Early Application of Negative Work via Eccentric Ergometry Following Anterior Cruciate Ligament Reconstruction: A Case Report

J. Parry Gerber, PT, DSc, SCS, ATC[1]
Robin L. Marcus, PT, PhD[2]
Leland E. Dibble, PT, PhD, ATC[3]
Patrick E. Greis, MD[4]
Paul C. LaStayo, PT, PhD, CHT[5]

Study Design: Case report.
Objectives: To present a progressively increasing negative-work exercise program via eccentric ergometry early after anterior cruciate ligament reconstruction (ACL-R) and to suggest the potential of negative work to amplify the return of quadriceps size and strength.
Case Description: The patient was a 26-year-old highly active recreational athlete who sustained an ACL tear while skiing in January 2004 and then again while skiing in February 2005. This individual underwent an arthroscopically assisted ACL-R with a double-loop semitendinosus-gracilis autograft initially, then a patellar tendon autograft following his ACL graft rupture. Beginning within 3 weeks after surgery, a progressive negative-work exercise program was initiated using an eccentric ergometer. The patient completed 31 training sessions of 5 to 30 minutes in duration over a 12-week period following the ACL-R and 33 training sessions of the same frequency and duration following the ACL revision.
Outcomes: Following ACL-R, quadriceps volume increased 28% (involved lower extremity) and 14% (uninvolved lower extremity) during the 12-week training program. Following revision, quadriceps volume returned to similar levels at the same postoperative period as those achieved after the initial surgery (2% less on the involved side and 2% greater on the uninvolved side). Quadriceps strength, 15 weeks after ACL-R, exceeded preoperative measures by an average of 20% (involved) and 14% (uninvolved). Quadriceps strength after ACL revision exceeded all previous measures.
Discussion: This case report suggests that if gradually and progressively applied, negative work via eccentric ergometry can be both safe and efficacious early after ACL-R. Eccentric exercise may mitigate the prevalent muscle size and strength deficits commonly observed after ACL-R. The results of this case suggest a need for continued research with early negative work interventions following ACL-R. *J Orthop Phys Ther 2006;36(5):298-307.* doi:10.2519/jospt.2006.2197

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[1] *Doctoral candidate, Division of Physical Therapy, University of Utah, Salt Lake City, UT; Doctoral candidate, Department of Exercise and Sport Science, University of Utah, Salt Lake City, UT.*
[2] *Clinical Associate Professor, Division of Physical Therapy, University of Utah, Salt Lake City, UT; Clinical Associate Professor, Department of Exercise and Sport Science, University of Utah, Salt Lake City, UT.*
[3] *Clinical Assistant Professor, Division of Physical Therapy, University of Utah, Salt Lake City, UT; Clinical Assistant Professor, Department of Exercise and Sport Science, University of Utah, Salt Lake City, UT.*
[4] *Associate Professor, Department of Orthopedics, University of Utah, Salt Lake City, UT.*
[5] *Associate Professor, Division of Physical Therapy, University of Utah, Salt Lake City, UT; Associate Professor, Department of Exercise and Sport Science, University of Utah, Salt Lake City, UT; Associate Professor, Department of Orthopedics, University of Utah, Salt Lake City, UT.*
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Address correspondence to J. Parry Gerber, University of Utah Department of Exercise and Sport Science, 520 Wakara Way, Salt Lake City, UT 84108. E-mail: J.Parry.Gerber@utah.edu

Quadriceps atrophy and strength deficits are the predominant impairments after anterior cruciate ligament reconstruction (ACL-R). The magnitude of atrophy and strength loss often exceeds 20% and 30%, respectively, during the first 3 months following surgery.[7,15,22,25,26,29-32,34] Resistance exercises during postoperative rehabilitation predictably mitigate these deficits; however, a 10% decrease in muscle size and a 10% to 20% decrease in strength may persist years after surgery.[1,5,7-9,12,19,22,25,28] Regaining quadriceps size and strength is clearly difficult following ACL-R and continues to be a rehabilitation challenge requiring novel interventions.

A muscle's force production ability is greatest when an external force exceeds that of the muscle and it lengthens eccentrically.[21] The resulting work performed by the muscle is termed "negative work" (when the muscle length change is opposite that of the muscle force vector, hence, work [force × distance] is negative). In this case report a progressively increasing application of negative work via a motorized eccentric (ECC) ergometer is described. Progressively increasing negative work, via an ECC ergometer intervention, early during ACL-R rehabilitation is novel.

Originally utilized as a paradigm for studying muscle damage, recent research suggests that controlled application of negative work is a potent stimulus for increasing muscle size and strength, which are the predominant impairments following ACL-R. Hortobagyi et al[10] compared a 12-week ECC versus concentric (CON) resistance training program via an isokinetic dynamometer after 3 weeks of knee immobilization on healthy college-age men and women. Improvements in muscle size in the ECC group were nearly double those of the CON group. The rate of muscle strength recovery was also amplified and significantly faster in the ECC group. Likewise, LaStayo et al[17] compared an 8-week ECC versus CON ergometry exercise program in healthy college-age males. Muscle fiber cross sectional area (CSA) and isometric quadriceps strength increased 52% and 36%, respectively, in the ECC group, while CSA and strength increased less than 10% in the CON group. The effects of ECC ergometry on frail elderly individuals (mean age, 80 years) who exercised 2 to 3 times per week for 11 weeks also resulted in large increases in muscle fiber size and strength (ie, a 60% increase in both muscle fiber CSA and maximum voluntary isometric contraction [MVIC] of the quadriceps).[16] It is worth noting that these elderly individuals tolerated the high forces of negative work exercise well. Only low levels of discomfort were reported throughout the training, and all who began the program completed it. Performance abilities (eg, balance and fall risk) also improved significantly in this group.

Because quadriceps atrophy and strength deficits are greatest during the first 3 months following ACL-R, it appears that the early postoperative period is a key time to maximize return of the quadriceps. Due to high force-producing capabilities, ECC exercise has the potential to induce muscle size and strength gains exceeding those changes described as following typical rehabilitation programs. When applied gradually and progressively, an eccentrically induced, negative-work exercise program can be tolerated without damage.[16,17]

The purpose of this case report is to detail both the quadriceps size and strength changes of a highly active recreational athlete who completed 12 weeks of negative-work exercise using ECC ergometry early after ACL-R and then again after ACL revision, in addition to a traditional accelerated rehabilitation program. This case report is novel and clinically relevant for several reasons. It is the first report to describe negative-work exercise via ECC ergometry following ACL-R. It is clinically relevant, because an early ECC intervention may facilitate quadriceps size and strength gains that are superior to those reported following current ACL-R rehabilitation programs. Because negative work via ECC exercise is such a potent stimulus to changes in muscle structure and function, this report will emphasize the judicious application of ECC resistance, based on the principles of muscle overload, exercise progression, and an individual's response to exercise.

CASE DESCRIPTION, PART 1

Prior to injury, the patient described himself as being in the ''best physical shape of my life.'' He was a college graduate student and avid snow skier (age, 26 years; height, 185 cm; body mass, 75 kg). During the summer months he averaged 8 to 10 hours of high-intensity bike riding and jogged 20 to 30 minutes, 3 times per week. In the fall, 3 days per week, he also participated in a dry-land training program for skiers that consisted of high-intensity running and jumping drills. He routinely lifted weights (squats, hamstring curls, calf press) 2 to 3 times per week. The patient skied (usually on the most difficult terrain) 20 to 30 hours per week in November and approximately 40 hours per week in December.

In early January 2004, the patient reported that he was going very fast down steep terrain and went off a small jump. To avoid hitting rocks he had to make a sharp jump turn. His hips, shoulders, and right ski all turned. His left ski tip ''caught an edge,'' causing his left knee to twist. It twisted until he heard and felt a large ''pop.'' He felt immediate knee instability, could not bear weight on his leg, and had to be shuttled down the mountain. Physical examination findings included a 2+ knee effusion, positive (++) Lachman and pivot shift tests, and a positive (++) valgus stress test. He was diagnosed with a compete tear of his left ACL and grade II sprain of his medial collateral ligament (MCL). The knee was placed in a straight-leg immobilizer for 3 weeks. Only isometric quadriceps muscle sets (quad sets) and straight-leg exercises were permitted during the immobilization phase. Range of motion (ROM) exercises and stationary biking were added following these initial 3 weeks. Two weeks later, after regaining knee ROM, an arthroscopic ACL-R was performed to stabilize the knee using the semitendinosus and gracilis in quadrupled fashion as a graft source.

ACL-R Surgery

A 3.5-cm incision was made over the medial aspect of the tibia directly over the semitendinosus and gracilis tendons. Sutures were placed in a whipstitch fashion in the distal 2.5 cm of each of the tendons. Using the tendon stripper, the tendons were harvested and fashioned into 2 grafts, each 22 cm in length. The stump of the torn ACL was debrided and a lateral notchplasty was performed to assure that the over-the-top position could be identified. Using an ACL aiming guide, a guide wire was drilled into the anatomic footprint of the ACL to position the tibial tunnel. The femoral tunnel was placed at the 2 o'clock position on the femur. The graft was passed through the knee and a Continuous Loop Endobutton (Smith & Nephew, Andover, MA) was used to secure the graft on the femoral side. The ends of the semitendinosus and gracilis graft were tensioned using the SE Graft Tensioner (CONMED Linvatec, Largo, FL). Sixty N of tension were placed in the semitendinosus graft and 40 N on the gracilis graft. An INTRAFIX tibial fixation system (DePuy Mitek Corp, Warsaw, IA) was used to secure the tibial side of the graft. The suture ends from the graft were then tied over a bicortical post and washer to provide back up fixation.[33]

Traditional Rehabilitation and the Eccentric Intervention

The patient progressed through a 3-phase traditional accelerated rehabilitation program[13,28,30] that was both criterion- and time-based (Table 1). The frequency of physical therapy was twice a week for 2 weeks, once a week for 4 weeks, and then once every other week until discharge criteria were met. The exercise prescription was determined by the individual response to exercise. Specifically, if exercises were completed without an increase in knee pain or effusion, the patient was considered ready to progress. Other exercises were then added or current exercises were continued at a higher intensity, frequency, and/or duration.

Beginning 3 weeks postsurgery, the patient began a 12-week negative work exercise program using a recumbent ECC ergometer, described previously in detail (Figure 1).[17,18] Briefly, the ergometer was driven by a 3-hp direct-current motor. Pedal speed was detected by an optical rpm sensor, and voltage and amperage outputs were monitored through an analog-to-digital board to a dedicated computer. The pedal speed was self-selected by the participant and ranged from 20 to 40 rpm. As the subject resisted the pedal motion, the eccentrically induced negative work rate was visible on the computer monitor and the total amount of negative work was recorded for each exercise session.

Prior to each session knee pain and thigh muscle pain were assessed on a 10-cm visual analog scale (VAS) anchored at one end of the scale (0 cm) by the descriptor "no pain" and at the other end (10 cm) by "extreme pain." Intensity of exercise was based on the Borg Rate of Perceived Exertion (RPE) Scale.[23] The first session was 5 minutes in duration at a "very, very light" intensity. Assuming a favorable individual response to exercise (ie, absence of increased knee pain, effusion, fatigue, etc), the patient was allowed to gradually progress in intensity and duration up to a maximum of 30 minutes.

TABLE 1. Details of the traditional rehabilitation guidelines.

Postoperative Phase	Rehabilitation Regimen
Phase 1 (duration, 2-3 wk)	• Early weight bearing and ROM exercises. Because this individual had significant knee hyperextension preoperatively, passive extension was not emphasized • Straight-leg strengthening and gait training • Goals for progression to phase 2: minimal pain and effusion, 0° to 100° knee ROM, good quadriceps contraction
Phase 2 (duration, 2-3 mo)*	• Endurance training (biking, stair stepper, etc) • Progressive resistance training (leg press, calf press, minisquats, hamstring curls, etc) • An emphasis was placed initially on low resistance and multiple repetitions, and then gradually replaced with sets of increasing resistance and fewer repetitions • Battery of balance exercises and beginning level plyometric exercises • Goals for progression to phase 3: full ROM, hop on 1 leg without pain
Phase 3 (duration, 3-6 months)	• Continued progressive resistance and endurance training • Jogging/running progression and advanced plyometric exercises • Advanced strengthening and functional exercise training to prepare the individual for full return to activity/sports • Goals for returning to full activity: 90% strength and performance ability compared to the non-surgical lower extremity

Abbreviations: ROM, range of motion.
* The 12-week negative-work exercise program via eccentric ergometry began upon entering phase 2.

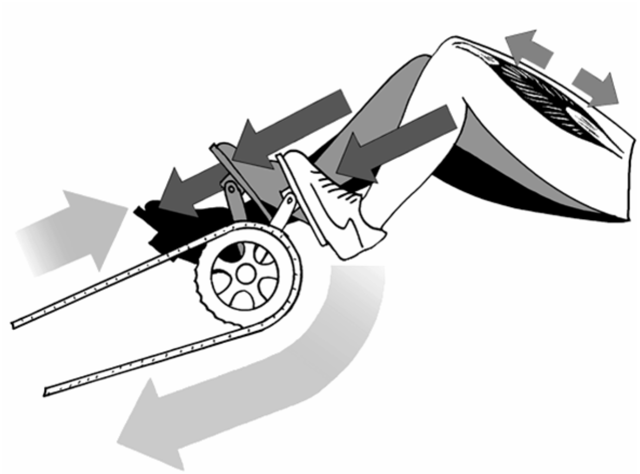

FIGURE 1. As the motor rotates the pedals at a set speed in a reverse direction (light, large arrows) the participant attempts to slow down the reverse moving pedals by applying force to the pedals (dark, medium arrows). Because the magnitude of force produced by the motor exceeds that produced by the participant, the pedals continue backward, resulting in eccentric lengthening of the quadriceps.

Tests and Measures

Postoperative clinical examinations and a magnetic resonance imaging (MRI) scan of the quadriceps were performed periodically throughout the rehabilitation process. Effusion was rated on a 0-to-3+ scale, as described by Roi et al.[27] A more comprehensive examination was performed preoperatively, 3 months and 1 year postsurgery. This included knee joint and thigh circumference measurements, KT1000 knee arthrometry, isokinetic quadriceps and hamstring testing (60°/s), functional testing (hop for distance test),[3] and completion of the Activity of Daily Living Scale-Knee Outcome Survey (ADLS-KOS)[11] (Table 2).

To determine muscle volume, an MRI of the quadriceps was performed prior to the training program (3 weeks postoperative), after the 12-week training program (15 weeks postoperative), and at 1 year postsurgery. A 1.5T GE Signa LX MRI instrument and body coil was used to obtain a coronal scout scan and axial T1-weighted images of the quadriceps. Bilateral thighs were scanned between the femoral head and the tibiofemoral joint line using an image matrix of 256 × 256, a field of view of 40 cm, a slice thickness of 8 mm, and an interslice distance of 15 mm. For this individual, this generated 21 MRI slices on each thigh for analysis. After electronic data transfer of images, CSA measurements and volume calculations were performed by use of custom-written image analysis software (Matlab; MathWorks, Natick, MA) on a desktop personal computer. For each image, the quadriceps was identified and manually traced using a computer mouse. The CSA of each slice was automatically computed. The quadriceps volume was calculated by multiplying the average of 2 consecutive CSA measurements by the interslice distance (23 mm) and then summing those values across the length of the muscle. The intratester reliability in this lab has been excellent using this measurement technique (intraclass correlation coefficient [ICC] = 0.99).

Rehabilitation course

After surgery the patient was instructed in a home exercise program that included rest, ice, elevation, ROM exercises, quad sets, and straight leg raises. He also used a home continuous passive motion (CPM) device.

Four days after surgery the patient began supervised rehabilitation. The patient was not taking any

CASE REPORT

TABLE 2. Outcome measures during the first postoperative year after anterior cruciate ligament reconstruction.

Days Postoperative	Knee ROM	Effusion*	Knee Circumference (cm)	Thigh Circumference (cm)†	KT1000 (mm)‡	Distance Hopped (cm)	ADLS-KOS§
Uninvolved							
–3	10°-0°-140°	0	37.0	45.0	-	169	-
100	10°-0°-140°	0	37.0	46.0	-	167	-
347	10°-0°-140°	0	37.0	46.0	-	178	-
Involved							
–3	8°-0°-130°	1+	37.5	43.5	6	128	56
4	0°-0°-80°	2+	-	-	-	-	-
14	0°-0°-100°	1+	-	-	-	-	-
21	5°-0°-110°	1+	37.5	41.0	-	-	57
61	7°-0°-130°	0/1+	37.5	45.0	-	-	69
100	8°-0°-130°	0	37.0	45.0	2	160	74
347	8°-0°-130°	0	37.0	46.0	2	165	80

Abbreviations: ROM, range of motion; ADLS-KOS, activity of daily living scale-knee outcome survey.
* Effusion was rated on a 0-to-3+ scale.
† Circumference of the thigh was taken 15 cm superior to mid patella.
‡ KT1000 value was the difference between injured and uninjured side.
§ 80 points total are possible on the ADLS-KOS.

TABLE 3. Details of the 12-week eccentric ergometry regimen following the initial anterior cruciate ligament reconstruction (starting at postoperative day 18).

Training Week	Exercise Session	Rate of Perceived Exertion	Time (min)
1	1	Very, very light	5
	2	Very light	10
	3	Fairly light	10
2	4	Light	14
	5	Somewhat hard	14
	6	Somewhat hard	15
3	7-9	Somewhat hard	15
4	10-12	Somewhat hard	18
5	13-15	Somewhat hard	20
6	16-18	Somewhat hard	20-25
7-8	19-23*	Somewhat hard	20-25
9-12	24-31*	Hard	26-30

Abbreviations: RPE, rate of perceived exertion.
* Denotes exercise session frequency less than 3 times per week.

medication at this time and entered the clinic carrying his crutches. The patient met all phase 1 rehabilitation goals by 2 weeks postsurgery, progressed to phase 2, and began ECC ergometry training at 3 weeks postsurgery. Details of the training program are included in Table 3. The patient completed 31 ECC ergometry sessions over the 12-week period. High values of negative work via ECC ergometry were tolerated well by this individual without appreciable increases in knee or thigh pain (Figure 2).

The patient met discharged criteria 16 weeks post ACL-R (after 11 physical therapy visits and 31 ECC training sessions). He continued unsupervised rehabilitation by regularly lifting weights, jogging 2 to 3 times per week, and completing his high-intensity biking routine 8 to 10 hours per week. Six months after surgery, he added hill sprints and the dry-land-skiing training program. He started skiing regularly once the ski season began 8 to 9 months after surgery.

OUTCOMES, PART 1

The early outcomes (after 12 weeks of ECC training [100 days postsurgery]) were excellent. Compared to 3-week postsurgical measures, quadriceps volume had improved 28% in the surgical thigh and 14% in the nonsurgical thigh. The quadriceps volume index (volume involved/volume uninvolved) improved from 80% (pretraining) to 90% (posttraining). Force production (peak torque at 60°/s) 15 weeks postsurgery was 20% greater on the surgical side and 14% greater on the nonsurgical side compared to preoperative measures (testing performed 5 weeks postinjury just prior to surgery). The quadriceps strength index was higher 15 weeks after surgery (84%), as compared to presurgery (80%). Hamstring strength was less 15 weeks after surgery bilaterally compared to presurgery values. Other outcome measures are displayed in Table 2.

Outcomes 1 year after surgery were superior to 15-week outcome measures in virtually all areas (Table 2). Quadriceps volume on the surgical side improved an additional 8% while the nonsurgical side added another 3% (Figure 3). The quadriceps volume index at that time was 96%. Quadriceps strength improved 7% (surgical side) and was 2% less on the nonsurgical side. The quadriceps strength index at that time was 93%. Force production of the hamstrings improved over 40% on the surgical side and 20% on the nonsurgical side. The hamstring strength index improved from 71% (presurgery), to 75% (15 weeks after surgery), to 100% (1 year after surgery) (Figure 4).

Functionally at 1 year postsurgery, the patient stated he had exceeded his physical level of a year previous. He reported he skied 10 times in November, 20 times in December, and 10 to 15 times in January with absolutely no limitations, saying, "I am skiing harder now than I have ever skied before."

DISCUSSION, PART 1

Restoration of the quadriceps is a primary goal for all those who undergo ACL-R, whether the person is an elite, recreational, or "armchair" athlete. This case report suggests negative-work exercise using ECC ergometry has the potential to facilitate quadriceps return early after ACL-R.

Roi et al[27] recently described an impressive case report of returning an elite soccer player to competition 77 days after ACL-R. In the current case, the goal of ECC intervention was not to hasten return to sport; rather, it was to facilitate a rapid return of the quadriceps size and strength. This goal was achieved. In only 12 weeks, quadriceps volume in the surgical lower extremity increased 28%. That value was actu-

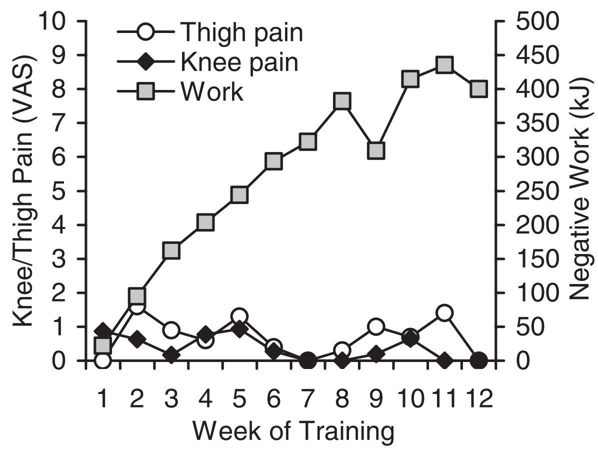

FIGURE 2. Values of negative work increased throughout training while knee and thigh pain remained at low levels (week 1 is 3 weeks post anterior cruciate ligament reconstruction using a hamstring autograft).

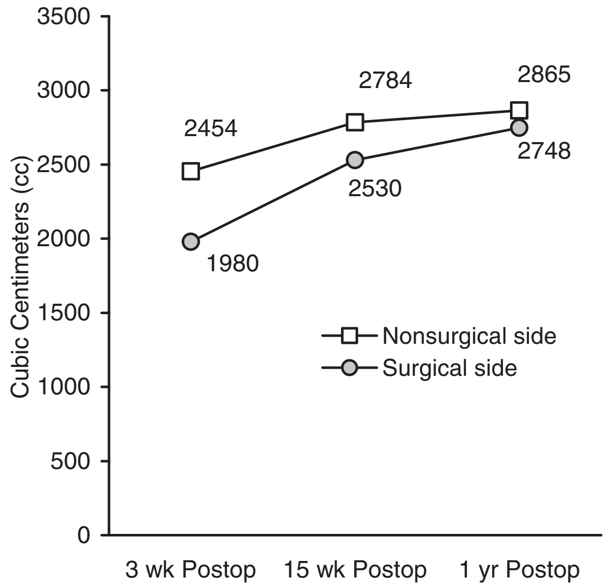

FIGURE 3. Quadriceps volume after anterior cruciate ligament reconstruction using a hamstring autograft.

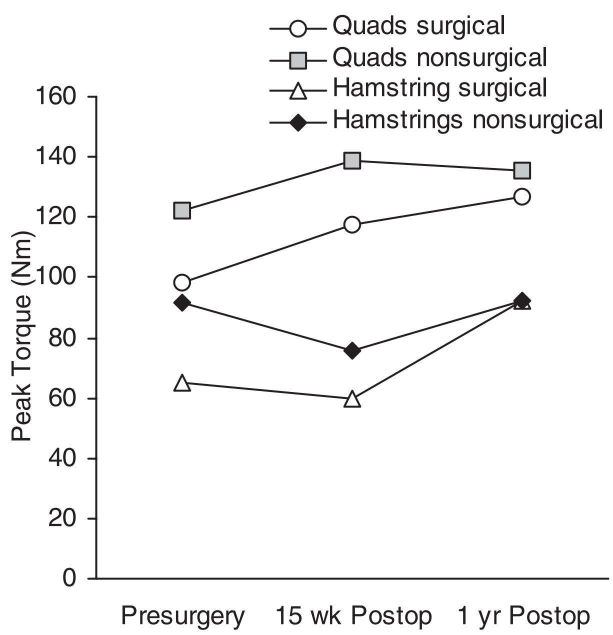

FIGURE 4. Quadriceps and hamstring isokinetic peak torque at 60°/s prior to and after anterior cruciate ligament reconstruction using a hamstring autograft. The presurgery measurement was done 5 weeks after initial injury.

ally 3% greater than the pretraining quadriceps volume of the nonsurgical lower extremity. By 15 weeks postsurgery, quadriceps strength was 20% (surgical lower extremity) and 14% (nonsurgical lower extremity) greater than preoperative measures. In contrast, most studies have reported a 10% or greater loss of quadriceps strength 3 to 6 months postsurgery of the involved side, with no change or slight loss of strength of the uninvolved side.[6,13,14] Keays et al[13] concluded "an intensive quadriceps rehabilitation program is insufficient to restore fully quadriceps strength by 6 months after surgery." Furthermore, many others have described persistent quadriceps deficits after ACL-R much longer than 6 months.[1,5,7-9,12,22,25,28] After completing 1- to 2-year follow-ups, Rosenberg et al[28] concluded that patients with ACL-R still experienced permanent weakness and deficits in performance. Given the current evidence, instead of asking how long it takes for full quadriceps recovery after ACL-R, perhaps one should be asking, "How can these large quadriceps deficits be prevented or at least curtailed?"

The chronic difficulties associated with a return of quadriceps size and function after ACL-R is the impetus for trying novel interventions. The application of negative work by exercising a muscle eccentrically is certainly not novel as a general strengthening regime, but its application in the rehabilitation setting (particularly following ACL-R) is still in its infancy. This is surprising, because negative-work exercise seems particularly well suited to increase structure and strength in severely atrophied or deconditioned muscle. ECC muscle actions are characterized by high force production at low metabolic costs, compared to CON muscle actions.[17] Exercising a muscle eccentrically, therefore, has the capability of producing greater overload to muscle, which leads to greater hypertrophy and strength gains. Remarkably, these adaptations can be achieved at a reduced energy expenditure.[4,17] This is an appealing combination for those participating in rehabilitation. If the primary goals include gaining muscle size and strength (as is commonly needed after ACL-R), negative work exercise seems ideally suited to assist a patient in reaching those goals.

Although seemingly beneficial, it is important to balance the potential benefits with the potential risks of adding an ECC intervention after ACL-R. In this case, adding ECC exercise early during postoperative rehabilitation might raise concerns about safety. It should be emphasized that the ECC intervention was gradually and progressively applied, and the resultant levels of negative work also increased progressively. The individual response to exercise was also carefully monitored throughout the training to minimize the possibility of joint articular cartilage damage or compromise of the surgical repair. The presence of minimal joint pain, decreasing joint effusion, a KT1000 difference of 2 mm, no subjective feeling of instability, and a continual progression in functional abilities all suggest that this intervention was tolerated well by this individual.

In a recent editorial, Wilk[35] addressed this topic regarding the "speed limits" during rehabilitation. We concur with his assessment; that after ACL-R, exceeding the rehabilitation speed limit could lead to long-lasting unsatisfactory knee function. Not going fast enough, however, may also lead to persistent knee dysfunction. For example, withholding or delaying early ROM exercises could lead to prolonged knee stiffness, limitation of knee extension, delay in strength recovery, and anterior knee pain.[30] On the other hand, the early emphasis on ROM exercises after ACL-R can decrease these complications.[30] Could the same be found for muscle? Could an early emphasis on quadriceps strengthening by progressively increasing eccentrically induced negative-work exercise mitigate muscle size and strength deficits following ACL-R?

It would not be uncommon for a recreational athlete to wait 2 to 3 months after tearing the ACL to have surgery. The volume and intensity of muscle activity would immediately diminish and dramatically decrease even more after surgery. This contributes to the well-known quadriceps atrophy and strength deficits observed after surgery. Phase 1 exercises and typical patient activities fail to sufficiently prevent atrophy of the quadriceps. Hence, atrophy peaks approximately 3 to 4 weeks after surgery.[24] Adding ECC training early after surgery could theoretically reduce the time of chronic quadriceps underloading and therefore lead to a quicker and possibly more complete quadriceps recovery.

Generally, the goal of rehabilitation is to return an individual quickly and safely to his or her highest functioning level. After ACL-R, this requires a safe, feasible, and effective rehabilitation strategy. For this individual, it appears that the gradual and progressive addition of negative work exercise via ECC ergometry early after ACL-R was both safe and efficacious. We are currently conducting a randomized clinical trial to further determine the safety, feasibility, and efficacy of early ECC intervention after ACL-R.

CASE DESCRIPTION, PART 2

It is difficult to expect a better outcome 1-year after ACL-R than what was seen for this individual. Even when considering that this individual's nonsurgical leg improved substantially in muscle size, strength, and functional performance following training, the surgical leg comparisons in muscle size, strength, and performance were over 90% in all areas. Clinical examination measures were near normal and self-report measures were outstanding. The patient had returned to full aggressive sports participation with no reports of instability.

Unfortunately, while skiing in late February 2005, the patient reported he jumped 10 m over a "cat track," misjudged the jump depth, and landed "tails first" (on the back of his skis). He attempted to recover by turning slightly and forcefully pulling his body to an upright position while his skis remained in contact with the snow. He reported his knee felt like it "popped." Immediately afterwards, he was able to ski carefully down without gross knee instability. Minimal pain and a small effusion were present on initial examination (general practitioner), and he was diagnosed with a "knee sprain." However, upon attempting to ski a week later, gross instability was experienced and ACL graft disruption was soon confirmed by orthopedic evaluation. The patient performed light exercise (stationary bike primarily) for 3 weeks until ACL revision surgery was performed using a patellar tendon autograft.

Surgery

Assessment of the tunnels from the previous surgery determined tunnel location to be appropriate. Therefore, following harvest of an 11-mm-wide strip of patella tendon with an 11 × 25-mm patella bone block and an 11 × 30-mm tibial bone block, the tunnels were cleared of soft tissue and drilled to accommodate the 11-mm bone plugs. Femoral fixation was achieved using the RIGIDFIX cross pin system (DePuy Mitek Corp, Warsaw, IA), placing 2 bioabsorbable pins across the femoral bone block. Tibial fixation was achieved using a 9 × 20-mm metal interference screw. Bone graft was placed in the patella defect, the patella tendon defect was closed, and a standard skin closure completed the procedure.[2]

Rehabilitation course

The patient followed the same postoperative rehabilitation course as with the hamstring graft procedure, with minor exceptions (Table 1). He did not use a CPM after surgery and he had 3 electrical muscle stimulation treatments during his first 3 postoperative rehabilitation sessions. The patient reported much more pain, stiffness, and difficulty contracting the quadriceps after the revision surgery. It also took 1 week longer to pedal a full circle on the stationary bicycle.

Intervention

The patient desired to follow a similar ECC training program after ACL revision. The 12-week negative work exercise program was conducted in a similar fashion; however, a different ECC ergometer (Eccentron, LLC, Denver, CO) was used (Figure 5). The first ergometer was similar to a recumbent cycle, while the second was similar to a recumbent stepper. The Eccentron (not available during the initial rehabilitation) was used after the ACL revision due to its increased durability and comfort. Although different in appearance, the concept of high force production leading to negative work remained the same. A 3-hp motor induced a load on the muscle that required the muscle to resist in an ECC fashion. As well, the motor performance requirements while exercising on

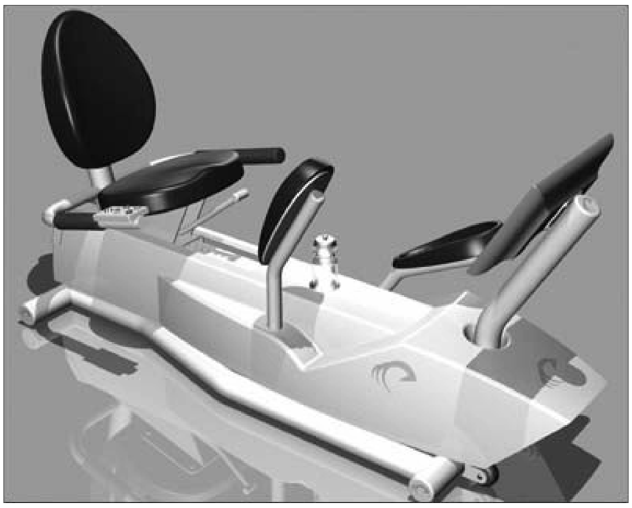

FIGURE 5. An internal motor powers the pedals to move in a reciprocal manner. As the pedal moves towards the participant (to the left in this figure) he or she attempts to slow it down by applying force to the pedal. Because the magnitude of force produced by the motor exceeds that produced by the participant, the pedal continues which results in eccentric lengthening of the quadriceps.

the 2 ergometers appeared similar. The participant resisted the motor-propelled pedals from approximately 20° to 60° of knee flexion in both cases, creating negative work via ECC contraction of the quadriceps.

The patient followed a similar course of ECC ergometry training (Table 3), although after revision he completed 33 ECC ergometry sessions over the 12-week training period and began on postoperative day 21. Knee pain was 3 times greater (compared to after the hamstring ACL-R) at the start of training, but decreased to similar low levels 3 weeks into training. High values of negative work via ECC ergometry were again tolerated well by this individual after ACL revision without appreciable increases in knee or thigh pain throughout the training program.

OUTCOMES, PART 2

MRI images were taken 4 weeks after reinjury (prior to surgery), 3 weeks after surgery, and after the 12-week training program. The quadriceps volume of both thighs decreased 6% to 7% from the time of reinjury to the time of surgery (in 4 weeks). Three weeks after revision surgery, the quadriceps of the surgical thigh atrophied an additional 15%, while the nonsurgical thigh atrophied an additional 2%.

After the 12-week training program, the quadriceps volumes were similar to the values reached after an ACL-R of a year previous (Figure 6). Force production of both quadriceps and hamstrings exceeded all previous measures (Table 4). Table 4 compares the outcomes 15 weeks after ACL-R using the hamstring autograft with the outcomes 15 weeks after ACL revision using the patellar tendon autograft.

DISCUSSION, PART 2

This case report provides an excellent illustration of changes in muscle size and strength over a course of 2 ACL injuries and the respective rehabilitation programs using an ECC intervention. The adaptation of muscle to a chronic overload is hypertrophy. The adaptation of muscle to a chronic "underload" is atrophy.[20] This concept is evident in Figure 6 and is described both in the Figure 6 legend and with the following 7 times. (Time 1) Preinjury quadriceps volume may not be known precisely; however, a reasonable estimation may be determined from the uninvolved lower extremity. Because this individual returned to similar high-level activities 1 year after surgery, preinjury quadriceps volume of both thighs was most likely similar (approximately 2800 cc) to the calculated quadriceps volume of the uninvolved thigh 1 year after surgery. (Time 2) After the first injury, 2 months of simply decreased activity lead to 13% quadriceps atrophy of the uninvolved lower extremity. The quadriceps of the involved lower extremity atrophied 29%, likely due to a much greater degree of decreased activity (3 weeks in a knee immobilizer prior to surgery, knee pain, and effusion from injury and surgery, decreased weight bearing, etc). (Time 3) After the first surgery, 12 weeks of ECC training and traditional rehabilitation led to hypertrophy of 28% (surgical quadriceps) and 14% (nonsurgical quadriceps). (Time 4) Following discharge from physical therapy after the first surgery, typical

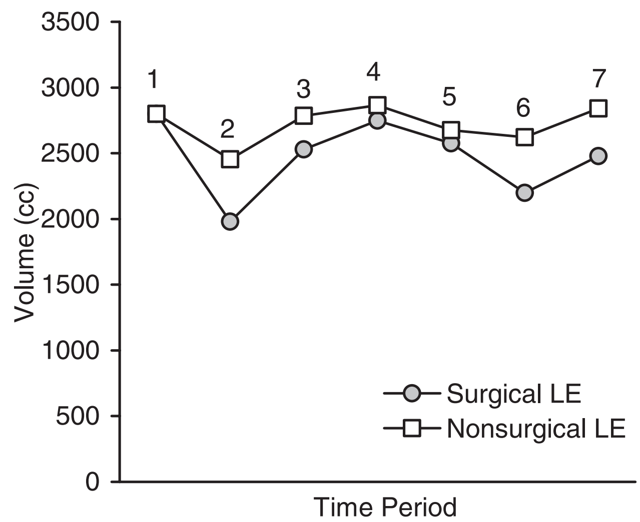

FIGURE 6. Quadriceps volume over time for the same individual after 2 anterior cruciate ligament reconstructions. (1) Estimated volume of both thighs prior to injury, based on post rehabilitation nonsurgical quadriceps volume; (2) Three weeks post ACL-R using hamstring autograft prior to initiating eccentric ergometric training program; (3) Fifteen weeks post ACL-R after 12 weeks of eccentric ergometric training; (4) One year post ACL-R; (5) Four weeks after reinjury, prior to surgical revision; (6) Three weeks after revision prior to initiating eccentric ergometric training program; (7) Fifteen weeks after revision after 12 weeks of eccentric ergometric training.

TABLE 4. Comparison of results 15 weeks after anterior cruciate ligament reconstruction (hamstring autograft) and anterior cruciate ligament revision (patellar tendon autograft).

Outcome Measure (Days Postsurgery)	ACL-R (100)	ACL revision (105)
Knee ROM	8°-0°-130°	8°-0°-130°
Effusion*	0/1+	0
Knee circumference (cm)	37	37
Thigh circumference (cm)	45	45
KT1000 difference (mm)	2	2
Distance hopped (cm)	160	176
ADLS-KOS†	74	72
Quadriceps strength (Nm)	118	149
Hamstring strength (Nm)	60	92

Abbreviations: ACL-R, anterior cruciate ligament reconstruction; ROM, range of motion; ADLS-KOS, activity of daily living scale-knee outcome survey.
* Effusion was rated on a 0-to-3+ scale.
† 80 points total are possible on the ADLS-KOS.

progressive-resistance exercises, running, sports training, and 2 months of aggressive skiing led to further increases in quadriceps volume of 9% (involved lower extremity) and 3% (uninvolved lower extremity). (Time 5) Unlike what occurred after the initial ACL disruption, only minimal pain an effusion was experienced after the reinjury. Also, during preoperative management, neither crutches nor a knee immobilizer was used. Therefore, quadriceps activity of both thighs decreased to a similar extent. Four weeks after reinjury quadriceps volume decreased 7% bilaterally. (Time 6) Further quadriceps atrophy was evident 3 weeks after revision surgery (an additional 15% on the surgical side and 2% on the nonsurgical side). (Time 7) After 12 weeks of ECC training and traditional rehabilitation following revision surgery, quadriceps volume returned to similar levels at the same postoperative time period as was achieved after the initial surgery (2% less on the surgical side and 2% greater on the nonsurgical side).

Clearly, the changes in quadriceps volume and strength of both lower extremities can be quite considerable when a person injures the ACL, has surgery, and undergoes rehabilitation. Research outcomes often focus on comparing muscle size, strength, and performance ability of the injured knee to the normal uninjured knee.[15,26,28,29] Unfortunately, the normal knee after ACL injury and reconstruction in many cases is in all likelihood significantly deconditioned and atrophied prior to the comparison. The first volume index (3 weeks after ACL-R) for this case report would have lead to the conclusion that the surgical quadriceps atrophied 19% compared to the normal thigh. However, a more accurate statement would have been that the surgical quadriceps were 19% smaller than the already 13% atrophied nonsurgical quadriceps. In this example, a quadriceps volume index would have been a good measure of muscle symmetry, but not necessarily a good measure of muscle recovery. The use of indices as outcome measures following ACL-R may provide useful information, but should be interpreted with caution.

CONCLUSIONS

This case report suggests that negative work exercise via ECC ergometry, if gradually and progressively applied, can be both safe and efficacious early after ACL-R. High values of negative work via ECC ergometry were tolerated well by this individual without any apparent adverse effects to the knee joint. Adding ECC training to traditional ACL rehabilitation has the potential to induce substantial muscle size and strength gains that exceed those changes described following traditional rehabilitation. Positive results can be obtained using different applications of ECC exercise to produce negative work and with the patient having either the hamstring or patellar tendon autograft procedure. This case suggests the tremendous plasticity of the quadriceps following ACL-R-induced atrophy and subsequent exposure to negative-work exercise, which resulted in an apparent amplified hypertrophic response and strength return. Further research is warranted to determine the short- and long-term effects of ECC intervention after ACL-R and on other rehabilitative conditions involving atrophied or deconditioned muscle.

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