figure 11. Tilt board balance during ball throws and catches. The tilt board is placed in a position to rock in an anterior-posterior direction.

hamstring muscles in athletes after muscle-training exercises. We use various specific exercises such as lateral lunges, vertical squats with stabilization, and balance drills with biofeedback applied to hamstring muscles to encourage activation. The lateral lunge is performed with a resistance cord applied to the athlete's waist with a belt. As the athletes lunge laterally, they are instructed to land with the knees flexed to approximately 25° to 30°. Having been trained to land with flexed knees, athletes learn to cocontract the quadriceps and hamstring muscles. We refer to this position as the "position of stability." Additionally, by encouraging knee flexion to 30°, quadriceps muscle activation is enhanced. Perry et al[66] reported the EMG activity of quadriceps muscles during exercise: 15° of flexion resulted in 15% maximum voluntary isometric contraction of the quadriceps, whereas, at 30°, the quadriceps EMG activity increased to 51%. We use a functional progression for the lateral lunges: straight-plane lateral lunges, multiple-plane lateral lunges (3 directions), lateral lunges with rotation, lateral lunges onto foam, lateral lunges with rotation and ball catches, and finally, lateral jump lunges (Figure 12). Another drill performed to enhance cocontraction and hamstring activation involves squats performed on an unstable platform (Figure 13). The athlete is instructed to perform the squat to 25° to 30° and to dynamically stabilize the platform to prevent platform movement. Wilk et al[51] have shown that vertical squats to 30° produce the greatest hamstrings-quadriceps muscle coactivation. In addition, once the athlete has mastered this drill, perturbations can be introduced to increase the challenge. Lastly, biofeedback applied to the hamstrings or gastrocnemius muscles, or both, during balance drills, such as balancing on a tilt board while catching and throwing (Figure 14), can also train the athlete to activate the hamstring muscles to stabilize the knee joint.

Muscular Training for Fast Reaction Times

The third factor to consider in the rehabilitation program is that females generate muscular force more slowly than males; therefore, we must train the female at fast speeds for quicker reaction times. This need is especially important for the stabilizing muscles of the knee joint, the hamstrings, and the

Figure 12. Lateral jump lunges. The patient is instructed to land with the knee flexed to 25° to 30°.

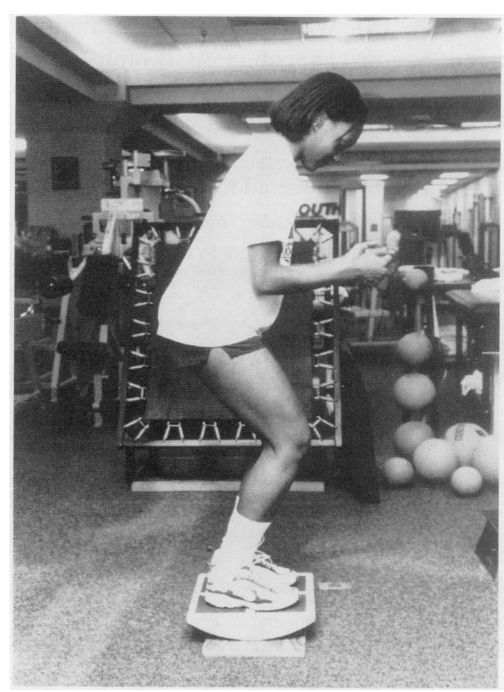

Figure 13. Vertical squats performed on a tilt board. The tilt board is positioned to rock in an anterior-posterior direction.

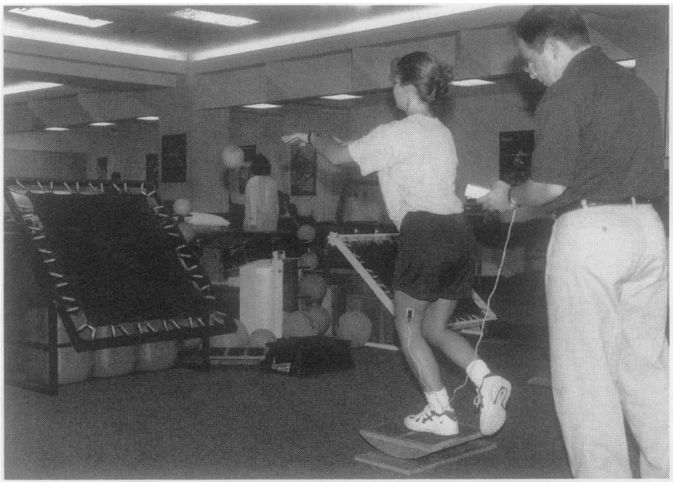

Figure 14. Vertical squats performed on a tilt board with biofeedback applied to the hamstring muscle group. Biofeedback is used to monitor and stimulate hamstring activity.

gastrocnemius. Specific rehabilitation drills performed to promote high-speed hamstring contractions are high-speed isokinetics (Biodex) (180° to 450°/s), backward running (maintaining a flexed-knee posture), high-speed knee flexions with a resistance cord, high-speed lateral jumping lunges, and alternating-leg rapid step-ups, and side shuffles.

Learn To Control the Hip and Pelvis

The next factor to consider is the loss of hip and trunk control when the athlete lands after a jump. A frequently seen mechanism is hip adduction with internal rotation and knee valgus, with the body falling laterally over the lower extremity (Figure 15). We refer to this as "the point of no return," a common mechanism of ACL injury in the female athlete. The goal of the rehabilitation training drills in this instance is to teach the athlete to control the hip and the trunk. By controlling the hip and trunk, we believe the athlete may be able to reduce adduction and abduction of the

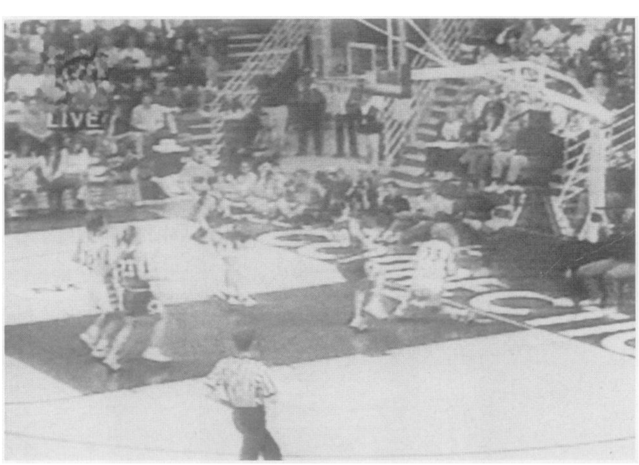

Figure 15. Mechanism of ACL injury in the female athlete involved in jumping sports.

knee joint. Specific training drills to fulfill this goal are lateral step-overs,[67] balance beam drills, neuromuscular control lateral step-ups, and squats on foam. The lateral step-over drill is performed over cones or cups (Figure 16). The athlete is instructed to raise the thighs as high as the hip while flexing and laterally stepping over the cones. The functional progression we use clinically is to have the athlete perform the first set at a comfortable speed, then the second as fast as possible, and the third as slowly as possible. Incorporating a skill, such as ball catches and throws, during the step-over enhances the neuromuscular control. The step-overs can be progressed to step-overs with

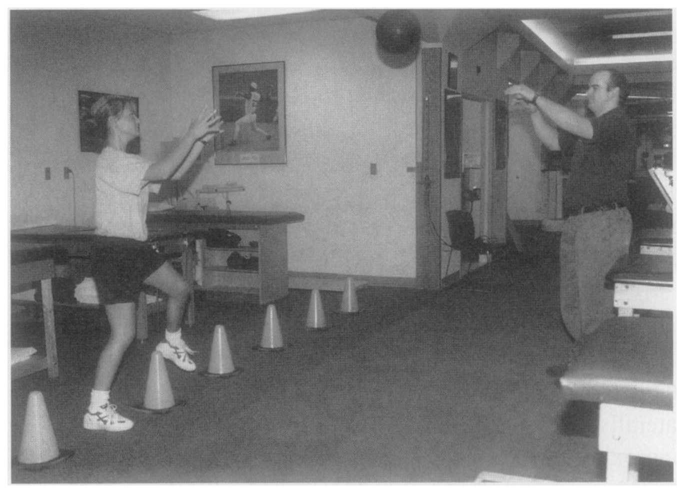

Figure 16. The lateral step-over drill. This drill is designed to enhance hip musculature control and knee joint stability. The athlete is required to perform a skill activity (catching and throwing a ball) while performing the lateral step-over.

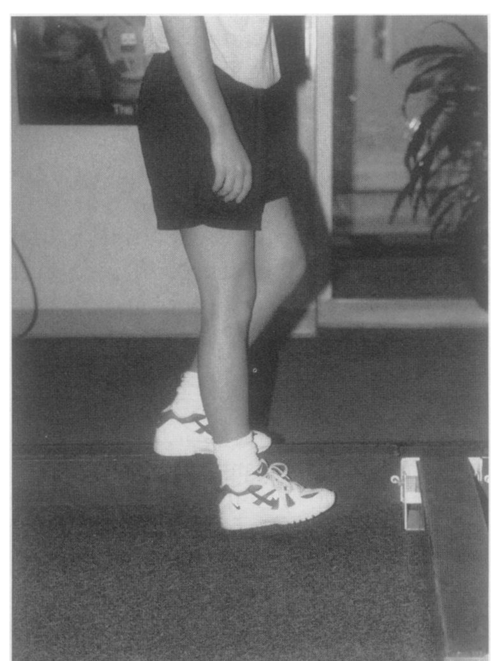

Figure 17. The dip-walk exercise performed on a balance beam.

rotation and step-overs onto foam. Another hip and trunk neuromuscular control drill is the dip walk (Figure 17). The dip walk is performed on a balance beam, and the athlete executes a lateral step-up and then forward steps the entire length of the beam as slowly as possible. A traditional lateral step-up can be performed with the foot on a piece of circular foam to enhance neuromuscular control (Figure 18). Lastly, the vertical squat or front lunge can be performed onto foam to stimulate and challenge the neuromuscular system and the hip and knee musculature.

Hip Joint and Trunk Stabilization Enhances Knee Stability

The female athlete generally exhibits a less-developed thigh musculature compared with the male athlete.[68] Thus, the female athlete must incorporate the hip musculature to assist in dynamic stabilization of the knee joint. The exercise drills to enhance hip musculature control include lateral step-overs, lateral lunges, dip walk, and balance beam drills.

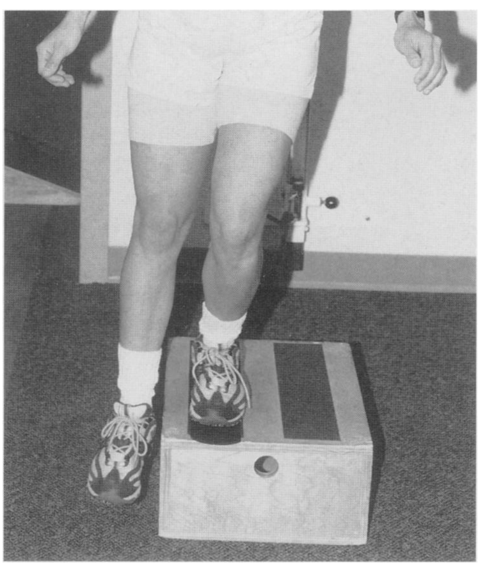

Figure 18. The lateral step-up exercise performed on a proprioceptive device.

Train Athlete to Control Knee Extension

The sixth unique characteristic is that females exhibit greater genu recurvatum and knee laxity compared with male athletes. The rehabilitation goal is to train the athlete to control knee extension and to learn to maintain the "position of stability." The position of stability is knee flexion between 25° and 30°, with coactivation of the quadriceps, the hamstrings, and the gastrocnemius muscle groups. The specific drills we use to train the athlete to control knee extension are plyometric jumping, bounding drills, and forward and backward step-over drills. The plyometric jumping drills are initiated on a leg press first, then progressed to the flat ground or onto boxes. We usually begin the plyometric jumping with 2-leg jumps progressing to single-leg jumps. The athlete is instructed to land with the knee flexed (Figure 19). If the athlete lands with the knee in extension, the drill is stopped, and the athlete is instructed in proper landing technique. By landing in full knee extension, the stabilizing muscles are less efficient, and the athlete is at risk for an ACL injury. Jump training programs have been advocated to increase performance and decrease injury risk in competitive athletes in jumping sports. Several high school, collegiate, and Olympic sports teams have developed jump training programs.[69–71]

Hewitt et al[24] reported that male athletes demonstrate 3-fold greater knee-extension movements (hamstring muscle activity) than female athlete when landing from a vertical jump. Additionally, the investigators noted a 22% decrease in peak landing forces in female athletes after an 8-week jump-training program. When performing plyometric training, we strongly encourage the athlete to work on landing techniques. Athletes are instructed to land lightly and softly. The athlete should flex the knees to increase shock absorption when landing. Several authors have stated that a high percentage of ACL injuries

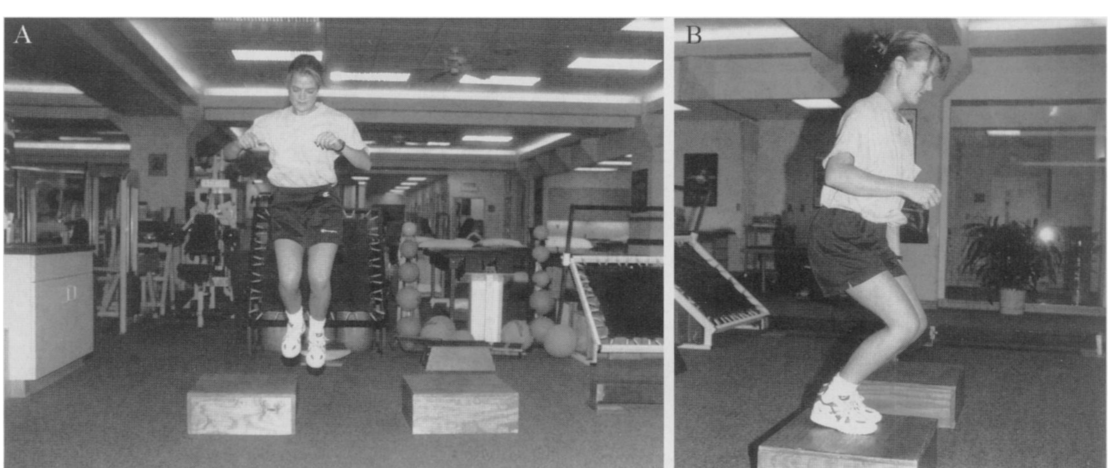

Figure 19. A and B, Plyometric jumping drills. B, Note the patient's knee-flexion position.

occur in jumping sports upon landing.[72,73] Thus, when performing a plyometric jump training program, proper technique and execution are crucial. Other drills to enhance knee extension control are bounding drills and forward and backward step-over drills. The rehabilitation specialist should carefully analyze the jumping and landing technique for each athlete when performing these drills.

Enhance Neuromuscular Control of the Lower Extremity

The next unique characteristic for the female athlete, and one of the most important, is that the female athlete exhibits less-effective dynamic stabilization patterns. Some authors[68,74,75] believe the protective mechanisms may not have been developed during the early developmental years in the female athlete compared with the male athlete because of fewer opportunities for the young female athlete. The goals of the training drills are to enhance neuromuscular control of the entire lower extremity and to improve the protective reflexes. The specific rehabilitation drills we use are designed to enhance neuromuscular reaction with perturbation training. The specific drills we employ are squats on a tilt board, walking and side shuffles on a balance beam with resistance cords fixed to the athlete's waist (Figure 20), and single-leg balancing on a tilt board in the stability position while throwing a ball (Figure 21). Specific perturbation training is performed with the athlete balancing on a tilt board and throwing a ball

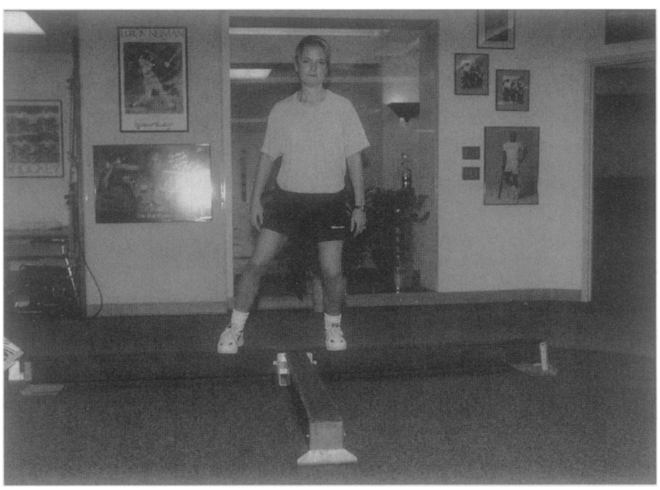

Figure 20. Side shuttle performed on a balance beam. To challenge the dynamic stabilizers, a resistance cord may be applied to the waist.

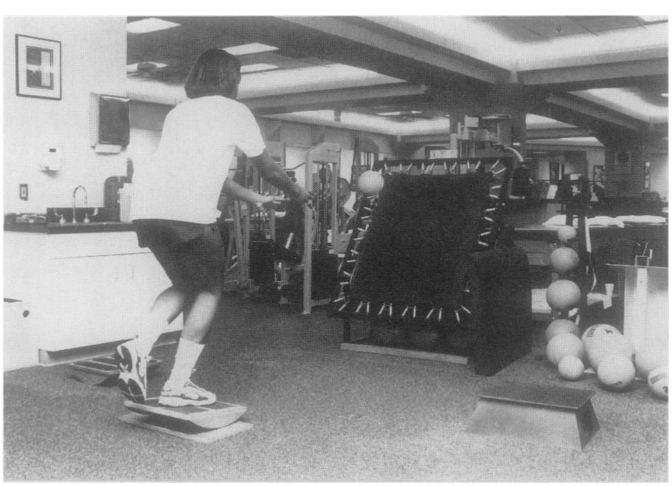

Figure 21. Single-leg stance (in a flexed position to 30°) performed on a tilt board while throwing and catching a plyoball. The key aspect of this drill is maintaining the flexed-knee posture.

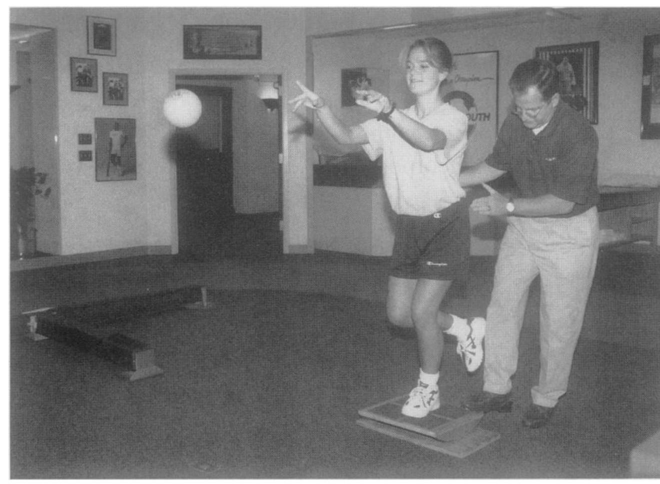

Figure 22. Single-leg stance on the tilt board while performing ball throws. The rehabilitation specialist performs a perturbation by striking the tilt board with the foot to cause a postural disturbance.

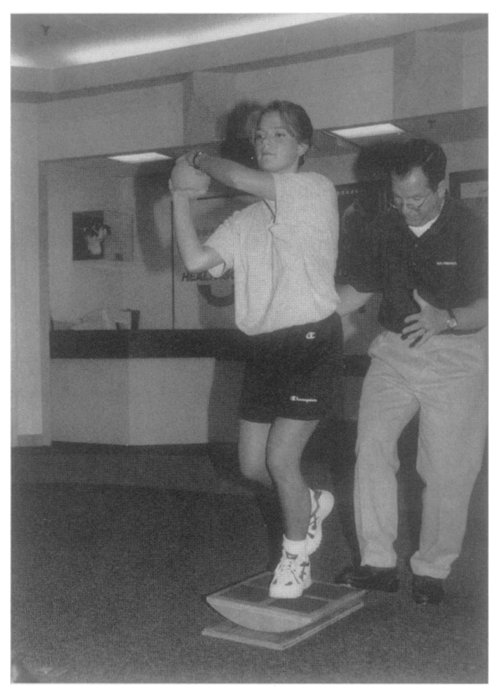

Figure 23. Single-leg stance on the tilt board while performing ball throws with perturbations. The side-to-side throw is illustrated with perturbations at the hip and on the tilt board.

while the clinician rocks the tilt board, creating a perturbation. The athlete must react and restabilize the platform as quickly as possible (Figures 22 and 23). We believe this is one of the best drills to train and enhance muscular reaction and neuromuscular control.

Train to Enhance Muscular Endurance

The eighth and final unique characteristic is the fact that female athletes have been shown to exhibit poorer muscular endurance ratios than male athletes. Once muscular fatigue occurs, proprioception and neuromuscular control diminish significantly.[76–78] Lattanzio et al[77] have demonstrated a significant decline in proprioception (joint angle reproduction) function after exercise bouts that resulted in muscular fatigue. Therefore, the female athlete must perform endurance training throughout the rehabilitation program. Exercises such as stair climbing and bicycling performed for long durations are preferred. Weight training using lower weights and higher repetitions should also be implemented. Specific exercises, such as the lateral step-up, front step-down, and front lunge, can be performed using higher repetitions and lower weights to promote muscular endurance. Exercises including knee extensions, leg presses, and vertical squats can be performed with lower weights and higher repetitions to enhance muscular strength. Additionally, we frequently recommend neuromuscular control drills, such as perturbations, at the end of a treatment session, after cardiovascular training. This type of training is performed to challenge the neuromuscular control of the knee joint complex when the dynamic stabilizers have been adequately fatigued.

SUMMARY

The female athlete appears to be more susceptible to ACL injuries than the male athlete. There are many reasons for this increased injury rate. Anatomical differences are obvious, but the subtle neuromuscular differences may be more important when rehabilitating an athlete after ACL surgery. Because of these differences, we have developed 8 special considerations for the female athlete. We recommend that these 8 considerations be taken into account when rehabilitating a female athlete. The goal is to enhance the outcome of the rehabilitation program, but also to provide a preventive program to reduce the incidence of noncontact ACL injuries in the female athlete. We have used the specific rehabilitation drills discussed in this article with early clinical success. We strongly encourage research and critical analyses of these techniques to assist in the development of a program to rehabilitate the female athlete successfully after ACL surgery, but perhaps more critically, to assist in a preventive program to reduce the incidence of noncontact ACL injuries.

REFERENCES

1. Malone TR, Hardaker WT, Garrett WE, Feagin JA, Bassett FH. Relationship to sex to anterior cruciate ligament injuries in intercollegiate basketball players. *J South Orthop Assoc.* 1993;2:36–39.
2. Pearl AJ. *The Female Athlete.* Champaign, IL: Human Kinetics Publishing; 1993:302–303.
3. Lindenfeld TN, Schmitt DJ, Hendy MD, Mangine RE, Noyes FR. Incidence of injury in indoor soccer. *Am J Sports Med.* 1994;22:364–371.
4. Ferretti A, Papandrea P, Conteduca F, Mariani PP. Knee ligament injuries in volleyball players. *Am J Sports Med.* 1992;20:203–207.
5. Chandy TA, Grana WA. Secondary school athlete injury in boys and girls: a three-year comparison. *Physician Sportsmed.* 1985;13(3):106–111.
6. Komi PV, Karlsson J. Skeletal muscle fibre types, enzyme activities and physical performance in young males and females. *Acta Physiol Scand.* 1978;103:210–218.
7. Hakkinen K. Force production characteristics of leg extensor, trunk flexor and extensor muscles in male and female basketball players. *J Sports Med Phys Fitness.* 1991;31:325–331.
8. Hakkinen K. Maximal force, explosive strength and speed in female volleyball and basketball players. *J Hum Mov Stud.* 1989;16:291–303.
9. Weiss AD. The locus of reaction time changes with set, motivation and age. *J Gerontol.* 1965;20:60–64.
10. Komi PV, Karlsson J. Physical performance, skeletal muscle enzyme activities, and fibre types in monozygous and dizygous twins of both sexes. *Acta Physiol Scand.* 1979;462(suppl):1–28.
11. Bell DG, Jacobs I. Electro-mechanical response times and rate of force development in males and females. *Med Sci Sports Exerc.* 1986;18:31–36.
12. Viitasalo JT, Komi PV. Interrelationships between electromyographic, mechanical, muscle structure and reflex time measurements in man. *Acta Physiol Scand.* 1981;111:97–103.
13. Winter EM, Brookes FB. Electromechanical response times and muscle elasticity in men and women. *Eur J Appl Physiol.* 1991;63:124–128.
14. Komi PV. Physiological and biomechanical correlates of muscle function: effects of muscle structure and stretch-shortening cycle on force and speed. *Exerc Sports Sci Rev.* 1984;12:81–121.
15. Beard DJ, Dodd CAF, Trundle HR, Simpson AH. Proprioception enhancement for anterior cruciate ligament deficiency. *J Bone Joint Surg Br.* 1994;76:654–659.
16. Hakkinen K, Pakarinen A, Kallinen M. Neuromuscular adaptations and serum hormones in women during short-term intensive strength training. *Eur J Appl Physiol.* 1992;64:106–111.
17. Yasuda K, Erickson, AR, Johnson RJ, et al. Dynamic strain behavior in the medial collateral and anterior cruciate ligaments during lateral impact loading. *Trans Orthop Res Soc.* 1992;17:127.
18. Zhou S, Carey MF, Snow RJ, Lawson DL, Morrison WE. Effects of muscle fatigue and temperature on electromechanical delay. *Electromyogr Clin Neurophysiol.* 1998;38:67–73.
19. Vos EJ, Harlaar J, van Ingen-Schenau GJ. Electromechanical delay during knee extensor contractions. *Med Sci Sports Exerc.* 1991;23:1187–1193.
20. Hakkinen K, Komi PV. Electromyographic and mechanical characteristics of human skeletal muscle during fatigue under voluntary and reflex conditions. *Electroencephalogr Clin Neurophysiol.* 1983;55:436–444.
21. Huston LJ, Wojtys EM. Neuromuscular performance characteristics in elite female athletes. *Am J Sports Med.* 1996;24:427–436.
22. Renstrom P, Arms SW, Stanwyck TS, Johnson RJ, Pope MH. Strain within the anterior cruciate ligament during hamstring and quadriceps activity. *Am J Sports Med.* 1986;14:83–87.
23. Beynnon BD, Fleming BC, Johnson RJ, Nichols CE, Renstrom PA, Pope MH. Anterior cruciate ligament strain behavior during rehabilitation exercises in vivo. *Am J Sports Med.* 1995;23:24–34.
24. Hewitt TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes: decreased impact forces and increased hamstring torques. *Am J Sports Med.* 1996;24:765–773.
25. Huston LJ, Wojtys EM. Neuromuscular performance characteristics in elite female athletes. *Am J Sports Med.* 1996;24:427–436.
26. Wojtys EM, Huston LJ, Ashton-Miller J. Active knee stiffness differs between young men and women. Presented at: 24th American Orthopaedic Society for Sports Medicine Meeting; Vancouver, BC; July 15, 1998.
27. Wilk KE, Andrews JR. Current concepts in the treatment of anterior

cruciate ligament disruptions. *J Orthop Sports Phys Ther.* 1992;15:279–293.
28. Wilk KE, Andrews JR, Clancy WG. Quadriceps muscular strength after removal of the central third patellar tendon for contralateral ACL reconstruction surgery: a case study. *J Orthop Sports Phys Ther.* 1993;18:692–697.
29. Hardin JA, Voight ML, Blackburn TA, Canner GC, Soffer SR. The effects of "decelerated" rehabilitation following ACL reconstruction on a hyperelastic female adolescent: a case study. *J Orthop Sports Phys Ther.* 1997;26:29–34.
30. Shelbourne KD, Nitz P. Accelerated rehabilitation after anterior cruciate ligament reconstruction. *Am J Sports Med.* 1990;18:292–299.
31. Rubenstein RA, Shelbourne KD. Preventing complication and minimizing morbidity after autogenous bone-patellar tendon-bone anterior cruciate ligament reconstruction. *Op Tech Sports Med.* 1993;1:72–78.
32. Ciccotti MG, Kerlan RK, Perry J, Pink M. An electromyographic analysis of the knee during functional activities, II: the anterior cruciate ligament-deficient and -reconstructed profiles. *Am J Sports Med.* 1994;22:651–658.
33. Lephart SM. EMG profile of the functional ACL deficient knee patient during dynamic activities. Presented at: American Orthopaedic Society for Sports Medicine; San Francisco, CA; February 13, 1997.
34. Lephart SM, Pincivero JL, Giraldo JL, Fu FH. The role of proprioception in the management and rehabilitation of athletic injuries. *Am J Sports Med.* 1997;25:130–137.
35. Lephart SM, Kocher MS, Fu FH, et al. Proprioception following ACL reconstruction. *J Sport Rehabil.* 1992;1:188–196.
36. Swanik BC, Lephart SM, Giannantonio FP, et al. Reestablishing proprioception and neuromuscular control in the ACL injured athlete. *J Sport Rehabil.* 1997;6:182–206.
37. Shelbourne KD, Wilckens JH, Mollabaashy A, DeCarlo MS. Arthrofibrosis in acute anterior cruciate ligament reconstruction: the effect of timing of reconstruction and rehabilitation. *Am J Sports Med.* 1991;9:332–336.
38. Shelbourne KD, Foulk AD. Timing of surgery in acute anterior cruciate ligament tears on the return of quadriceps muscle strength after reconstruction using an autogenous patellar tendon graft. *Am J Sports Med.* 1995;23:686–689.
39. Rubenstein RA Jr, Shelbourne KD, Van Meter CD, McCarroll JR, Rettig AC, Gloyeske RL. Effect on knee stability if full hyperextension is restored immediately after autogenous bone-patellar tendon-bone anterior cruciate ligament reconstruction. *Am J Sports Med.* 1995;23:365–368.
40. Herzog W, Read LJ. Lines of action and moment arms of the major force-carrying structures crossing the human knee joint. *J Anat.* 1993;182(pt 2):213–230.
41. Zheng N, Fleisig GS, Escamilla RF, Barrentine SW. An analytical model of the knee for estimation of internal forces during exercise. *J Biomech.* 1998;31:963–967.
42. Delitto A, Rose SJ, McKowen JM, Lehman RC, Thomas JA, Shively PA. Electrical stimulation versus voluntary exercise in strengthening thigh musculature after anterior cruciate ligament surgery. *Phys Ther.* 1988;68:660–663.
43. Eriksson E, Haggmark T. Comparison of isometric muscle training and electrical stimulation supplementing isometric muscle training in the recovery after major knee ligament surgery: a preliminary report. *Am J Sports Med.* 1979;7:169–171.
44. Wigerstadt-Lossing I, Grimby G, Jonsson T, Morelli B, Peterson L, Renstrom P. Effects of electrical muscle stimulation combined with voluntary contractions after knee ligament surgery. *Med Sci Sports Exerc.* 1988;20:93–98.
45. Morrissey MC, Brewster CE, Shields CL Jr, Brown M. The effects of electrical stimulation on the quadriceps during postoperative knee immobilization. *Am J Sports Med.* 1985;13:40–44.
46. Snyder-Mackler L, Delitto A, Bailey SL, Stralka SW. Strength of the quadriceps femoris muscle and functional recovery after reconstruction of the anterior cruciate ligament: a prospective, randomized clinical trial of electrical stimulation. *J Bone Joint Surg Am.* 1995;77:1166–1173.
47. Grood ES, Suntay WJ, Noyes FR, Butler DL. Biomechanics of the knee extension exercise: effect of cutting the anterior cruciate ligament. *J Bone Joint Surg Am.* 1984;66:725–734.
48. Lindahl OL, Movin A. The mechanics of extension of the knee joint. *Acta Orthop Scand.* 1967;38:226–234.
49. Beynnon B, Howe JG, Pope MH, Johnson RJ, Fleming BC. The measurement of anterior cruciate strain in vivo. *Int Orthop.* 1992;16:1–12.
50. Arms SW, Pope MH, Johnson RJ, Fischer RA, Arvidsson L, Eriksson E. The biomechanics of anterior cruciate rehabilitation and reconstruction. *Am J Sports Med.* 1984;12:8–18.
51. Wilk KE, Escamilla RF, Fleisig GS, Barrentine SW, Andrews JR, Boyd ML. A comparison of tibiofemoral joint forces and electromyographic activity during open and closed kinetic chain exercises. *Am J Sports Med.* 1996;24:518–527.
52. Wilk KE, Zheng N, Fleisig GS, et al. Kinetic chain exercise: implications for the ACL patient. *J Sport Rehabil.* 1997;6:125–143.
53. Jenkins WL, Munns SW, Jayaraman G, Werzberger KL, Neely K. A measurement of anterior tibial displacement in the closed and open kinetic chain. *J Orthop Sports Phys Ther.* 1997;25:49–56.
54. Beynnon BD, Johnson RJ, Fleming BC, Stankewich CJ, Renstrom PA, Nichols CE. The strain behavior of the ACL during squatting and active flexion-extension: a comparison of an open and a closed kinetic chain exercise. *Am J Sports Med.* 1997;25:823–829.
55. Wilk KE, Andrews JR. The effects of pad placement and angular velocity on tibial displacement during isokinetic exercise. *J Orthop Sports Phys Ther.* 1993;17:24–30.
56. Arrigo CA, Fuller CS, Wilk KE. Aquatic rehabilitation following ACL-PTG reconstruction. *Sports Med Update.* 1993;22–27.
57. Fuller CS. Aquatic rehabilitation. In: *Physical Rehabilitation of the Injured Athlete.* Andrews JR, Harrelson GL, Wilk KE, eds. Philadelphia, PA: WB Saunders; 1998:615–631.
58. Wilk KE, Andrews JR, Clancy WG, et al. Anterior cruciate ligament reconstruction rehabilitation— the results of aggressive rehabilitation: a 12-week follow-up in 212 cases. *Isokin Exerc Sci.* 1992;2:82–91.
59. Perrin DH. *Isokinetic Exercise and Assessment.* Champaign, IL: Human Kinetics Publishers; 1993.
60. Perrin DH. Open chain isokinetic assessment and exercise of the knee. *J Sport Rehabil.* 1993;3:245–254.
61. Wilk KE, Romaniello WT, Soscia SM, Arrigo CA, Andrews JR. The relationship between subjective knee scores, isokinetic testing, and functional testing in the ACL-reconstructed knee. *J Orthop Sports Phys Ther.* 1994;20:60–73.
62. Noyes FR, Barber SD, Mangine RE. Abnormal lower limb symmetry determined by function hop test after anterior cruciate ligament rupture. *Am J Sports Med.* 1991;19:513–518.
63. Barber SD, Noyes FR, Mangine RE, McCloskey JW, Hartman W. Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. *Clin Orthop.* 1990;255:204–214.
64. Markolf KL, Graff-Radford A, Amstutz HC. In vivo knee stability: a quantitative assessment using an instrumented clinical testing apparatus. *J Bone Joint Surg Am.* 1978;60:664–674.
65. Barratta R, Solomonow M, Zhou BH, Letson D, Chuinard R, D'Ambrosia R. Muscular coactivation: the role of the antagonist musculature in maintaining knee stability. *Am J Sports Med.* 1988;16:113–122.
66. Perry J, Antonelli D, Ford W. Analysis of knee joint forces during flexed-knee stance. *J Bone Joint Surg Am.* 1975;57:961–967.
67. Mangine RE, Noyes FR. Rehabilitation of the allograft reconstruction. *J Orthop Sports Phys Ther.* 1992;15:294–302.
68. Wojtys EM. ACL injuries in the female athlete: special considerations. Presented at: Cincinnati Sports Medicine Course in Advances of the Knee and Shoulder; Hilton Head Island, SC; May 28, 1998.
69. Dunnam LO, Hunter GR, Williams BP, et al. Comprehensive evaluation of the University of Alabama at Birmingham's women's volleyball training program. *Natl Strength Conditioning Assoc J.* 1988;10:50–52.

70. Marsit JL, Kraemer WJ. Beginning off-season workout for high school volleyball. *Natl Strength Conditioning Assoc J.* 1992;14:62–66.
71. McGown CM, Corlee RK, Sucec AA, et al. Gold medal volleyball: the training program and physiological profile of the 1984 Olympic champions. *Res Q Exerc Sport.* 1990;61:196–200.
72. Dufek JS, Bates BT. Biomechanical factors associated with injury during landing in jump sports. *Sports Med.* 1991;12:326–327.
73. Gerberich SG, Luhmann S, Finke C, Priest JD, Beard BJ. Analysis of severe injuries associated with volleyball activities. *Physician Sportsmed.* 1987;15(8):75–79.
74. Ireland ML. Special concerns of the female athlete. In: Fu FH, Stone DA, eds. *Sports Injuries: Mechanisms, Prevention, Treatment.* Philadelphia, PA: Williams & Wilkins; 1994:153–187.
75. Ireland ML, Gaudette M, Crook S. ACL injuries in the female athlete. *J Sport Rehabil.* 1997;6:97–110.
76. Skinner HB, Wyatt MP, Hodgdon JA, Conard DW, Barrack RL. Effect of fatigue on joint position sense of the knee. *J Orthop Res.* 1986;4:112–118.
77. Lattanzio PJ, Petrella RJ, Sproule JR, Fowler PJ. Effects of fatigue on knee proprioception. *Clin J Sports Med.* 1997;7:22–27.
78. Lattanzio PJ, Petrella RJ. Knee proprioception: a review of mechanisms, measurements, and implications of muscular fatigue. *Orthopedics.* 1998; 21:463–470.