[CLINICAL COMMENTARY]

RAFAEL F. ESCAMILLA, PT, PhD, CSCS, FACSM[1] • **TORAN D. MACLEOD,** PT, PhD[2] • **KEVIN E. WILK,** PT, DPT[3]
LONNIE PAULOS, MD[4] • **JAMES R. ANDREWS,** MD[5]

Anterior Cruciate Ligament Strain and Tensile Forces for Weight-Bearing and Non–Weight-Bearing Exercises: A Guide to Exercise Selection

There are an estimated 200 000 injuries related to the anterior cruciate ligament (ACL) annually in the United States, over half of which result in a complete ACL rupture. Consequently, there are approximately 100 000 ACL reconstructions annually.[37] Surgical reconstruction of the ACL, a common orthopaedic knee surgery, is often recommended after an ACL tear and is usually followed by 4 to 9 months of outpatient sports or orthopaedic physical therapy. There is, therefore, a need for the sports and orthopaedic physical therapist to understand the mechanical properties of the ACL, the ACL-reconstructed knee, and how different exercises and technique variations play a role in ACL loading.[6] The reconstructed ACL should be loaded cautiously during the first several postoperative weeks to protect the healing tissue, and the clinician needs to be aware how performing weight-bearing (WB) and non–weight-bearing (NWB) exercises may affect the surgically reconstructed knee.[6] For example, clinicians should understand that NWB exercises generally load the ACL more than WB exercises and that, for both types of exercises, the ACL is loaded to a greater extent between 10° and 50° compared to 50° and 100° of knee flexion.[2-5,12-16,20,23]

SYNOPSIS: There is a growing body of evidence documenting loads applied to the anterior cruciate ligament (ACL) for weight-bearing and non–weight-bearing exercises. ACL loading has been quantified by inverse dynamics techniques that measure anterior shear force at the tibiofemoral joint (net force primarily restrained by the ACL), ACL strain (defined as change in ACL length with respect to original length and expressed as a percentage) measured directly in vivo, and ACL tensile force estimated through mathematical modeling and computer optimization techniques. A review of the biomechanical literature indicates the following: ACL loading is generally greater with non–weight-bearing compared to weight-bearing exercises; with both types of exercises, the ACL is loaded to a greater extent between 10° to 50° of knee flexion (generally peaking between 10° and 30°) compared to 50° to 100° of knee flexion; and loads on the ACL change according to exercise technique (such as trunk position). Squatting with excessive forward movement of the knees beyond the toes and with the heels off the ground tends to increase ACL loading. Squatting and lunging with a forward trunk tilt tend to decrease ACL loading, likely due to increased hamstrings activity. During seated knee extension, ACL force decreases when the resistance pad is positioned more proximal on the anterior aspect of the lower leg, away from the ankle. The evidence reviewed as part of this manuscript provides objective data by which to rank exercises based on loading applied to the ACL. The biggest challenge in exercise selection post–ACL reconstruction is the limited knowledge of the optimal amount of stress that should be applied to the ACL graft as it goes through its initial incorporation and eventual maturation process. Clinicians may utilize this review as a guide to exercise selection and rehabilitation progression for patients post–ACL reconstruction. *J Orthop Sports Phys Ther 2012;42(3):208-220. doi:10.2519/jospt.2012.3768*

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The goal of rehabilitation of patients post–ACL reconstruction is to resolve impairments such as swelling, pain, and lack of range of motion, and to normalize lower extremity muscle strength and dynamic stability without interfering with the healing process of the graft. Understanding how the ACL is loaded during rehabilitation can help clinicians better prescribe training and exercise regimens in a safe manner, enhance and possibly expedite the rehabilitation process, and return the athlete to sport or activity. Therefore, the purpose of this manuscript

[1] Professor, Department of Physical Therapy, California State University, Sacramento, CA. [2] Postdoctoral Scholar, Department of Radiology & Biomedical Imaging, University of California, San Francisco, CA. [3] Associate Clinical Director, Champion Sports Medicine, Birmingham, AL. [4] Orthopaedic Surgeon, Joint Preservation and Sports Injury Clinic, Salt Lake City, Utah. [5] Medical Director, American Sports Medicine Institute, Birmingham, AL; Medical Director, Andrews Institute for Orthopaedics & Sports Medicine, Gulf Breeze, FL. Address correspondence to Dr Rafael Escamilla, California State University, Sacramento, Department of Physical Therapy, 6000 J St, Sacramento, CA 95819-6020. E-mail: rescamil@csus.edu

is to discuss the biomechanical factors related to ACL loading during common WB and NWB exercises performed during ACL rehabilitation. Clinicians may utilize this review as a guide to exercise selection and progression for patients with ACL pathology or reconstruction.

MEASURING ACL LOADING

Butler et al[9] have shown that the ACL provides 86% of the total resistance to an anterior translation of the tibia relative to the femur. As tensile forces produced by the quadriceps and hamstrings can result in anteriorly or posteriorly directed translation forces at the tibiofemoral joint, there is potential for the muscles surrounding the knee to load or unload the ACL. The quadriceps, when contracting, exerts via the patellar tendon an anteriorly directed force on the proximal tibia when the knee is between approximately 0° and 60° of flexion, loading the ACL.[9,25] Conversely, an active quadriceps exerts a posteriorly directed force when the knee is in greater than approximately 60° of flexion, unloading the ACL.[9,25] In contrast, the hamstrings, when contracting, exert a posteriorly directed force on the proximal end of the tibia throughout the full range of knee motion, and especially at higher knee flexion angles, unloading the ACL. Excluding other forces that may also load the ACL (externally applied forces, ground reaction forces, etc), when the anteriorly directed force component of the patellar tendon exceeds the posteriorly directed force from the hamstrings during an exercise or activity, a net anteriorly directed force is applied to the proximal end of the tibia, loading the ACL.[4] Therefore, when performing various exercises and activities, the relative amount of activation of both the quadriceps and hamstrings has the ability to change the load sustained by the ACL.

Both direct in vivo measurements[2-4,18,19,23] and experimental biomechanical models[12-17,44,49-54,61,62] have been used to quantify ACL strain or tensile force during WB and NWB exercises, with both approaches having advantages and disadvantages. It should be emphasized that, with either approach, none of the data from the literature are from individuals with a recent ACL reconstruction, or from individuals who had significant weakness of the knee musculature. Therefore, the results should be interpreted cautiously, as they reflect loading on an intact normal ACL for individuals with no postsurgical edema, pain, range-of-motion limitations, and, most importantly, strength deficits.

The advantage of in vivo studies is that ACL strain is directly measured by using strain sensors attached to the anteromedial bundle of the ACL, and all strain values obtained during various exercises can be referenced to the ACL strain obtained with an instrumented Lachman test performed with 150 N of force. But there are several disadvantages to measuring ACL strain in vivo. It is an invasive procedure that is time consuming, costly, and is performed on patients during or immediately after intra-articular knee surgery not involving the cruciate ligaments (eg, meniscectomy), which limits the types of activities that can be performed. In addition, the exercise techniques used by the patients in these studies were generally not well controlled. For example, there are many variations in the performance of a squat that affect muscle forces and ACL loading, such as using a narrow or wide stance, turning the feet in or out, having a near-vertical trunk position versus a trunk-forward position of 30° to 45° relative to vertical, or controlling the distance that the knees move forward beyond the toes. Other disadvantages of in vivo studies are that they typically use a nonathletic population, generally employ only body weight or light external resistance during the exercises, and usually collect ACL strain data at selected knee flexion angles and only for the anteromedial bundle of the ACL. Therefore, the ability to generalize the results of ACL strain measurements made in vivo to the active athletic population, which comprises the majority of individuals who sustain ACL injuries and who often train with moderate to heavy external resistance over a large knee range of motion, is limited. In vivo data should, therefore, be interpreted cautiously.

Experimental biomechanical knee models[7-12,20-28] have several advantages. They allow a wide range of exercises with a wide range of external resistance and knee ranges of motion to be studied, they are inexpensive and noninvasive, and the estimated loads are better generalized to the active athletic population, because variables related to how the exercises were performed are often better controlled.

The obvious disadvantage of experimental biomechanical knee models is that ACL loading is not measured directly, therefore, the models only provide an estimate. However, if the same experimental model is used for all exercises, a good relative comparison of ACL loads resulting from these exercises can be obtained. Another limitation in using experimental biomechanical knee models is that most are limited to sagittal plane motion, which may be reasonable because squatting, lunging, and similar exercises are performed primarily in the sagittal plane with only minimal transverse plane rotary motions and frontal plane valgus/varus motions. However, these studies may underestimate the ACL loading of individuals with weak hip abductors and external rotators who perform these exercises without good femoral control (ie, with excessive transverse plane rotary motions and frontal plane valgus/varus motions).[45]

Therefore, reported ACL loading values measured directly in vivo and indirectly from experimental models should both be interpreted with caution. However, several in vivo studies[2-4,18,19,23] that directly measured ACL loading during squatting and lunging exercises reported a peak ACL strain of approximately 2.8% to 4% (approximately 100 to 150 N) at knee flexion angles between 0° and 30°, which are values of similar magnitude to the peak ACL forces derived from experimental biomechanical knee models for the same exercises.[12-17,23] Therefore, there is evidence that these 2 methods of measurement provide results that are in general agreement with each other, providing some level of validity to the data and also allowing cautious comparisons of data obtained within and between measurement techniques.

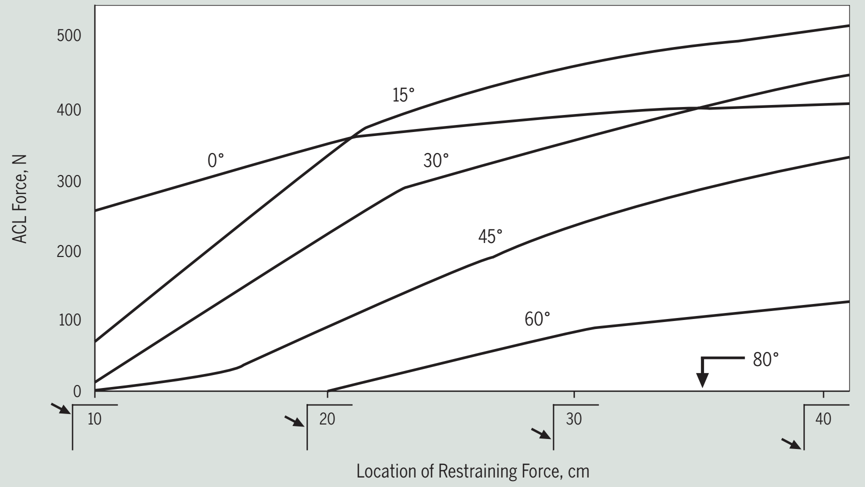

FIGURE. Changes in ACL loading during the seated knee extension exercise with proximal or distal resistance applied on the lower leg. The location of the restraining force is given relative to the distance from the knee joint. Given a constant external knee torque applied to the leg, moving the restraining force closer to the knee joint axis decreases ACL force. Abbreviation: ACL, anterior cruciate ligament. Adapted from Pandy and Shelburne.[43] Reproduced with permission.

ACL GRAFTS

In healthy adults, the ultimate strength of the native ACL is approximately 2000 N.[63] The ACL graft should eventually exhibit similar ultimate strength, although it may vary considerably depending on graft type, donor age, and donor characteristics (eg, autograft versus allograft; patellar tendon versus hamstrings graft, etc).[7,8,22] However, in the first few months post–ACL reconstruction, the ACL graft and the graft fixation sites are potentially significantly weaker than their eventual ultimate strength and may potentially be injured with considerably less force. Immediately after surgery, the graft fixation sites require time for incorporation with the surrounding bone. Also, over time, after an initial weakening and revascularization process, the graft itself must mature by undergoing a process referred to as "ligamentization."[39] As the maturation process occurs over a period of several weeks, the ultimate tensile properties of the graft increase. Unfortunately, it is not known how much force to the graft and its fixations is either too great and potentially injurious or too little and potentially provides inadequate stimulus for the enhancement of healing in the early phases of ACL rehabilitation.

There are several factors related to graft types to consider when selecting an exercise progression, the 2 most important of which are the type of graft fixation and the origin of the graft (allograft versus autograft). First, hamstring grafts require fixation of soft tissue (tendon) to bone, which appears to not be as strong as the bone-to-bone fixation provided by a bone-patellar tendon-bone graft during the first 2 to 3 months following ACL reconstruction. Rodeo et al[47] investigated the biomechanical and histological characteristics of the healing of tendon to bone, and reported that between 8 and 12 weeks postsurgery the mode of failure during tensile loading of the graft changed from pull-out at the tendon-bone interface to failure at the tendon-clamp junction or the midsubstance of the graft. Based on these observations, the authors recommended a period of 8 to 12 weeks for proper incorporation of soft tissue grafts at their insertion sites. These authors also suggested that the strength of the soft tissue-bone interface may increase most during the first 4 weeks after the transplantation of the tendon. Therefore, minimizing tensile loading of the hamstring graft may be especially important during the initial 4 weeks postsurgery. In contrast to the up to 12 weeks needed for the healing of the soft tissue graft to bone, the fixation strength of a bone autograft (eg, patellar tendon graft) to bone has been shown to occur in 6 to 8 weeks.[11,60] Therefore, during the early phases of ACL rehabilitation, the tensile load into the hamstring graft may need to be minimized compared to the tensile load in the bone-patellar tendon-bone graft; although more research is needed to make conclusive statements and determine the exact nature of these differences.

Early after surgery, relative protection of the autograft donor site must also be considered. Therefore, force generation from the hamstrings should be minimized when a hamstring autograft is employed and, conversely, force generation from the quadriceps should be minimized when a bone-patellar tendon-bone autograft is employed.

The second factor that has received significant attention in the literature is whether differences should be made in exercise selection and timing of progression for allografts versus autografts. There is general agreement that strength of the fixations and maturation of the graft itself are delayed with allografts. Patients undergoing an allograft ACL procedure require more time for the graft to be incorporated into the body. The incorporation rates for allografts have been stated to be about twice the length of time compared to an autograft.[32] It is, therefore, recommended that exercise selection be more conservative and return to sport delayed following ACL reconstruction using an allograft.[32] However, again, additional work and outcome data are needed to establish the exact nature of these differences, if warranted.

Clearly, more basic and clinical outcome data are needed to determine the extent to which different graft or fixation types affect exercise selection. Nevertheless, at this time, the clinician should know which graft was used to reconstruct the ACL and should adjust the rehabilitation process based on our current knowledge that suggests a more conservative approach with soft tissue fixations and allografts.

ACL LOADING DURING NWB EXERCISES

Seated Knee Extension

TABLES **1** THROUGH **3** AND THE **FIGURE** present ACL strain, ACL tensile force, and anterior shear force (ACL loading) data for knee extension performed in a seated position. Peak ACL strain (**TABLE 1**) was between 3.2% and 4.4% and occurred between 10° and 30° of knee flexion, while peak ACL tensile force (**TABLE 2**) was approximately 150 to 350 N and also generally occurred between 10° and 30° of knee flexion. Noteworthy is the influence of added resistance on the magnitude of ACL strain when performing knee extension in a seated position, with ACL strain increasing from 2.8% without external resistance to 3.8% when adding only 45 N (10 lb).[5]

Technique variations during performance of seated knee extension exercises can also affect ACL tensile force (**FIGURE**). For example, given a constant external knee torque applied to the lower leg, ACL force decreases when the resistance pad is moved up the anterior aspect of the lower leg, closer to the knee.[43] For a constant external knee torque applied to the lower leg at a 30° knee flexion angle (**FIGURE**), the tensile force on the ACL is approximately 2 times greater when the resistance pad is positioned near the ankle (approximately 400 N) compared to when it is positioned near the middle of the lower leg (approximately 200 N).

TABLE 1

ACL STRAIN AND CORRESPONDING KNEE FLEXION ANGLE FOR NON–WEIGHT-BEARING AND WEIGHT-BEARING EXERCISES

Non–Weight-Bearing Exercises

Author	Exercise	ACL Strain (%)*	Knee Flexion Angle (°)
Beynnon et al[2]	Isometric seated knee extension using a 27-Nm torque as resistance	3.2	30
	Isometric seated knee extension using a 27-Nm torque as resistance	–2.5	90
	150-N (34-lb) Lachman test	3.7	30
	Anterior drawer test, 150 N (34 lb)	1.8	90
Beynnon et al[4]	Dynamic seated knee extension (0°-90° of knee flexion) using a 45-N (10-lb) force as resistance	3.8†	10
	Dynamic seated knee extension (0°-90° of knee flexion) without external resistance	2.8†	10
	Isometric seated knee extension using a 30-Nm torque as resistance	4.4	15
	Isometric seated knee extension using a 30-Nm torque as resistance	2.0	30
	Isometric seated knee extension using a 30-Nm torque as resistance	–0.2	60
	Isometric seated knee extension using a 30-Nm torque as resistance	–0.5	90
Fleming et al[19]	100-N (22.5-lb) Lachman test	3.0	30
	150-N (34-lb) Lachman test	3.5	30

Weight-Bearing Exercises

Author	Exercise	ACL Strain (%)	Knee Flexion Angle (°)
Heijne et al[23]	Single-leg sit-to-stand (without external resistance) tested at knee angles of 30°, 50°, and 70°	2.8†	30
	Step-up (without external resistance) tested at knee angles of 30°, 50°, and 70°	2.5†	30
	Step-down (without external resistance) tested at knee angles of 30°, 50°, and 70°	2.5 to 2.6†	30
	Forward lunge (without external resistance) tested at knee angles of 30°, 50°, and 70°	1.8 to 2.0†	30
Fleming et al[18]	Stair climbing (112 steps per min without external resistance)	2.8†	20
	Stair climbing (80 steps per min without external resistance)	2.7†	11
Fleming et al[19]	Stationary bicycling (175 W, 60 rpm)	2.0†	38
Beynnon et al[5]	Squatting (0°-90° of knee flexion) with or without 136-N (30-lb) resistance	3.6 to 4.0†	10
Kulas et al[35]	Single-leg squatting (0°-65° of knee flexion) without external resistance	3.2†	15 to 25

Abbreviations: ACL, anterior cruciate ligament; rpm, revolutions per minute.
**Negative values imply that there was no ACL strain.*
†Peak ACL strain and its corresponding angle measured for this exercise.

The **FIGURE** also shows how ACL loading decreases progressively as the

TABLE 2 Peak ACL Tensile Force and Corresponding Knee Angle for Non–Weight-Bearing and Weight-Bearing Exercises

Non–Weight-Bearing Exercises

Author	Exercise	Peak ACL Force (N)	Knee Flexion Angle (°)
Toutoungi et al[57]	Isokinetic seated knee extension (0°-90° of knee flexion) at 60°/s	349	35 to 40
	Isokinetic seated knee extension (0°-90° of knee flexion) at 120°/s	325	35 to 40
	Isokinetic seated knee extension (0°-90° of knee flexion) at 180°/s	254	35 to 40
	Isokinetic seated knee flexion (0°-90° of knee flexion) at 60°/s	0	
	Isokinetic seated knee flexion (0°-90° of knee flexion) at 120°/s	0	
	Isokinetic seated knee flexion (0°-90° of knee flexion) at 180°/s	0	
	Isometric seated knee extension	396	35 to 40
	Isometric seated knee flexion	0	
Escamilla et al[12]	Dynamic seated knee extension (0°-90° of knee flexion) using 12 repetitions of maximum resistance*	158	15

Weight-Bearing Exercises

Author	Exercise	Peak ACL Force (N)	Knee Flexion Angle (°)
Escamilla et al[12]	Barbell squat (0°-90° of knee flexion) using 12 repetitions of maximum resistance*	0	
	Leg press (0°-90° of knee flexion) using 12 repetitions of maximum resistance*	0	
Escamilla et al[13]	Barbell squat (0°-90° of knee flexion) with narrow stance using 12 repetitions of maximum resistance*	0	
	Barbell squat (0°-90° of knee flexion) with wide stance using 12 repetitions of maximum resistance*	0	
	Leg press (0°-90° of knee flexion) with narrow stance with high foot placement using 12 repetitions of maximum resistance*	0	
	Leg press (0°-90° of knee flexion) with wide stance with high foot placement using 12 repetitions of maximum resistance*	0	
	Leg press (0°-90° of knee flexion) with narrow stance with low foot placement using 12 repetitions of maximum resistance*	0	
	Leg press (0°-90° of knee flexion) with wide stance with low foot placement using 12 repetitions of maximum resistance*	0	

Table continued on page 213.

knee flexion angle goes from 15° (approximately 500 N with the resistance pad positioned near the ankle and 325 N with the pad near the middle of the lower leg) to 60° (approximately 100 N and 0 N, respectively, based on resistance location), with no ACL loading at knee flexion angles greater than 60°. Nisell et al[41] reported similar findings of less ACL loading with a more proximally positioned resistance pad when performing isokinetic seated knee extension exercises at 30°/s and 180°/s. It can be concluded from these data that when the goal is to minimize ACL loading, this exercise should be performed at higher knee flexion angles (between 50° and 100°), regardless of the location of the resistance pad, and with the resistance pad located closer to the knee if exercising at lesser knee flexion angles.

This approach may also be useful for individuals with an ACL-deficient knee, because in this population performing seated knee extension exercises with the pad positioned nearer the ankle may promote excessive anterior tibial translation, which may result in altered and possibly injurious tibiofemoral joint loading.[33,59] Wilk and Andrews[61] also examined individuals with ACL-deficient knees during the performance of isokinetic exercises, and concluded that tibial translation can be reduced by utilizing a proximally positioned pad and performing the exercises at higher angular velocities (180°/s and 300°/s versus 60°/s).

Seated Knee Flexion

Isometric and isokinetic knee flexion exercises performed in a seated position (knee flexion exercises can also be performed in prone or standing positions) have been shown to produce no loading on the ACL (**TABLE 2**).[57] Toutoungi et al,[57] using a biomechanical model, estimated peak forces applied to the ACL while subjects performed seated isokinetic knee flexion at 60°/s, 180°/s, and 300°/s, and isometric knee flexion exercises at 15°, 30°, 45°, 60°, and 75° of knee flexion. The authors reported that the line of action of the hamstring muscles lay parallel to the tibial plateau at about 90° of knee flexion, so the hamstrings likely unload the ACL during seated resisted knee flexion exercises by producing a posteriorly directed force on the proximal end of the tibia.

Therefore, seated resisted knee flexion exercises are appropriate for rehabilitation post–ACL reconstruction if a bone-patellar tendon-bone graft was used, as these NWB exercises generate very little or no load on the ACL. However, for individuals with a hamstring autograft, knee flexion exercises that stress the hamstrings musculature should be delayed for 6 to 8 weeks to allow healing of the graft harvest site.[10,46] This exercise should be avoided because it applies stress on the semitendinosus muscle and impedes the healing of the semitendinosus to the semimembranosus muscle. Isometric knee flexion exercises typically begin around week 6 postsurgery, with resisted dynamic knee flexion exercises beginning around week 8. During weeks 8 to 12 postoperatively, hamstring exercises for patients with hamstring graft should be performed in the usually pain-free range of motion of approximately 0° to 90°. Thereafter, range of motion and load can be progressed as the patient becomes stronger and the semitendinosus muscle heals to the adjacent semimembranosus muscle.

TABLE 2 Peak ACL Tensile Force and Corresponding Knee Angle for Non-Weight-Bearing and Weight-Bearing Exercises (continued)

Author	Exercise	Peak ACL Force (N)	Knee Flexion Angle (°)
Weight-Bearing Exercises			
Escamilla et al[14]	Wall squat (0°-90° of knee flexion) with heels positioned far from the wall using 12 repetitions of maximum dumbbell resistance*	0	
	Wall squat (0°-90° of knee flexion) with heels positioned close to the wall using 12 repetitions of maximum dumbbell resistance*	0	
	Single-leg squat (0°-90° of knee flexion) using 12 repetitions of maximum dumbbell resistance*	59	30
Escamilla et al[15]	Forward lunge (0°-90° of knee flexion) while taking a long step forward using 12 repetitions of maximum dumbbell resistance*	0	
	Forward lunge (0°-90° of knee flexion) while taking a short step forward using 12 repetitions of maximum dumbbell resistance*	0	
Escamilla et al[16]	Forward lunge (0°-90° of knee flexion) while taking a normal-length step forward using 12 repetitions of maximum dumbbell resistance*	0	
	Side lunge (0°-90° of knee flexion) while taking a normal-length step sideways using 12 repetitions of maximum dumbbell resistance*	0	
	Lunging forward and sideways (0°-90° of knee flexion) while taking a normal-length step using 12 repetitions of maximum dumbbell resistance*	0	
	Lunging forward and sideways (0°-90° of knee flexion) while keeping both feet stationary using 12 repetitions of maximum dumbbell resistance*	0	
Toutoungi et al[57]	Squat (0°-90° of knee flexion) with heel off the ground without external resistance	95	<50
	Squat (0°-90° of knee flexion) with heel on the ground without external resistance	28	<50
	Single-leg squat (0°-90° of knee flexion) without external resistance	142	<50
Kulas et al[35]	Single-leg squat (0°-90° of knee flexion) without external resistance	124	15 to 25
Shelburne et al[54]	Level-ground walking	303	15 to 20
Shelburne and Pandy[50]	Dynamic squat-to-stand	20	25
Pflum et al[44]	Double-foot drop landing stepping off a 60-cm platform	253	33 to 48
Shin et al[55]	Single-leg landing from running to a stop	1294	25 to 30

Abbreviation: ACL, anterior cruciate ligament.
**Heaviest resistance possible that allowed the performance of 12 consecutive repetitions with proper form and technique.*

ACL LOADING DURING WB EXERCISES

Single-Leg and Double-Leg Squats

The standard squat typically results in minimal or no ACL tensile force (**TABLE 2**). The minimal or absence of ACL loading during the squat is, in part, due to the increased hamstrings activity and force generated during squatting. Escamilla et al[12] and Wilk et al[62] reported that peak hamstring activity during the barbell squat was between approximately 40% and 80% of a maximum voluntary isometric contraction, and even at smaller knee flexion angles (eg, 30°) when peak ACL loading potentially occurs, hamstring activity was still approximately 30% to 60% of a maximum voluntary isometric contraction. Moreover, peak hamstrings force during the single-leg squat has been reported to be 200 N or greater.[14,35]

In contrast to when performing knee extension in a seated position, peak ACL strain was not significantly different when squatting with or without 136 N (30 lb) of external resistance.[3,4,23] Therefore, increasing resistance during the squat, at least up to 136 N, does not seem to increase the amount of strain on the ACL. Among several other potential factors, it may be that adding resistance affects muscle recruitment, including recruitment of the hamstrings to a greater extent, which has the potential to unload the ACL.[35,42]

Technique variations of the squat may affect ACL loading. For example, squatting with the heels off the ground, which typically results in greater forward knee movement beyond the toes at greater knee flexion angles, results in over 3 times more ACL loading compared to squatting with the heels on the ground.[57] It has been demonstrated that during a squat, as the knees go forward beyond the toes, the tibial plateaus slope anteriorly, resulting in increased ACL loading.[41] Escamilla et al[12,14] reported significantly greater ACL loading during the single-leg squat, in which the knee moved forward an average ± SD of 10 ± 2 cm beyond the toes, compared to performing a double-leg squat with the knees remaining over the feet.

TABLE 3 Peak Anterior Shear Force (ACL Loading) and Corresponding Knee Angle for Non–Weight-Bearing and Weight-Bearing Exercises

Author	Exercise	Anterior Shear Force (N)	Knee Flexion Angle (°)
Non–Weight-Bearing Exercises			
Wilk and Andrews[61]	Dynamic seated knee extension (0°-90° of knee flexion) using 12 repetitions of maximum resistance*	248	14
Weight-Bearing Exercises			
Author	**Exercise**	**Anterior Shear Force (N)**	**Knee Flexion Angle (°)**
Wilk et al[62]	Barbell squat (0°-90° of knee flexion) using 12 repetitions of maximum resistance*	0	
	Leg press (0°-90° of knee flexion) using 12 repetitions of maximum resistance*	0	
Nagura et al[40]	Full squat (0°-140° of knee flexion) using no external resistance	66	10.9
	Rising from kneeling	111	40.9
	Level-ground walking	355	16.8
	Stair climbing	146	50.8
Pflum et al[44]	Double-foot drop landing	220	33 to 48

Abbreviation: ACL, anterior cruciate ligament.
**Heaviest resistance possible that allowed the performance of 12 consecutive repetitions with proper form and technique.*

Trunk position during the performance of a squat can also affect ACL loading. Compared to a more vertical trunk position, performing a squat with the trunk tilted forward, using hip flexion, has been shown to decrease ACL loading.[35,42] This seems to be consistent with the increase in hamstring muscular activity and force measured while squatting with the trunk tilted forward approximately 30° to 40° (from a vertical position) compared to squatting with a more erect trunk position (10° to 15° of forward tilt).[35,42] Ohkoshi et al[42] reported that there was no ACL loading at any of the knee flexion angles (15°, 30°, 60°, and 90°) tested when maintaining a squat position with the trunk tilted forward, with a forward trunk tilt of 30° or more being optimal for relatively high recruitment of the hamstrings and minimizing ACL loading. Progressively increasing forward trunk tilt during the squat tends to increase hamstrings activity and decrease quadriceps activity, both resulting in ACL unloading at knee angles less than 60°.[42] In addition, Kulas et al[35] demonstrated that performing a single-leg squat with a forward trunk tilt of 35° to 40° compared to 10° to 15° resulted in a 24% decrease in ACL tensile force and a 16% decrease in ACL strain, which was suggested to be primarily due to a 35% increase in hamstrings force. There is, therefore, consistent evidence that trunk position can be used to promote recruitment of the hamstrings and further reduce ACL loading during single- and double-leg squatting.

It should be emphasized that it is not possible to squat down very deeply in a vertical trunk position without the knees moving forward beyond the toes, which likely also causes the heels to raise off the floor. These 2 factors, as discussed above, may lead to greater load on the ACL during a squat. Maintaining a vertical trunk position during the squat progressively moves the trunk's center of mass in a posterior direction as the knees go into flexion and, to maintain the body's center of mass over the base of support (the feet), the knees must move forward beyond the toes. Therefore, squatting with a vertical trunk position, which decreases hamstrings activity and increases quadriceps activity, leads to higher ACL loading.[14,35,42] Conversely, squatting with the trunk tilted forward 30° to 40° appears to be ideal to increase hamstrings activity and minimize ACL loading.

Escamilla et al[12,14] reported greater peak ACL loading (59 N) in the single-leg squat exercise compared to the double-leg wall squat exercise (0 N)[14] and the double-leg barbell squat (0 N). It is, therefore, appropriate to start ACL rehabilitation with double-leg squatting and progress to single-leg squatting. Resistance and technique variations can also be employed with the double-leg and single-leg squat, such as using a more forward trunk position to recruit greater hamstrings activity compared to a more erect trunk position that results in greater quadriceps activation.[14,35] Although squatting that employs larger knee flexion angles (eg, 50° to 100°) minimizes the loads on the ACL compared to squatting that employs smaller knee flexion angles (eg, 0° to 50°), these larger knee flexion angles may not be appropriate early after ACL reconstruction due, in part, to knee swelling and pain. Therefore, performing double-leg squat exercises early in the ACL rehabilitation process through a limited range of motion (eg, 0° to 45°), with light resistance (initially body weight alone), may be appropriate due to minimal or no ACL loading (depending on squat technique, which affects ACL loading). These types of WB exercises may also enhance lower extremity proprioception. Therefore, through the rehabilitation process, based on goals, variations in knee angle and technique may be used to change how much loading occurs on the ACL.

Forward and Side Lunge

Like the squat, ACL loading is minimal during the forward and side lunge (**TABLES 1** and **2**). The low ACL loading during the forward and side lunge is, in part, due to relatively high hamstrings activation, peaking at approximately 150 N at knee angles less than 30°.[15,16]

Like squatting, a forward trunk tilt may also decrease ACL loading during the forward-lunge exercises. Lunging with increased forward trunk tilt compared to a more erect trunk position has been shown to increase hamstrings activity,[17] and an increase in hamstrings force has been shown to decrease ACL loading.[15,16,35] Because of low ACL loading, forward and side lunging may be beneficial after ACL reconstruction, beginning with limited range of motion (eg, 0° to 45° of knee flexion) and lower intensity, and, as the knee becomes more mobile, later progressing to full knee range of motion and moderate intensity, with the added benefit of excellent knee and hip muscle recruitment.

Leg Press

ACL loading during the leg press is shown in **TABLES 1** through **3**.[14-16,62] No anterior shear force or tensile forces were produced when subjects performed a leg press using the heaviest resistance possible, allowing the completion of 12 consecutive repetitions.[12,62] Further, no ACL tensile forces were measured under combinations of high or low foot placement, using either a wide or narrow stance.[13] Therefore, the leg press can be an effective exercise to employ during ACL rehabilitation.

During the early rehabilitation process following ACL reconstruction, the patient may begin the leg press with light resistance between 0° and 45° knee flexion angles. As the patient's knee swelling decreases and lower extremity strength improves, the patient can perform the leg press with increasing knee flexion angles between 0° and 90°, and with increasing loads. Although ACL strain has been shown to be low during the leg press, only limited technique variations have been investigated.[12,13] Because quadriceps activity is high during the leg press (especially with higher-intensity training),[12,62] which has the potential to load the ACL at lower knee flexion angles (especially between 0° and 30°) when employing a variety of technique variations, it may be appropriate to perform the leg press at higher knee flexion angles (eg, 40° to 90°) once these knee angles are obtainable. Higher knee flexion angles minimize ACL loading and are more effective in recruiting the quadriceps, hamstrings, and gluteal musculature than lower knee flexion angles, when performing the leg press.[12,62] The authors prefer to perform the leg press using these larger knee flexion angles prior to performing deeper squats, as the leg press facilitates controlling the effects of gravity, and to monitor proper body position and knee alignment. Like lunge exercises, the leg press is an excellent exercise to employ for knee and hip muscle recruitment and minimal ACL loading.

Bicycling

ACL strain has been examined in vivo while riding a stationary bicycle.[19] In this study, 8 subjects were examined who had a variety of meniscal or chondral defects, but the fitness or athleticism of the participants was not reported.[19] Subjects pedaled at 3 different power levels (75, 125, and 175 W) and at 2 different cadences (60 and 90 rpm), performed in a random order. There was no significant difference in ACL strain found between the 2 cadences or between the 3 power levels. The average peak ACL strain ranged from 1.2% (175 W and 90 rpm) to 2.1% (125 W and 60 rpm) across the power and cadence combinations, and occurred at a mean of 38° of knee flexion (ranging from 37° to 50°). However, peak ACL strain values were highly variable among subjects (ranging from −3.4% to 5.1%), with 1 subject never producing greater than zero strain, indicating that the ACL was unloaded for all conditions while bicycling. Given that the Lachman test, performed on those same individuals to provide a reference value, produced strains of 3% and 3.5% with application of 100-N and 150-N anterior shear forces to the tibia, respectively, the peak ACL strain values recorded while bicycling can be considered relatively low. Further, the findings that peak ACL strain values did not increase with increased cadence or power output indicate that individuals undergoing rehabilitation following ACL reconstruction may use the stationary bicycle to increase muscular and cardiovascular workload without producing additional loading on the ACL.

Functional Activities

A number of studies have looked at functional activities such as walking, stair climbing, step-up and step-down, and rising from kneeling. Walking on level ground resulted in greater ACL loading compared to WB exercises and most NWB exercises (**TABLES 2** and **3**). Peak ACL tensile force during level walking was approximately 300 N and occurred near opposite foot toe-off, when the knee of the WB limb is in approximately 15° to 20° of knee flexion. Therefore, peak ACL loading during level walking is similar to that measured when performing NWB seated isokinetic and isometric knee extension exercises, and several times greater than the ACL tensile forces reported for WB exercises. Gait training is usually a focus of rehabilitation early following ACL reconstruction, emphasizing normal range of motion, symmetry, and the elimination of assistive devices.[38] However, early after ACL reconstruction, crutches and partial weight bearing are generally used. Despite the fact that the ACL is loaded during level walking, early weight bearing has been shown to lead to better outcomes than late weight bearing.[1] Therefore, level walking should be incorporated once pain, joint effusion, and symmetrical knee extension are under control.[36]

Peak ACL strain was not significantly different between stair climbing at slower versus faster rates.[3,4,23] It can be concluded that increasing the rate of stepping during stair climbing may not increase ACL strain. ACL loading was similar between rising from a kneeling position and stair climbing, but greater in level walking (**TABLE 3**). Step-ups and step-downs generated the same amount of ACL strain (**TABLE 1**).

Plyometric Activities

A double-leg drop jump from a 60-cm platform only resulted in approximately 250 N of ACL tensile force,[44] which was similar to the ACL loading that occurred when performing knee extension exercises in a seated position. Therefore, lower-intensity plyometric exercises, such as the double-leg drop jump, should precede higher-intensity plyometric exercises, such as the single-leg drop jump, which come later in the ACL rehabilitation process.

The rate of deceleration should also be considered when performing plyometric exercises, as a higher rate of deceleration likely results in greater ACL loading. Teaching proper landing techniques, such as landing softly with adequate knee flexion and forward trunk tilt to enhance hamstrings activity, as well as controlling knee valgus and hip adduction and internal rotation, should also be emphasized to minimize ACL loading.[26-31] Finally, it should be noted that, as more advanced exercises like plyometrics are employed, the assumption that the ACL load is the same between the healthy individuals who participated in the studies measuring ACL loading and individuals with an ACL reconstruction is potentially only valid once the strength of the surrounding musculature is returned to a level similar to that in healthy subjects. Quality of motion, such as during jumping or landing from a plyometric exercise, should also be considered, as the knee moving into valgus with hip adduction and internal rotation can greatly increase ACL loading.[26-31]

NWB VERSUS WB EXERCISES

Both WB and NWB exercises have been used and shown to be effective for rehabilitation post–ACL reconstruction and return to sport.[48] However, there is evidence to suggest that individuals who perform predominantly WB exercises, compared to NWB exercises, in their rehabilitation tend to have less knee pain and more stable knees, are generally more satisfied with the end result, and return to their sport sooner.[24]

There are conflicting reports in the literature regarding the outcomes of accelerated ACL rehabilitation protocols, which may include WB and NWB exercises. In a review article by Fleming et al,[20] the authors suggested that knee function, patient satisfaction, and graft healing may not be affected by controlled WB and NWB exercises. However, other systematic reviews[21,58] have suggested that the evidence is not conclusive regarding the early inclusion of NWB exercise for ACL rehabilitation and have recommended caution in the early introduction of NWB exercises. There are many factors that may influence outcomes (eg, laxity, quadriceps strength), including the timing of the introduction of NWB exercise, as well as how the exercise was performed, and these factors are not always controlled or comparable between studies. For instance, in one prospective randomized clinical trial, the authors compared the introduction of NWB exercise at 4 weeks versus 12 weeks postsurgery and found that the earlier introduction of NWB exercises significantly increased anterior knee laxity but did not result in any significant difference for knee extension torques.[24] The NWB exercise included in this study was seated knee extension, with the range of motion progressed to include full extension (0°-90°) in the fifth week and external resistance provided within the patient's tolerance. In contrast, between weeks 5 and 8 postsurgery and in addition to a standard rehabilitation protocol, Tagesson et al[56] examined the early introduction of NWB exercise for ACL rehabilitation by having a NWB group perform a single-leg standing hip extension exercise and a seated knee extension exercise, while a WB group performed a single-leg squat in a Smith machine. Findings included no difference in anterior knee laxity between the WB and NWB groups, significantly greater isokinetic quadriceps strength in the NWB group, and no other functional differences between the 2 groups.

However, the 2 studies[24,56] differ in terms of the timing of the introduction of the NWB exercise, and the exercise techniques were not well described in either study. Finally, the literature provides no clear indication as to when it is best to include NWB exercises and what the limitations of exercise techniques should be. We also do not have a clear understanding of the limitations for different graft types or populations (eg, athletic versus nonathletic).

TABLES 1 through **3** present ACL strain, ACL tensile force, and anterior shear force (ACL loading) data from selected papers in the scientific literature. For both WB and NWB exercises, ACL strain is typically greatest between 10° to 30° of knee flexion, gradually decreases between 30° to 60° of knee flexion, and is 0% at knee flexion angles greater than 60°. For example, during the seated isometric knee extension exercise using 30-Nm torque as resistance, ACL strain was maximum (4.4%) at 15° of knee flexion, and was 0% at 60° and 90° of knee flexion.[23] Moreover, when tested at knee flexion angles of 30°, 50°, and 70°, squatting, lunging, and step-up/step-down exercises had the greatest ACL strain at the 30° knee flexion angle.[23] Therefore, if the rehabilitation goal is to minimize ACL loading, training with NWB and WB exercises at higher knee flexion angles (eg, 50° to 100°) is recommended over performing these exercises at lower knee flexion angles (eg, 10° to 50°). However, the deeper knee angles, because of the greater muscular efforts they require and the potential limitations (eg, swelling and pain) of acquiring higher knee angles, may not be practical or advisable for WB exercises in the early stages of rehabilitation. ACL strain with the knee in full extension (0°) during exercise has not been measured and reported but is assumed to be minimal, due to the knee being in a very stable closed pack position.

It should be emphasized that ACL strain for both NWB and WB exercises at knee angles less than 60°, while higher than ACL strain at greater knee flexion angles, is still of relatively small magnitude (estimated to be approximately 150 N or less) (**TABLE 1**). This is based on the data that a 150-N Lachman test performed at 30° of knee flexion produced between 3.5% and 3.7% strain of the ACL,[2,19] and the ACL strain data reported in **TABLE 1** are typically less than 3.5%.

Peak ACL strain was generally greater when performing seated knee extension as compared to most WB exercises (**TABLE 1**).[23] For example, performing a leg press with 40% body weight resistance, stair climbing, and forward lunging all produced less ACL strain compared to performing knee extension with no external resistance in a seated position.[23] Interestingly, performing seated knee extension (quadriceps activation only) with no external resistance produced the same amount of ACL strain as that produced by performing a single-leg sit-to-stand movement or stair climbing (**TABLE 1**), with the WB exercises being much more challenging in recruiting important hip and thigh musculature (quadriceps, hamstrings, and hip extensors, abductors, and external rotators), which helps stabilize the knee and protect the ACL.[23] Therefore, for the same muscular challenge, WB exercises minimize ACL strain to a greater extent than NWB seated knee extension, and WB exercises are more functional multijoint, multimuscle exercises that are effective in developing important hip and thigh musculature. However, NWB exercises can also be effective when employed correctly and at the correct time, and are often selected for their ability to isolate training of individual muscles, such as the quadriceps.

Peak ACL tensile force is also of relatively low magnitude, typically under 150 N for WB exercises and between approximately 150 and 350 N for the seated knee extension exercise (**TABLE 2**). These peak values occurred at lower knee angles, typically between 15° and 35°. The highest ACL tensile forces between NWB and WB exercises occurred during maximal-effort isokinetic seated knee extension exercises, in which ACL tensile force was approximately 40% greater at 60°/s compared to a faster speed of 180°/s.

CLINICAL IMPLICATIONS

The rehabilitation specialist should be concerned about the patient's ACL graft strength and fixation when developing and selecting the most appropriate therapeutic exercises. Immediately following ACL surgery, the weak link is the fixation of the graft into the femoral and tibial tunnels. While incorporation of an autograft in the tibial and femoral tunnels may take 6 to 8 weeks for a patellar tendon graft, the time line is 8 to 12 weeks for soft tissue autografts. Concurrently, after an initial weakening of the graft itself in the first 2 to 4 weeks postsurgery, the graft subsequently undergoes a progressive process of revascularization and maturation, which over a period of several weeks progressively increases its tensile strength. Furthermore, it is generally accepted that the incorporation and maturation process of allografts takes longer than that of autografts, potentially indicating a need for slower progression in rehabilitation and return to sport in these individuals. The exercises chosen in early, intermediate, and advanced phases of ACL rehabilitation must therefore be carefully selected based on the stages of incorporation and maturation of the graft and with consideration of the differences in the nature of the graft fixation and source of the graft.

Early after ACL reconstruction, it may be prudent to choose exercises that minimize loading of the ACL graft. In theory, early after surgery, the best approach to begin strengthening important hip and thigh musculature, while minimizing loading of the ACL graft, would be to exercise at higher knee flexion angles (eg, 50° to 100°), using both WB and NWB exercises. However, early after surgery pain, swelling and inadequate knee range of motion may prevent exercising at these higher knee flexion angles, especially using WB exercise due to the greatly increased muscular demands with higher knee flexion angles (eg, 50° to 100°) compared to lower knee flexion angles (eg, 0° to 50°). Because ACL loading is less with WB compared to NWB exercises, and because ACL loading is relatively low using WB exercises at lower knee flexion angles, early after surgery it may be appropriate to begin with WB exercises like minisquats and lunges performed in a range of 0° to 45° knee flexion range using partial body weight (ie, assistance of the contralateral limb) initially and gradually progressing to full weight bearing and a 0° to 90° knee flexion range. The WB leg press exercise can also begin between 0° to 45° of knee flexion using low-intensity loads. When higher knee flexion ranges are obtained, higher-intensity loads can be employed between 50° to 100° knee flexion during the NWB seated knee extension and the WB leg press, which allows enhanced hip and thigh strengthening (compared to lower-intensity loads) without loading the ACL (due to employing higher knee flexion angles). Cycling can also be performed, initially using a partial knee range of motion with low intensity and progressing to higher knee flexion angles and higher intensity. Neuromuscular electrical stimulation has also been shown to be a useful adjunct to strengthening exercises in individuals post -ACL reconstruction, especially for quadriceps strengthening, since quadriceps inhibition due to swelling and pain can limit volitional quadriceps strengthening.[34]

Another approach of reducing ACL loading while performing lower extremity exercises is to facilitate a greater hamstring contraction during squatting, lunges, and balance activities. This can be accomplished by maintaining a forward trunk tilt (using hip flexion) between 30° and 40° or higher at the lowest position of lunging and squatting exercises, and by maintaining the heels on the ground and the knees over the feet. During squatting and lunging, care should be taken not to allow the knee to move forward excessively beyond the toes (greater than 8 to 10 cm).

The rate of performing exercise movements should also be carefully considered early after ACL reconstruction. Explosive movements involving high accelerations should be avoided. This involves both rapidly slowing down or speeding up an exercise movement, as this creates greater muscular effort (eg, higher quadriceps activity and force) and potentially increased loading to the ACL, especially a lower knee flexion angles (eg, 0° to 50°).

The intermediate phases of the ACL rehabilitation program shift from protection of the ACL graft to progressive strengthening exercises and drills of the entire lower extremity. At this stage, the quadriceps may be targeted with specific exercises if needed. During this phase, we suggest employing moderate resistance intensity and exercises such as bicycling through full range of motion, stair climbing machines, step-ups/step-downs, lunges, squats, leg presses, and wall/ball squats, and that progressive quadriceps, hamstrings, and hip-strengthening exercises be continued.

The advanced phases of ACL rehabilitation involve running, jumping, higher-intensity plyometrics, and sport-specific training. We recommend progression from double-leg drills to single-leg drills and employing caution when initiating rapid deceleration, cutting drills, and single-leg landing from a jump. Our recommendations are to initiate straight-line running first and to gradually progress to deceleration and cutting when appropriate neuromuscular control, dynamic stability, and strength are exhibited. Rapid deceleration activities, such as single-leg landing from a jump or running and cutting movements, generate very high ACL loading and are often implicated in ACL injuries, especially in individuals with inadequate control of the femur in the frontal and transverse planes, often due to weak hip external rotators and abductors.[45] Plyometric exercises should be performed prior to final return to sport and closely supervised to ensure proper technique. Because Hewett and colleagues[26-31] have demonstrated that plyometric exercises are foundational exercises for ACL injury prevention, it is reasonable to assume that plyometrics are very important to prevent additional ACL injuries after ACL reconstruction.

It should be noted that many of these recommendations are based more on clinical experience rather than scientific data, as there is a scarcity of data on optimal performance and timing for many exercises used in ACL rehabilitation.

SUMMARY

When summarizing the overall data on ACL loading during exercises, we conclude that for both NWB and WB exercises, greater ACL loading occurs at lower knee flexion angles (10° to 50°), with peak loading occurring between 10° to 30° of knee flexion. For both types of exercises, ACL loading progressively decreases from approximately 30° to 60° of knee flexion, with no ACL loading occurring at knee flexion angles beyond 60°. One noteworthy difference between WB and NWB exercises is that the magnitude of ACL loading between 10° and 50° is greater with the NWB knee extension exercises. Therefore, performing seated knee extension exercises between 10° and 50° of knee flexion range of motion, with or without resistance, produces significantly greater ACL loading compared to WB exercises (such as double-leg and single-leg squats, leg presses, lunging, stair climbing, step-ups/step-downs, and bicycling) performed in that same range of motion.

It is our perspective that WB exercises also have the advantage of recruiting important muscle groups at the hip (hip extensors, abductors, and external rotators) and the knee (quadriceps and hamstrings) that serve to control lower-limb alignment and enhance knee proprioception. With all WB exercises, using a forward trunk tilt of 30° to 40° serves to further recruit the hamstrings, which provides muscular coactivation at the knee and unloads the ACL. To minimize the loads on the ACL during WB exercises, it is also important to pay close attention to proper lower-limb alignment in the transverse and frontal planes (eg, avoiding knee valgus, hip adduction and internal rotation), keeping the heels on the ground, and keeping the knee from extending beyond the toes more than 8 to 10 cm as the knee is going into flexion. A further benefit of WB exercises is that the addition of external resistance does not appear to increase ACL loading, which is in contrast to what has been documented for seated knee extension exercises.

Therefore, given the limited and somewhat inconclusive results of clinical outcome studies that have compared the use of NWB and WB exercises post–ACL reconstruction, we recommend that a cautious approach be used for exercise selection in the early stages of rehabilitation. We suggest focusing on a combination of WB exercises performed within a comfortable range of knee motion (likely 0° to 45°) and seated knee extension exercises performed within the limited range of motion of 90° to approximately 45° of flexion. We also believe that, in the absence of conclusive data, these recommendations are especially important for ACL grafts that use a soft tissue fixation (eg, hamstrings) and for all ACL allografts. ◉

REFERENCES

1. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. *Br J Sports Med*. 2011;45:596-606. http://dx.doi.org/10.1136/bjsm.2010.076364
2. Beynnon B, Howe JG, Pope MH, Johnson RJ, Fleming BC. The measurement of anterior cruciate ligament strain in vivo. *Int Orthop*. 1992;16:1-12.
3. Beynnon BD, Fleming BC. Anterior cruciate ligament strain in-vivo: a review of previous work. *J Biomech*. 1998;31:519-525.
4. 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.
5. Beynnon BD, Johnson RJ, Fleming BC, Stankewich CJ, Renstrom PA, Nichols CE. The strain behavior of the anterior cruciate ligament 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.
6. Beynnon BD, Johnson RJ, Naud S, et al. Accelerated versus nonaccelerated rehabilitation after anterior cruciate ligament reconstruction: a prospective, randomized, double-blind investigation evaluating knee joint laxity using roentgen stereophotogrammetric analysis. *Am J Sports Med*. 2011;39:2536-2548. http://dx.doi.org/10.1177/0363546511422349
7. Blevins FT, Hecker AT, Bigler GT, Boland AL, Hayes WC. The effects of donor age and strain rate on the biomechanical properties of bone-patellar tendon-bone allografts. *Am J Sports Med*. 1994;22:328-333.
8. Brown CH, Jr., Steiner ME, Carson EW. The use of hamstring tendons for anterior cruciate ligament reconstruction. Technique and results. *Clin Sports Med*. 1993;12:723-756.
9. Butler DL, Noyes FR, Grood ES. Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study. *J Bone Joint Surg Am*. 1980;62:259-270.
10. Carofino B, Fulkerson J. Medial hamstring tendon regeneration following harvest for anterior cruciate ligament reconstruction: fact, myth, and clinical implication. *Arthroscopy*. 2005;21:1257-1265. http://dx.doi.org/10.1016/j.arthro.2005.07.002
11. Clancy WG, Jr., Narechania RG, Rosenberg TD, Gmeiner JG, Wisnefske DD, Lange TA. Anterior and posterior cruciate ligament reconstruction in rhesus monkeys. *J Bone Joint Surg Am*. 1981;63:1270-1284.
12. Escamilla RF, Fleisig GS, Zheng N, Barrentine SW, Wilk KE, Andrews JR. Biomechanics of the knee during closed kinetic chain and open kinetic chain exercises. *Med Sci Sports Exerc*. 1998;30:556-569.
13. Escamilla RF, Fleisig GS, Zheng N, et al. Effects of technique variations on knee biomechanics during the squat and leg press. *Med Sci Sports Exerc*. 2001;33:1552-1566.
14. Escamilla RF, Zheng N, Imamura R, et al. Cruciate ligament force during the wall squat and the one-leg squat. *Med Sci Sports Exerc*. 2009;41:408-417. http://dx.doi.org/10.1249/MSS.0b013e3181882c6d
15. Escamilla RF, Zheng N, Macleod TD, et al. Cruciate ligament forces between short-step and long-step forward lunge. *Med Sci Sports Exerc*. 2010;42:1932-1942. http://dx.doi.org/10.1249/MSS.0b013e3181d966d4
16. Escamilla RF, Zheng N, MacLeod TD, et al. Cruciate ligament tensile forces during the forward and side lunge. *Clin Biomech (Bristol, Avon)*. 2010;25:213-221. http://dx.doi.org/10.1016/j.clinbiomech.2009.11.003
17. Farrokhi S, Pollard CD, Souza RB, Chen YJ, Reischl S, Powers CM. Trunk position influences the kinematics, kinetics, and muscle activity of the lead lower extremity during the forward lunge exercise. *J Orthop Sports Phys Ther*. 2008;38:403-409. http://dx.doi.org/10.2519/jospt.2008.2634
18. Fleming BC, Beynnon BD, Renstrom PA, et al. The strain behavior of the anterior cruciate ligament during stair climbing: an in vivo study. *Arthroscopy*. 1999;15:185-191. http://dx.doi.org/10.1053/ar.1999.v15.015018
19. Fleming BC, Beynnon BD, Renstrom PA, Peura GD, Nichols CE, Johnson RJ. The strain behavior of the anterior cruciate ligament during bicycling. An in vivo study. *Am J Sports Med*. 1998;26:109-118.
20. Fleming BC, Oksendahl H, Beynnon BD. Open- or closed-kinetic chain exercises after anterior cruciate ligament reconstruction? *Exerc Sport Sci Rev*. 2005;33:134-140.
21. Glass R, Waddell J, Hoogenboom B. The effects of open versus closed kinetic chain exercises on patients with ACL deficient or reconstructed knees: a systematic review. *N Am J Sports Phys Ther*. 2010;5:74-84.
22. Handl M, Drzik M, Cerulli G, et al. Reconstruction of the anterior cruciate ligament: dynamic strain evaluation of the graft. *Knee Surg Sports Traumatol Arthrosc*. 2007;15:233-241. http://dx.doi.org/10.1007/s00167-006-0175-x
23. Heijne A, Fleming BC, Renstrom PA, Peura GD, Beynnon BD, Werner S. Strain on the anterior cruciate ligament during closed kinetic chain exercises. *Med Sci Sports Exerc*. 2004;36:935-941.
24. Heijne A, Werner S. Early versus late start of open kinetic chain quadriceps exercises after ACL reconstruction with patellar tendon or hamstring grafts: a prospective randomized outcome study. *Knee Surg Sports Traumatol Arthrosc*. 2007;15:402-414. http://dx.doi.org/10.1007/s00167-006-0246-z
25. 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.
26. Hewett TE, Ford KR, Myer GD. Anterior cruciate ligament injuries in female athletes: part 2, a meta-analysis of neuromuscular interventions aimed at injury prevention. *Am J Sports Med*. 2006;34:490-498. http://dx.doi.org/10.1177/0363546505282619
27. Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *Am J Sports Med*. 1999;27:699-706.
28. Hewett TE, Myer GD, Ford KR. Prevention of anterior cruciate ligament injuries. *Curr Womens Health Rep*. 2001;1:218-224.
29. Hewett TE, Myer GD, Ford KR. Reducing knee and anterior cruciate ligament injuries among female athletes: a systematic review of neuromuscular training interventions. *J Knee Surg*. 2005;18:82-88.
30. Hewett TE, Paterno MV, Myer GD. Strategies for enhancing proprioception and neuromuscular control of the knee. *Clin Orthop Relat Res*. 2002;402:76-94.
31. Hewett 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.
32. Jackson DW, Windler GE, Simon TM. Intraarticular reaction associated with the use of freeze-dried, ethylene oxide-sterilized bone-patella tendon-bone allografts in the reconstruction of the anterior cruciate ligament. *Am J Sports Med*. 1990;18:1-10; discussion 10-11.
33. Jacobsen K. Osteoarthrosis following insufficiency of the cruciate ligaments in man. A clinical study. *Acta Orthop Scand*. 1977;48:520-526.
34. Kim KM, Croy T, Hertel J, Saliba S. Effects of neuromuscular electrical stimulation after anterior cruciate ligament reconstruction on quadriceps strength, function, and patient-oriented outcomes: a systematic review. *J Orthop Sports Phys Ther*. 2010;40:383-391. http://dx.doi.

org/10.2519/jospt.2010.3184

35. Kulas AS, Hortobagyi T, DeVita P. Trunk position modulates anterior cruciate ligament forces and strains during a single-leg squat. *Clin Biomech (Bristol, Avon)*. 2012;27:16-21. http://dx.doi.org/10.1016/j.clinbiomech.2011.07.009

36. Kvist J. Rehabilitation following anterior cruciate ligament injury: current recommendations for sports participation. *Sports Med*. 2004;34:269-280.

37. Lyman S, Koulouvaris P, Sherman S, Do H, Mandl LA, Marx RG. Epidemiology of anterior cruciate ligament reconstruction: trends, readmissions, and subsequent knee surgery. *J Bone Joint Surg Am*. 2009;91:2321-2328. http://dx.doi.org/10.2106/JBJS.H.00539

38. Manal TJ, Snyder-Mackler L. Practice guidelines for anterior cruciate ligament rehabilitation: a criterion-based rehabilitation progression. *Oper Tech Orthop*. 1996;6:190-196.

39. Marumo K, Saito M, Yamagishi T, Fujii K. The "ligamentization" process in human anterior cruciate ligament reconstruction with autogenous patellar and hamstring tendons: a biochemical study. *Am J Sports Med*. 2005;33:1166-1173. http://dx.doi.org/10.1177/0363546504271973

40. Nagura T, Matsumoto H, Kiriyama Y, Chaudhari A, Andriacchi TP. Tibiofemoral joint contact force in deep knee flexion and its consideration in knee osteoarthritis and joint replacement. *J Appl Biomech*. 2006;22:305-313.

41. Nisell R, Ericson MO, Nemeth G, Ekholm J. Tibiofemoral joint forces during isokinetic knee extension. *Am J Sports Med*. 1989;17:49-54.

42. Ohkoshi Y, Yasuda K, Kaneda K, Wada T, Yamanaka M. Biomechanical analysis of rehabilitation in the standing position. *Am J Sports Med*. 1991;19:605-611.

43. Pandy MG, Shelburne KB. Dependence of cruciate-ligament loading on muscle forces and external load. *J Biomech*. 1997;30:1015-1024.

44. Pflum MA, Shelburne KB, Torry MR, Decker MJ, Pandy MG. Model prediction of anterior cruciate ligament force during drop-landings. *Med Sci Sports Exerc*. 2004;36:1949-1958.

45. Powers CM. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. *J Orthop Sports Phys Ther*. 2010;40:42-51. http://dx.doi.org/10.2519/jospt.2010.3337

46. Ristanis S, Tsepis E, Giotis D, Stergiou N, Cerulli G, Georgoulis AD. Electromechanical delay of the knee flexor muscles is impaired after harvesting hamstring tendons for anterior cruciate ligament reconstruction. *Am J Sports Med*. 2009;37:2179-2186. http://dx.doi.org/10.1177/0363546509340771

47. Rodeo SA, Arnoczky SP, Torzilli PA, Hidaka C, Warren RF. Tendon-healing in a bone tunnel. A biomechanical and histological study in the dog. *J Bone Joint Surg Am*. 1993;75:1795-1803.

48. Shelbourne KD, Nitz P. Accelerated rehabilitation after anterior cruciate ligament reconstruction. *Am J Sports Med*. 1990;18:292-299.

49. Shelburne KB, Pandy MG. Determinants of cruciate-ligament loading during rehabilitation exercise. *Clin Biomech (Bristol, Avon)*. 1998;13:403-413.

50. Shelburne KB, Pandy MG. A dynamic model of the knee and lower limb for simulating rising movements. *Comput Methods Biomech Biomed Engin*. 2002;5:149-159. http://dx.doi.org/10.1080/10255840290010265

51. Shelburne KB, Pandy MG. A musculoskeletal model of the knee for evaluating ligament forces during isometric contractions. *J Biomech*. 1997;30:163-176.

52. Shelburne KB, Pandy MG, Anderson FC, Torry MR. Pattern of anterior cruciate ligament force in normal walking. *J Biomech*. 2004;37:797-805. http://dx.doi.org/10.1016/j.jbiomech.2003.10.010

53. Shelburne KB, Pandy MG, Torry MR. Comparison of shear forces and ligament loading in the healthy and ACL-deficient knee during gait. *J Biomech*. 2004;37:313-319.

54. Shelburne KB, Torry MR, Pandy MG. Muscle, ligament, and joint-contact forces at the knee during walking. *Med Sci Sports Exerc*. 2005;37:1948-1956.

55. Shin CS, Chaudhari AM, Andriacchi TP. The influence of deceleration forces on ACL strain during single-leg landing: a simulation study. *J Biomech*. 2007;40:1145-1152. http://dx.doi.org/10.1016/j.jbiomech.2006.05.004

56. Tagesson S, Oberg B, Good L, Kvist J. A comprehensive rehabilitation program with quadriceps strengthening in closed versus open kinetic chain exercise in patients with anterior cruciate ligament deficiency: a randomized clinical trial evaluating dynamic tibial translation and muscle function. *Am J Sports Med*. 2008;36:298-307. http://dx.doi.org/10.1177/0363546507307867

57. Toutoungi DE, Lu TW, Leardini A, Catani F, O'Connor JJ. Cruciate ligament forces in the human knee during rehabilitation exercises. *Clin Biomech (Bristol, Avon)*. 2000;15:176-187.

58. van Grinsven S, van Cingel RE, Holla CJ, van Loon CJ. Evidence-based rehabilitation following anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2010;18:1128-1144. http://dx.doi.org/10.1007/s00167-009-1027-2

59. Vilensky JA, O'Connor BL, Brandt KD, Dunn EA, Rogers PI. Serial kinematic analysis of the canine hindlimb joints after deafferentation and anterior cruciate ligament transection. *Osteoarthritis Cartilage*. 1997;5:173-182.

60. Walton M. Absorbable and metal interference screws: comparison of graft security during healing. *Arthroscopy*. 1999;15:818-826. http://dx.doi.org/10.1053/ar.1999.v15.0150811

61. 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.

62. 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.

63. Woo SL, Hollis JM, Adams DJ, Lyon RM, Takai S. Tensile properties of the human femur-anterior cruciate ligament-tibia complex. The effects of specimen age and orientation. *Am J Sports Med*. 1991;19:217-225.