Open- or Closed-Kinetic Chain Exercises After Anterior Cruciate Ligament Reconstruction?

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Abstract and Introduction

Abstract

Open-kinetic chain (OKC) and closed-kinetic chain (CKC) exercises may not differ in their effects on the healing response of t cruciate ligament (ACL)-reconstructed knee. Recent biomechanical studies have shown that the peak strains produced on a g similar. Clinical studies suggest that both play a beneficial role in the early rehabilitation of the reconstructed knee.

Introduction

The optimal rehabilitation program after anterior cruciate ligament (ACL) reconstruction has changed considerably over the pa Accelerated rehabilitation programs, which permit early ROM, immediate weight-bearing, and early return to sport, have beco accepted standard. The trend toward accelerated rehabilitation, however, has been based primarily on clinical perception, retr observations, and the patients' desire to return to full activity quickly-not on prospective randomized controlled trials. The optir rehabilitation program after ACL reconstruction remains undetermined.

One of the goals of postoperative rehabilitation is to restore range of knee motion and muscle strength to the injured knee, wh protecting the healing graft from forces that could permanently deform it. It is generally thought that the biomechanical enviror the healing graft can be optimized by prescribing "closed kinetic chain" (CKC) exercises and avoiding open kinetic chain (OK(exercises early in the rehabilitation program. CKC exercises have been justified for early rehabilitation, in part, because they: the anterior-directed intersegmental forces that act on the tibia relative to the femur;[2,5,6,8,9,12] 2) increase tibiofemoral compre forces;[5,6,8,9] 3) increase cocontraction of the hamstrings;[2,7,12] 4) mimic functional activities more closely than OKC exercises 5) reduce the incidence of patellofemoral complications.[5,6,10]

Despite the frequent use and acceptance of the OKC and CKC terminology, a variety of definitions can be found in the literatu Purpose of this article, we defined OKC exercises as those in which the foot is not in contact with a solid surface. The resistive applied to the tibia and transferred directly to the knee (Fig. 1). Only the muscles spanning the knee are required to perform th Leg extension exercises and kicking are examples of OKC exercises. We defined CKC exercises as those in which the foot is with a solid surface. The foot is opposed by a ground reaction force, which is transmitted to all of the joints in the lower extrem Muscles spanning all of the joints of the lower extremity are used. Examples of CKC exercises are the squat, leg press, and lu

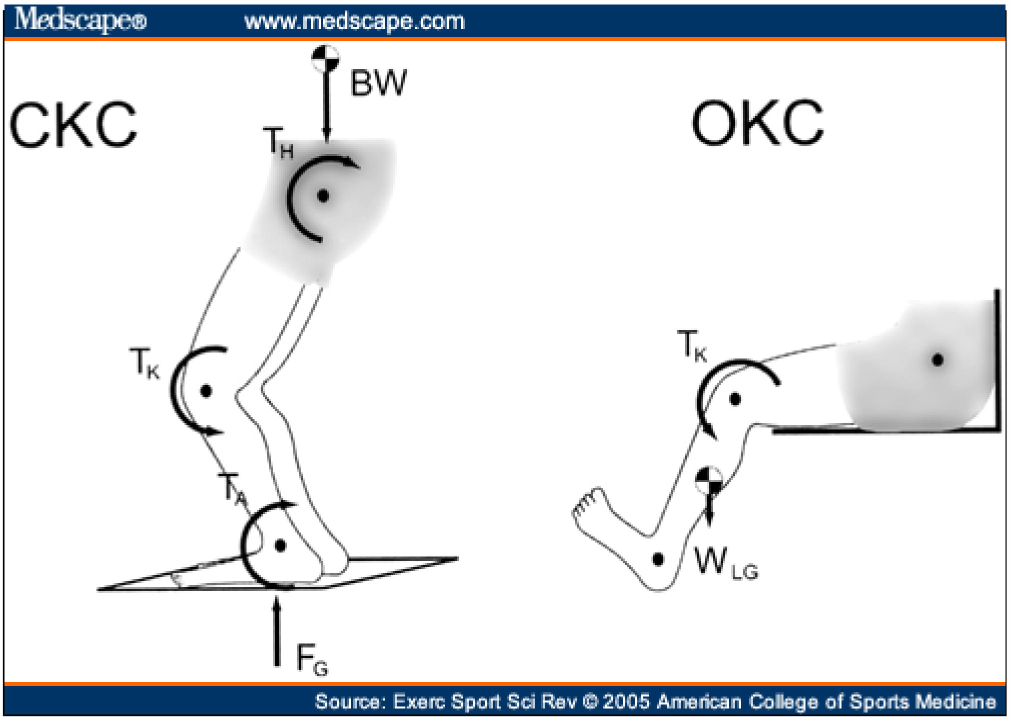

Figure 1.

The critical difference between OKC and CKC exercises is not the kinematic arrangement but the resultant loads transmitted to the knee. For OKC exercises, the resistive load (WLG) is applied to the tibia and transmitted to the knee (T_K). For CKC exercises, the ground reaction force (F_G) is transmitted to all the joints of the leg (T_A, T_K, and T_H).

In this brief review article, we explore the hypothesis that OKC and CKC for the rehabilitation of the ACL-reconstructed knee c in their effects on graft healing, postoperative knee function, and patient satisfaction (Fig. 2). The article focuses on the OKC a exercises involving knee flexion-extension. The review uses relevant biomechanical and clinical studies to assess the potentia that these exercises may have on graft healing. These include studies evaluating the intersegmental kinematics/kinetics of the ligament strains, and clinical outcome through prospective randomized clinical trials.

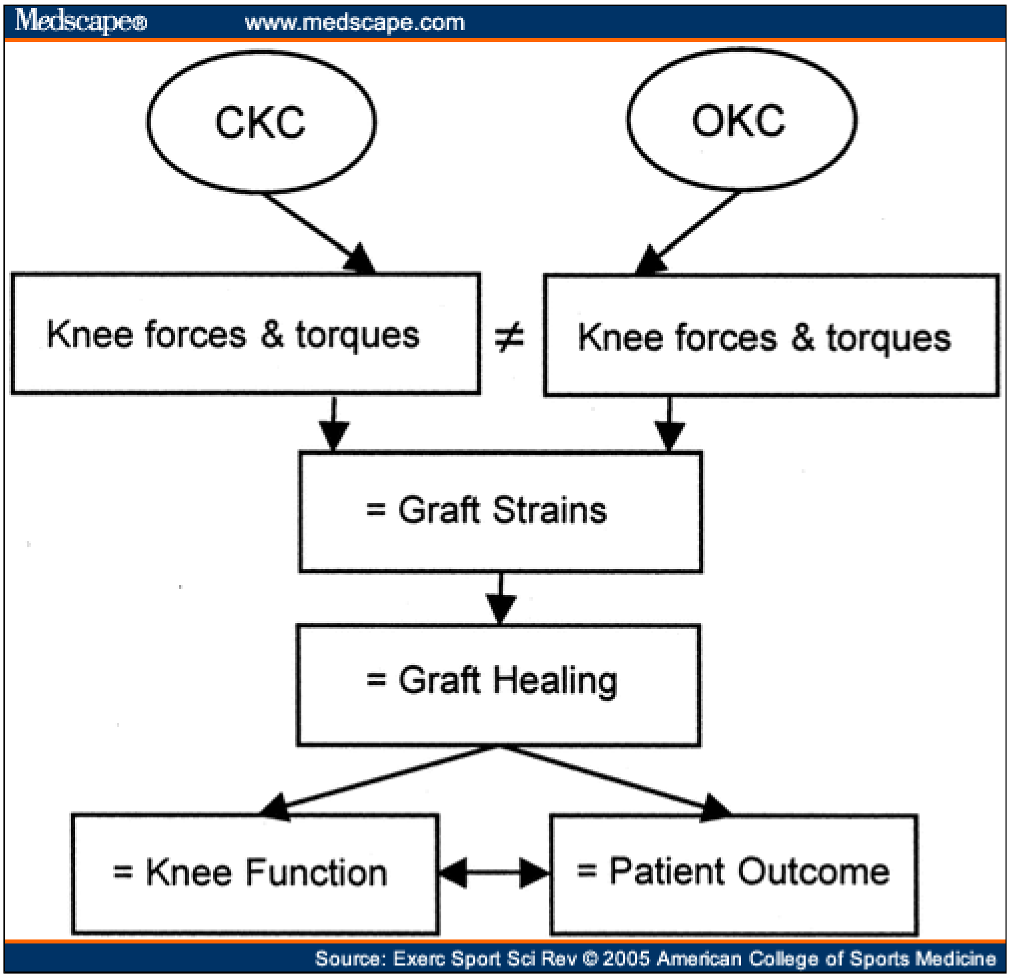

Figure 2.

The hypothesis is that OKC and CKC exercises for the early rehabilitation of the ACL-reconstructed knee do not differ their effects on graft healing, postoperative knee function, and patient satisfaction.

Studies of Intersegmental Kinematics/Kinetics of the Knee

Measurements of anterior tibial displacement in an ACL-deficient knee during different rehabilitation exercises have been rout to infer the strain environment of the healing ACL graft.[12] These techniques are based on the premise that the ACL is the pri restraint to anterior translation of the tibia. An increase in anterior tibial displacement in the ACL-deficient knee relative to the contralateral ACL-intact knee suggests that the ACL, or ACL graft, would be strained to a greater extent.

Several studies have reported significantly greater anterior tibial translations in the ACL-deficient knee during OKC exercises compared against CKC exercises. Jonsson *et al.* reported a 1.9-mm increase in the average anterior-directed tibial displacem ACL-deficient knee (relative to the ACL-intact knee) during the active knee extension exercise (OKC) when the knee was nea (15° to 10°), whereas no differences were found when the knee was extended during the step-up exercise (CKC).[11] Kvist an compared anterior tibial translation during three squatting exercises (CKC) and active knee extension exercises against three resistances (OKC) with those produced when a 90-N anterior-directed shear load was applied directly to the tibia relative to th immobilized thigh (*i.e.*, a Lachman test).[12] In the ACL-injured knees, all exercises (except for active knee extension against t resistance (8 kg)) produced similar peak anterior tibial displacements that equaled those produced during the Lachman test. the peak translations for all of the exercises occurred when the knee was near 20° of flexion. The OKC exercises with 8 kg of produced displacements exceeding those produced by the Lachman test by 20%.[12]

Analytical models have also been developed to predict the intersegmental forces in the knee, and the forces generated in the subjects perform OKC and CKC activities.[6] Inverse dynamic models, which incorporate limb geometry, kinematics, and the e applied forces (*i.e.*, ground reaction force) as inputs, are used to predict the net intersegmental loads at the knee. To maintair equilibrium, the net intersegmental loads produced at the knee are balanced by the ligaments, contact surface geometry, and musculature. Equilibrium models are then used to estimate the tibiofemoral compressive forces and cruciate ligament forces f intersegmental resultant loads using EMG, and estimates of muscle, ligament, and contact surface geometry and properties. approach, Escamilla *et al.* determined that the mean peak force on the ACL was 158 N during the OKC exercise when the kn 15° of flexion (leg extension against 78 kg), whereas it was not loaded during the CKC exercises (leg press and squatting aga weights) in experienced weight lifters.[6]

Analytical modeling provides an indirect and noninvasive means to predict the force on a healing ACL graft. Unfortunately, ma assumptions are required when constructing the models. The complex geometry of the articular surface and soft tissue structu knee are generally ignored, and the interactions between the ligaments, bony geometry, and the menisci must be considered. accurate forward dynamic model that incorporates the 3-dimensional morphometry of the knee with the appropriate represent ligament, menisci, and articular surface geometry and their material properties or a direct measurement approach is needed t accurately establish the loading environment on the ACL graft.

Studies of Ligament Strain *In Vivo*

The rehabilitation program after ACL reconstruction regulates the strain environment of the graft while preventing muscle atro Autogenous grafts have a viable cell population at the time of implantation that respond to mechanical strain. Although strain s healing, excessive strains could permanently stretch out or fail the tissue. The failure strain of the ACL is approximately 15%, that of a patellar tendon graft is 20% less.[4] Unfortunately, the failure strain and strength of the tissue are significantly reduced graft is implanted. The magnitude, optimal frequency, and duration of strain required to optimize healing remain unknown.

Direct measurements of ACL strains have been performed in humans to gain insight into the strains applied to the healing AC when rehabilitation exercises are performed.[2,8,9] For these studies, the ACL serves as a surrogate for the graft because it is r possible for the patients to perform these tasks at the time of their reconstruction. ACL strains were measured in subjects und diagnostic arthroscopy for minor meniscal lesions or chondral débridement with the use of local anesthesia[2,8,9] or spinal anes using an implantable strain transducer (differential variable reluctance transducer (DVRT))[2] ACL strains were measured in re activation of selected muscles,[2,7] tibiofemoral compressive loading,[8,9] and various OKC and CKC exercises.[2,8]

Using the DVRT, Beynnon *et al.*[2] determined that ACL strains were dependent on the knee flexion angle and extension torqu during isometric quadriceps contractions.[2] At 30 Nm of extension torque, ACL strain values produced at 15° of knee flexion v significantly greater than those produced at 30°, whereas no strain was produced at 60 and 90° (Table 1). For isometric ham contractions, the ACL strains were found to be independent of flexion torque or knee position; hamstrings contractions did not ACL at any knee angle tested (Table 1). The strain values produced by cocontraction of the quadriceps and hamstrings at 1 were less than those produced during isolated isometric quadriceps contractions (Table 1).

Because the proximal tendons of the gastrocnemius span the tibial plateau and insert on the posterior-distal aspect of the fem contraction could potentially strain the ACL by forcing the tibial plateau anterior. Using the *in vivo* strain measurement approa strains produced by gastrocnemius contractions were determined.[7] These patients underwent spinal anesthesia, and the con were induced using electrical stimulation to isolate the muscle contractions. With the knee at 5 and 15° of flexion, contractions gastrocnemius increased ACL strains relative to the relaxed state to levels close to that of an isolated quadriceps contraction With the knee in greater flexion (30 and 45°), gastrocnemius contraction did not strain the ACL (Fig. 3). Furthermore, it was demonstrated that cocontraction of the hamstrings or gastrocnemius with the quadriceps did not significantly reduce the ACL when the knee was near extension.

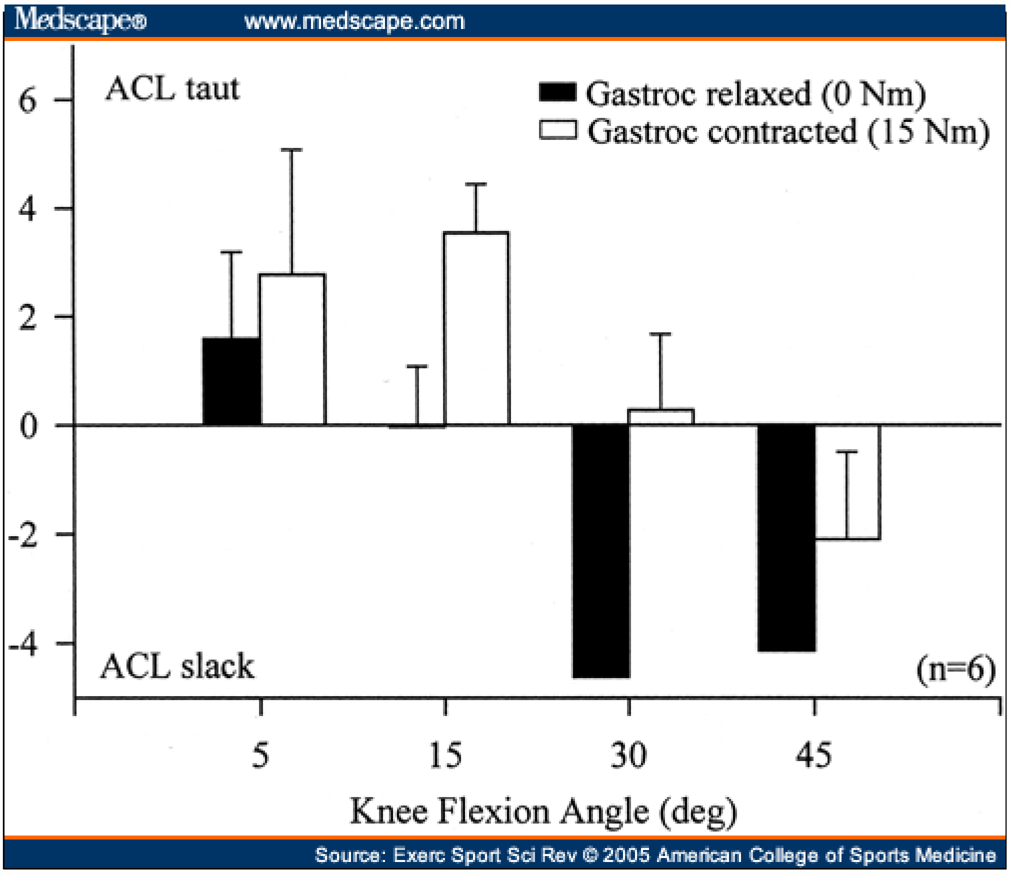

Figure 3.

Isolated contractions of the gastrocnemius muscle produced strains in the ACL when the knee was near extension. A negative strain value indicates that the ligament is slack (not load bearing), whereas a positive value indicates it is taut (load bearing).

Tibiofemoral compressive loads have been shown to increase joint stiffness and decrease anterior displacement of the tibia, a therefore thought to protect the healing ACL graft. The effects of applying an external compressive load to the knee, such as t produced by body weight or the leg-press exercise, were assessed with the knee at 20° of flexion.[9] The ACL was strained as transitioned from no compressive load (the OKC condition) to a compressive load equal to 40% of body weight (the CKC cond 4). The strain is most likely produced by the anterior neutral shift of the tibia that has been observed in ACL-deficient patients undergo the transition between nonweight bearing and weight bearing.[3]

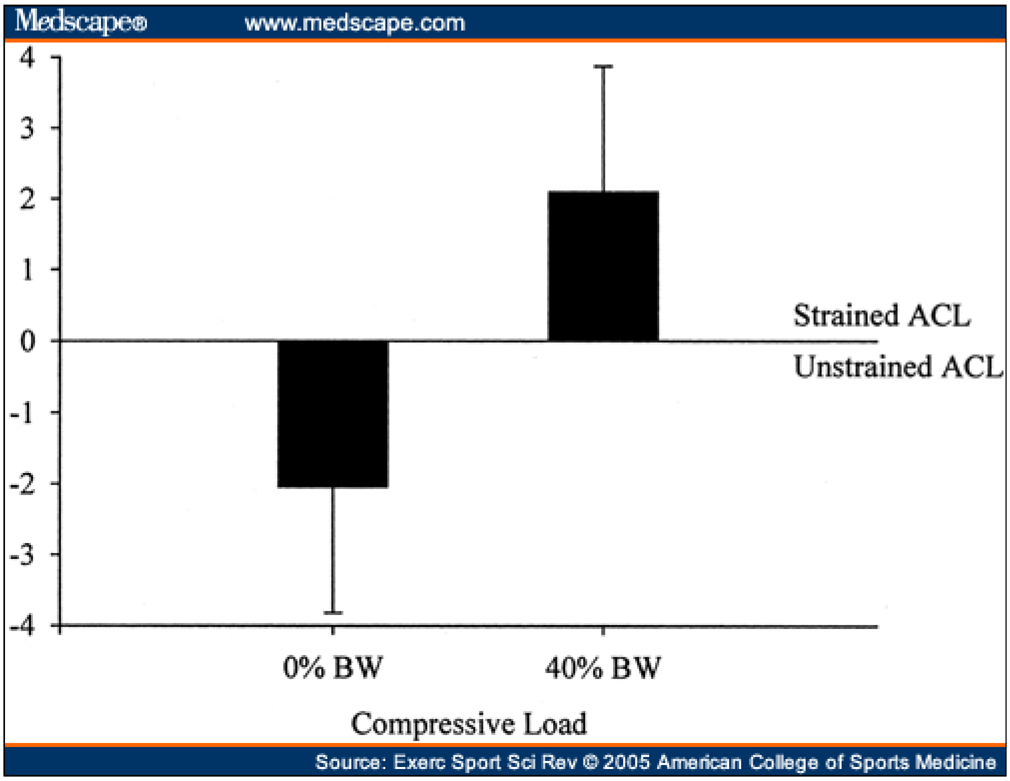

Figure 4.

The ACL was strained when an external compressive load was applied to the knee and the knee was at 20° of flexion.

Beynnon *et al.* also reported that the maximum ACL strains produced during a simple squat (90° to 10°), a closed-kinetic chai were similar to those produced during active extension of the knee (90° to 10°), an open-kinetic chain exercise (Fig. 5).[2] It wa however, that an increase in resistance during an OKC exercise (active extension vs active extension against 44 N of resistar increased ACL strains, whereas this did not occur during CKC exercises (squatting vs squatting with Sport Cord). Other CKC such as stationary bicycling, also did not exhibit the increase in strain with an increase in resistance.

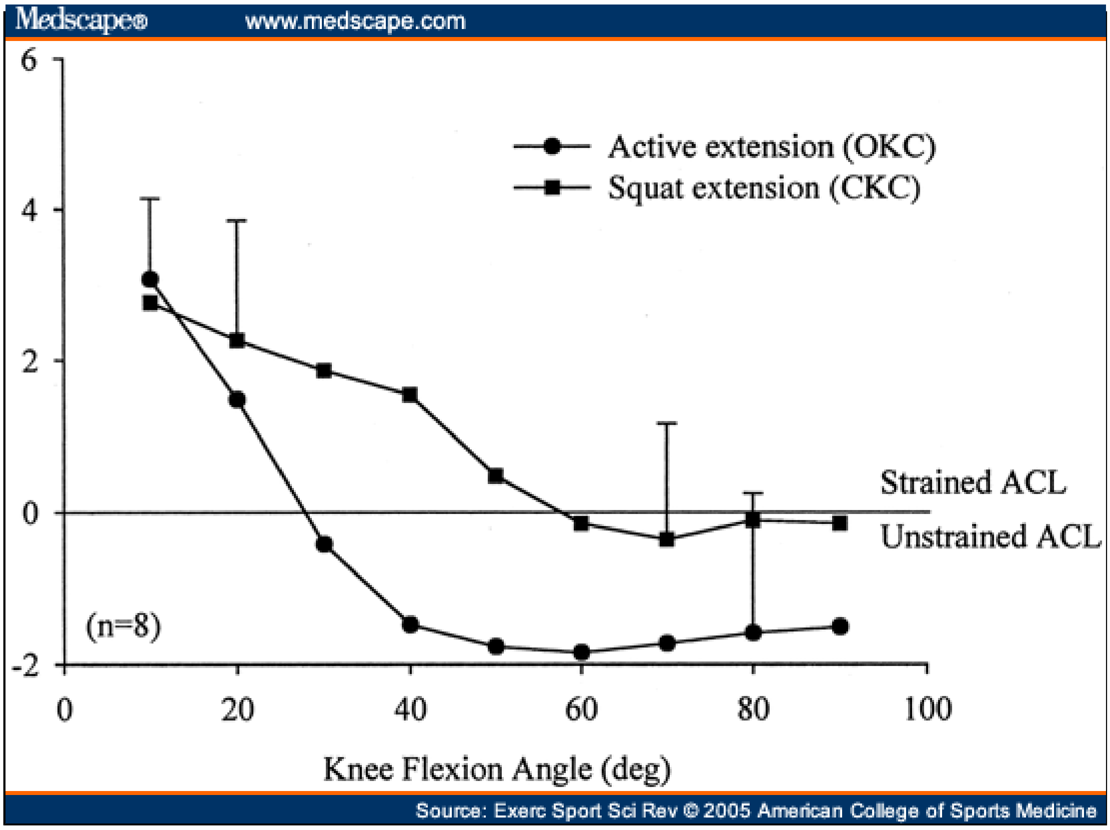

Figure 5.

The peak strains produced on the ACL during squatting (a CKC exercise) and active knee extension against gravity (a OKC exercise) were similar in magnitude.

To systematically evaluate the effects of increasing resistance and external compressive load during exercise, ACL strains we measured while subjects performed flexor and extensor exercises against increasing resistance with and without a compressi applied to a foot in an effort to simulate the CKC and OKC conditions, respectively (Fig. 6).[8] During the extensor exercise (qu dominant), a significant increase in ACL strain was observed with an increase in resistance when no external compressive loa applied to the foot (OKC), whereas no significant increase in ACL strain was observed with increased resistance when the ext compressive load was applied (CKC). The increase in strain from 2.3% to 3.8%, which occurred during the OKC simulation fr 24 Nm of resistance torque, respectively, was equal to that produced when an anterior shear load of 150 N was applied direct proximal tibia when the knee was at 30° of flexion (*i.e.*, the Lachman test) (Fig. 7). Although the increase in strain was signific between 0 and 24 Nm of torque for the OKC condition, there was no statistical difference between the mean peak strains of th and CKC conditions with the 24-Nm resistance applied, a relatively high load for early rehabilitation of the knee.

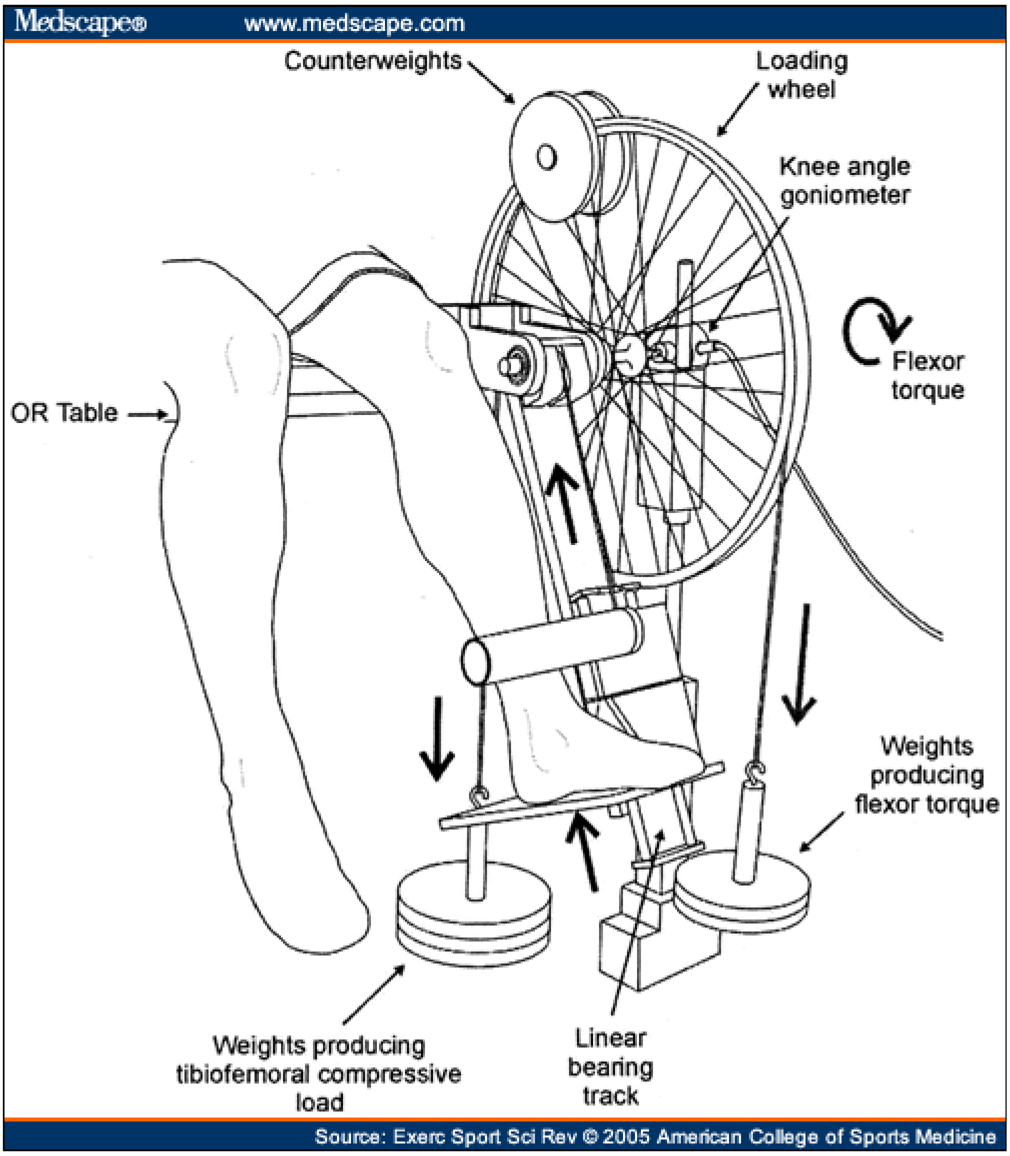

Figure 6.

Test apparatus that was used to independently evaluate the effects of resistance and compressive load during flexion extension exercises to evaluate whether an increase in resistance would affect the strains produced on the ACL during OKC (no external compressive load) or CKC exercise (with external compressive load). (Reprinted from Fleming, B.C., P.A. Renstrom, G. Ohlen, R.J. Johnson, G.D. Peura, B.D. Beynnon, and G.J. Badger. The gastrocnemius muscle is an antagonist of the anterior cruciate ligament. J. Orthop. Res. 19:1178-1184, 2001. Copyright © 2001 American Orthopa Society for Sports Medicine. Used with permission.)

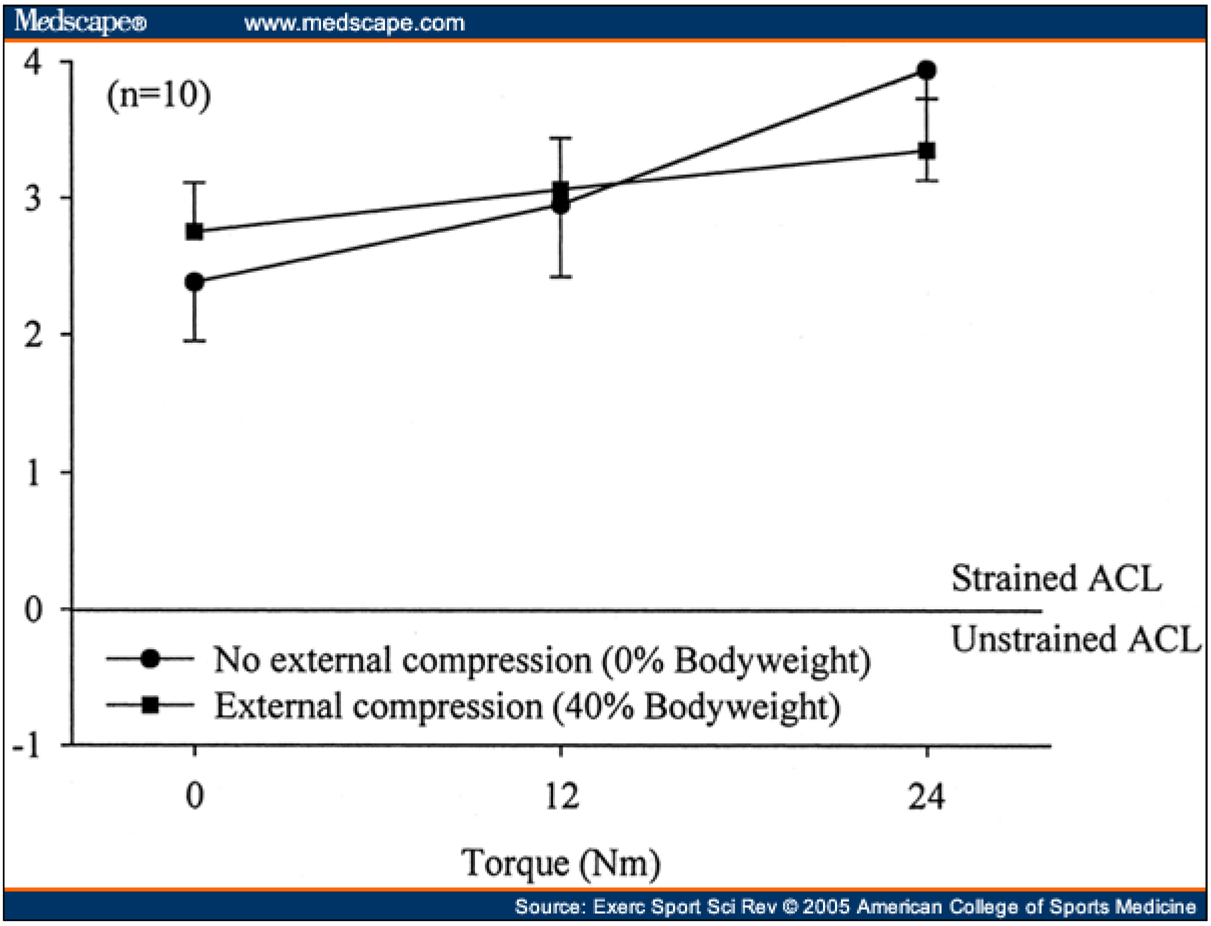

Figure 7.

A significant increase in ACL strain occurred with increasing resistance with the OKC extensor exercise. The increase the CKC exercise was not significant. Nonetheless, the strains produced during the OKC exercise with 24-Nm resistan were similar to those produced during a Lachman test. (Reprinted from Fleming, B.C., P.A. Renstrom, G. Ohlen, R.J. Johnson, G.D. Peura, B.D. Beynnon, and G.J. Badger. The gastrocnemius muscle is an antagonist of the anterior cruc ligament. J. Orthop. Res. 19:1178-1184, 2001. Copyright © 2001 American Orthopaedic Society for Sports Medicine. U with permission.)

Direct measurements of ACL strain have provided insight into the healing environment of the ACL. However, several limitatior approach should be noted. First, the strain measurements were performed on the intact ACL. However, Beynnon *et al.*[1] have that the strain patterns produced in the patellar tendon graft were similar to those of the ACL during passive knee motion. Thu reasonable to assume that exercises inducing high strains on the ACL would produce high strains on an ACL graft during dyn activities. Second, subjects were undergoing arthroscopic partial meniscectomy or chondral débridement, which could alter kr kinematics. However, there was no evidence of ligamentous damage. Third, the measurements were performed under intraar anesthesia, which could potentially alter the way the muscles function. Finally, the DVRT is only capable of measuring the stra response of the anteromedial bundle of the ACL *in vivo*, and not the entire strain distribution of the ligament. This bundle com of the total cross-sectional area of the ligament.

Randomized Clinical Trials Comparing Okc and Ckc Exercises

The effects of OKC and CKC exercises on functional outcome have been evaluated in three independent prospective random clinical trials.[5,10,14] Bynum *et al.* performed a clinical trial comparing outcomes after ACL reconstruction with patellar tendon g 19 months of healing.[5] Patients were randomized to rehabilitation programs that consisted of either OKC or CKC exercises. that the mean side-to-side difference in knee laxity of the OKC group (3.3 mm) was significantly greater than that of the CKC g mm). In addition, the CKC group had a faster return to sport. At 9 months, patellofemoral pain was reported in 15% of the CK((compared with 38% in the OKC group), although there was no difference at 19 months. They also reported no significant diffe Lysholm score, Tegner activity score, overall subjective rating of the knee (Lachman and pivot shift test), or ranges of knee m However, when comparing the two rehabilitation protocols, there were differences in the levels of resistance and the progress exercise between the groups. The OKC group performed cocontraction isometrics, hamstring concentric and eccentric isotoni single-leg raises at 30° of flexion in the first 6 wk; the CKC group performed double one-third knee bends, seated leg presses hamstring curls in the first 6 wk. The CKC group was also allowed to begin jogging against Sport Cord resistance at 8 wk, anc specific exercises at 16 wk, whereas the OKC began isotonic quadriceps exercises at 6 wk, progressing to isokinetic at 24-wk group did not begin jogging until 16 wk, and sport-specific exercises were initiated at 7 to 8 months. These differences may ac the faster return to previous level of activity of the CKC group.

Mikkelsen *et al.* measured anterior knee laxity, isokinetic muscle torque, and the time to return to sports after 6 months of hea patients who underwent ACL reconstruction.[13] Subjects were randomized to one of two rehabilitation programs; one used Ck exercises for a 24-wk period, the other used the same CKC rehabilitation program with the addition of OKC exercises from we 24. The OKC exercises consisted of isokinetic quad strengthening between 90° and 40° at 6 wk, and progressed to between ! by 12 wk. The treatment group using both exercise types had significantly higher quadriceps torque, and a greater proportion patients returned to sports at their preinjury level. No comments relating to patellofemoral complications in either group were r study indicates that the addition of the limited range of motion OKC exercises in week 6 increasing to near-full extension by w may benefit subjects. However, the improvement may be because of the addition of exercises, and not dependent on the type exercise added. Nonetheless, the addition of the OKC exercises in this time frame did not produce a negative outcome.

Morrissey and Hooper studied the effects of prescribing OKC versus CKC hip and knee extensor muscle exercises after surge In both treatment groups, the rehabilitation program was initiated 2 wk after surgery and completed after week 6. In designing programs, they attempted to control for training velocity, ROM (90° to 0°), and the number of exercise repetitions. The knee-la obtained at the Conclusion of the rehabilitation period using OKC or CKC exercises were not significantly different (OKC = 10 CKC = 10.0 mm; *P* = 0.32).[14] No differences were found for knee pain.[15] Gait analysis was also performed in these patients differences in joint kinematics and kinetics during level walking, stair ascent, and stair descent.[10] Patients also assessed thei disability using the Hughston Clinic visual analog scales. The only gait variable affected by the rehabilitation program was the flexion angle at contact during step-up. This kinematic parameter was improved by an average of 2° in the patients who perfo OKC exercises, and is probably not clinically significant. The effects of the OKC and CKC exercise programs relative to all oth parameters of knee kinetics and kinematics were not significantly different. The authors concluded that there are no clinically differences in the functional improvement resulting from the choice of OKC and CKC exercises in the early period of rehabilita These findings may be limited because of the short period of supervised rehabilitation (2-6 wk).

Discussion

This review highlights specific studies that investigate the five potential differences between OKC and CKC exercises in an ef address the hypothesis (Fig. 2). The intersegmental forces at the knee indicate that the CKC exercises produce lower anterio on the tibia, increase the tibiofemoral compressive forces, enhance muscle cocontraction, and decrease patellofemoral compı forces near extension, all factors thought to protect the graft and restore knee function. The *in vivo* strain data also provide ev the ACL is a primary restraint to anterior-directed shear load as demonstrated by the Lachman data (Table 1), and that knee cocontractions reduce ACL strains relative to isolated contractions of the quadriceps and/or gastrocnemius muscles. Althougł are reduced, they are not eliminated when the knee is near extension (<30°). Application of a compressive load to the tibiofen such as that produced by weight bearing, strains the ACL, suggesting that the compressive load does not strain shield the lig previously thought. Direct comparison of the peak ACL strains during OKC exercises were similar to the CKC exercises, altho increase in resistance during the OKC exercise produced increases in strain that did not occur during CKC exercises. Noneth strains produced during the knee extension exercise against the 24-Nm resistance were similar to those produce during a Lac with a 150-N anterior shear load (Table 1), a test that is frequently performed in the early postoperative healing period.

The effects of these exercises on graft healing, knee function, and patient satisfaction must be assessed through prospective randomized clinical trials. The two studies directly comparing OKC and CKC protocols provide different conclusions: one sug OKC program produces an increase in joint laxity and patellofemoral problems,[5] whereas the other does not.[10,13,14] Knee fu patient satisfaction were similar between groups in both studies. The study comparing a CKC-based rehabilitation protocol wi contains CKC and OKC exercises indicates that the latter Results in better function and earlier return to sport without increase laxity.[13] It is well known that muscle strengthening is task specific. In reviewing these data, the combination of exercise types necessary to fully rehabilitate ACL-reconstructed patients back to their previous level of function.

Conclusions

The review supports our hypothesis that controlled OKC and CKC exercises for rehabilitation of the ACL-reconstructed knee differ in their effects on graft healing, postoperative knee function, and patient satisfaction. Although noninvasive biomechanic suggest that OKC and CKC exercises produce different loads at the knee, the direct ACL strain measurements comparing leg exercises up to 24-Nm resistance with squatting exercises indicate that the differences may not be clinically significant. Most randomized clinical trials, although somewhat limited, suggest that both exercise types, in combination, may be important for rehabilitation. Additional prospective randomized clinical trials must be performed to determine the optimal time to introduce tl exercises.

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Table 1. Rank Comparison of Peak ACL Strains Measured During Commonly Prescribed Rehabilitatio Exercises (Mean ± Standard Error)

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Rehabilitation Exercise	Peak Strai
Isometric quadricep contraction at 15 degrees (30 Nm of extension torque) (OKC)	4.4 (0.6
Squatting with sport cord (CKC)	4.0 (0.6
Active flexion–extension of the knee with 45 N weight boot (OKC)	3.8 (0.5
Lachman test (150 N of anterior shear load; 30-degree flexion)	3.7 (0.8
Squatting (CKC)	3.6 (0.5
Active flexion–extension (no weight boot) of the knee (OKC)	2.8 (0.8
Simultaneous quadricep and hamstring contraction at 15 degrees (OKC)	2.8 (0.9
Isometric quadricep contraction at 30 degrees (30 Nm extension torque) (OKC)	2.7 (0.5
Stair climbing (CKC)	2.7 (1.2
Leg press at 20-degree flexion (40% body weight) (CKC)	2.1 (0.5
Lunge (CKC)	1.9 (0.5
Stationary bicycling (CKC)	1.7 (0.7
Isometric hamstring contraction at 15 degrees (to −10 Nm flexion torque) (OKC)	0.6 (0.9
Simultaneous quadricep and hamstring contraction at 30 degrees (OKC)	0.4 (0.5
Isometric quadricep contraction at 60 degrees (30 Nm extension torque) (OKC)	0.0
Isometric quadricep contraction at 90 degrees (30 Nm extension torque) (OKC)	0.0
Simultaneous quadricep and hamstring contraction at 60 degrees, 90 degrees (OKC)	0.0
Isometric hamstring contraction at 30, 60, and 90 degrees (−10 Nm flexion torque) (OKC)	0.0

The failure strains of the normal ACL are approximately 15% (Butler (4)). There is a mixed ordering of OKC and CKC exercises.

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Abbreviation Notes

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reconstruction, graft, healing, rehabilitation, exercise, biomechanics

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