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Accelerated Versus Nonaccelerated Rehabilitation After Anterior Cruciate Ligament Reconstruction

A Prospective, Randomized, Double-Blind Investigation Evaluating Knee Joint Laxity Using Roentgen Stereophotogrammetric Analysis

Bruce D. Beynnon,*† PhD, Robert J. Johnson,† MD, Shelly Naud,† PhD, Braden C. Fleming,‡ PhD, Joseph A. Abate,† MD, Bjarne Brattbakk,† MS, PT, and Claude E. Nichols,† MD
Investigation performed at the University of Vermont College of Medicine, Burlington, Vermont

Background: The relationship between the biomechanical dose of rehabilitation exercises administered after anterior cruciate ligament (ACL) reconstruction and the healing response of the graft and knee is not well understood.

Hypothesis: After ACL reconstruction, rehabilitation administered with either accelerated or nonaccelerated programs produces the same change in the knees' 6 degrees of freedom, or envelope, laxity values.

Study Design: Randomized controlled trial; Level of evidence, 1.

Methods: Patients who underwent ACL reconstruction with a bone–patellar tendon–bone autograft were randomized to rehabilitation with either accelerated (19 week) or nonaccelerated (32 week) programs. At the time of surgery, and then 3, 6, 12, and 24 months later, the 6 degrees of freedom knee laxity values were measured using roentgen stereophotogrammetric analysis and clinical, functional, and patient-oriented outcome measures.

Results: Eighty-five percent of those enrolled were followed through 2 years. Laxity of the reconstructed knee was restored to within the limits of the contralateral, normal side at the time of surgery (baseline) in all participants. Patients in both programs underwent a similar increase in the envelope of knee laxity over the 2-year follow-up interval (anterior-posterior translation 3.2 vs 4.5 mm, and coupled internal-external rotations 2.6° vs 1.9° for participants in the accelerated and nonaccelerated programs, respectively). Those who underwent accelerated rehabilitation experienced a significant improvement in thigh muscle strength at the 3-month follow-up ($P < .05$) compared with those who participated in nonaccelerated rehabilitation, but no differences between the programs were seen after this time interval. At the 2-year follow-up, the groups were similar in terms of clinical assessment, patient satisfaction, function, proprioception, and isokinetic thigh muscle strength.

Conclusion: Rehabilitation with the accelerated and nonaccelerated programs administered in this study produced the same increase in the envelope of knee laxity. A majority of the increase in the envelope of knee laxity occurred during healing when exercises were advanced and activity level increased. Patients in both programs had the same clinical assessment, functional performance, proprioception, and thigh muscle strength, which returned to normal levels after healing was complete. For participants in both treatment programs, the Knee Injury and Osteoarthritis Outcome Score (KOOS) assessment of quality of life did not return to preinjury levels.

Keywords: knee; anterior cruciate ligament; rehabilitation; reconstruction

After anterior cruciate ligament (ACL) reconstruction, immobilization of the knee can produce undesired effects for the articular cartilage, ligaments, capsule, musculature, and periarticular bone.[22-24,30] Rehabilitation programs that incorporate immediate motion of the knee appear to be safe and effective compared with programs that delay the onset of motion,[17,31,32,35] and it is clear that early mobilization with full weightbearing is possible without damaging the graft.[26,37,38,42] There is, however, little known about how much activity promotes adequate rehabilitation without permanently elongating the graft or producing abnormal

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laxity of the knee, which can damage the articular cartilage and menisci.[10] In comprehensive reviews of randomized controlled studies on rehabilitation after ACL injury, Trees et al[41] concluded that "there is insufficient evidence to support the efficacy of one exercise intervention over another in the conservative or post-reconstruction treatment of adults," and Andersson et al[2] concluded that "weaknesses pertaining to study design were discovered among the included randomized controlled trials, which intelligibly stress the need for further high-quality studies."

In an effort to gain insight into the effect that rehabilitation exercise dosing has on the healing response of the graft and knee, a pilot prospective, randomized study of accelerated versus nonaccelerated rehabilitation after ACL reconstruction was performed.[10] Participants in both treatment groups underwent a similar increase of anterior displacement of the tibia relative to the femur, had similar clinical assessment, and were equally satisfied. This study focused on a single degree of freedom of knee laxity, anterior-posterior (A-P) displacement of the tibia relative to the femur, and served as the motivation for the current investigation, which built on this prior work by comparing the same rehabilitation programs using highly accurate roentgen stereophotogrammetric analysis (RSA) to measure the 6 degrees of freedom (the entire envelope) laxity behavior of the tibiofemoral joint and including a comprehensive selection of secondary outcome measures. The primary hypothesis was that there would be no difference in the envelope of knee laxity for patients treated with accelerated versus nonaccelerated rehabilitation programs, while the secondary hypothesis was that there would be no difference in clinical assessment, patient satisfaction, functional performance, proprioception, activity level, and thigh muscle strength between the programs.

MATERIALS AND METHODS

This investigation was designed as a prospective, randomized controlled trial of accelerated versus nonaccelerated rehabilitation and was based on an intent-to-treat protocol and analysis. The investigation was approved by our institution's Committee on Human Research.

Before we conducted this investigation, the sample size was justified based on the change of A-P laxity between the baseline and 2-year follow-up interval. A 2.0-mm difference in the baseline to 2-year follow-up change of A-P laxity between the accelerated and nonaccelerated treatments and a corresponding standard deviation of 2.0 mm was considered to be clinically relevant, well within the measurement resolution of RSA, and produced a moderate effect size. It was determined that a sample size of 15 patients per group would be necessary to detect the 2.0-mm difference with 80% power when alpha was set equal to .05. Anticipating that we would lose 20% of participants enrolled at long-term follow-up, we planned to enroll 21 patients in each group.

Participants, Eligibility Criteria, and ACL Reconstruction Technique

Between December 1998 and May 2001, a total of 390 patients who had an ACL tear visited our university-affiliated private practice clinic and sought care from 1 of 2 orthopaedic surgeons (Figure 1). The study was carried out at a single center and patients were referred to our clinic by their primary care provider, our university-affiliated emergency department, or they were self-referred to our clinic. As patients were seen at our clinic, they were screened to determine if they met the eligibility criteria. Patients were excluded before surgery if they had a previous injury or operation to either knee; were either younger than 18 or older than 50 years of age; had a simultaneous fracture or a concurrent injury to the posterior cruciate ligament, posterior lateral corner, or lateral collateral ligament; had a grade II or III medial collateral ligament tear, evidence of osteoarthritis radiographically, or a suspected tear of the meniscus; had a Tegner score of 4 or less before injury; suffered from disease such as diabetes or rheumatoid arthritis; or were pregnant. Patients were excluded from the study at the time of surgery if a significant portion of the ACL remained intact, they had cartilage lesions with exposed bone, or if they underwent meniscus repair. Those who required debridement or partial meniscectomy were included.

The treatment and care programs, other than the accelerated and nonaccelerated programs, were identical for all study participants. Reconstruction was performed with the same technique in all cases with a bone–patellar tendon–bone graft that was constructed from the central third of the patient's ipsilateral patellar tendon. Anatomic landmarks were used to position the tibial and femoral bone tunnels such that the posterior edge of the tibial tunnel was 2 mm anterior to the posterior cruciate ligament and the posterior edge of the femoral tunnel left no more than 1 to 2 mm of cortex relative to the over-the-top position.[21] The femoral bone block was fixed in the femoral tunnel with an interference screw; the knee was then moved to 10° of flexion, and the graft was tensioned by pulling on the sutures located within the tibial bone block. The graft tensioning procedure was designed to restore normal A-P laxity and establish common baseline conditions for all study participants. This was accomplished by partially fixing the graft within the tibial tunnel using an interference screw and then measuring

*Address correspondence to Bruce D. Beynnon, PhD, McClure Musculoskeletal Research Center, Department of Orthopaedics and Rehabilitation, University of Vermont College of Medicine, 438A Stafford, 95 Carrigan Drive, Burlington, VT 05405-0084 (e-mail: Bruce.Beynnon@uvm.edu).

†McClure Musculoskeletal Research Center, Department of Orthopaedics and Rehabilitation, University of Vermont College of Medicine, Burlington, Vermont.

‡Department of Orthopaedics, Warren Alpert Medical School of Brown University, Providence, Rhode Island.

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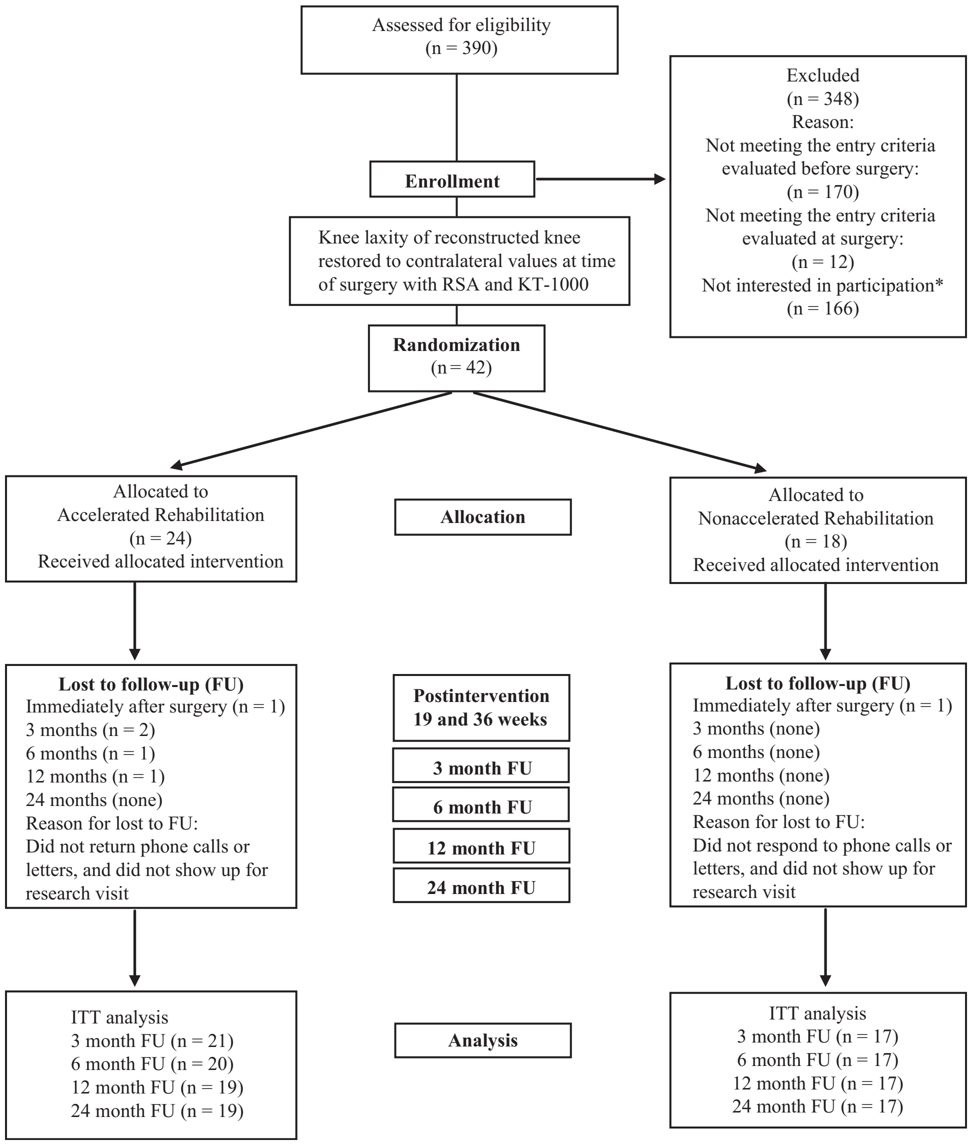

Figure 1. Movement of patients through the study.

A-P laxity of the knee with the KT-1000S arthrometer (MEDmetric Inc, San Diego California). If A-P laxity was greater than 1 mm of the contralateral, normal side, the screw was removed and the graft tension adjusted until the difference in laxity between the reconstructed and normal knees was less than 1 mm.

Randomization and Assignment of Study Participants to Accelerated and Nonaccelerated Rehabilitation Programs

Immediately after surgery, participants were randomized into either the accelerated or nonaccelerated rehabilitation program using a computer-based random number generation program. The patient, treating physician, and individual responsible for making the follow-up measurements were blinded from the randomization procedure; they were blinded to the treatment groups to which the patients were assigned; and assignment of the treatment was concealed prior to allocation with the use of sealed envelopes.

The literature on rehabilitation after ACL reconstruction has been based on study designs that have compared many variables within the same study (eg, exercises, restrictions, limitations, precautions, use of modalities, return to sport/activity), and we designed a study to gain insight into how the "biomechanical dose" of rehabilitation exercises affected the outcomes by administering the same treatment program over 2 time intervals: a 32-week nonaccelerated program and a 19-week accelerated program. Detailed, day-by-day, descriptions of the programs are presented in the form of the daily logs that were used to administer them to the study participants (see Appendices A and B; all appendices for this article are available online at http://ajs.sagepub.com/supplemental/). The rationale for selecting the exercises and time frames when they were initiated in each program was based on the fact that we truly do not know the temporal biomechanical and biological response of the healing graft and knee after ACL injury and reconstruction.[10] Most of what is known about the material and structural properties of the ACL graft during healing has been derived from studies performed with animal models and these findings are difficult to apply to humans. Consequently, we conducted a study that was designed to provide a controlled comparison of rehabilitation administered over time intervals that were chosen based on how they strained the healing graft. Briefly, the programs were based on prior in vivo studies of ACL strain biomechanics performed in humans,[6-8] which considered the important weightbearing and muscle loads that affect the biomechanical environment of the graft and knee during healing. Crutch use, the amount of weightbearing permitted, the magnitude of quadriceps activity, the flexion angle at which quadriceps dominated exercises were applied, and the time frame when the exercises were initiated were selected to produce a difference in the magnitude of strain to which the healing graft was exposed. For example, based on prior studies,[6,8] we know that weightbearing strains the ACL and consequently crutch use was discontinued on day 8 for those assigned to the accelerated program and on day 22 for those in the nonaccelerated program. As another example, exercises that involved contraction of the quadriceps in isolation with the knee near extension produce considerable strain across the healing graft and consequently these exercises were started earlier in the accelerated program and they were delayed in the nonaccelerated program relative to a point in time that we estimated the graft and knee were most vulnerable (ie, the time interval over which the graft was undergoing necrosis, revascularization, repopulation with new cells, its material properties were degrading, and consequently it was likely to be at risk to exposure to high strain values). Exercises that increased ACL strain values such as extension of the knee by contraction of the quadriceps muscles were initiated earlier in the accelerated program than the nonaccelerated program, while exercises that did not strain the ACL were started at the same point in time in both programs. The same approach was used to prescribe restrictions, limitations, precautions, and return to sport/activity for each program; these details are presented in Appendices A and B.

Rehabilitation was administered by the same physical therapist using an established approach.[10] Participants in both programs were instructed to perform exercises daily. Over the duration of the program, the patients visited our rehabilitation center 3 times per week to perform the exercises under supervision. Participants from different programs did not attend rehabilitation sessions at the same time and at other times they performed exercises at home. Each patient received a daily log that outlined the goals of the programs, explained restrictions, described how the specific exercises were performed, and highlighted the number of exercise sets, repetitions, and sessions that were prescribed for each program (Appendices A and B). Participants used the log daily to record the number of sets, repetitions, and sessions of each exercise they completed. The logs were reviewed with the therapist weekly in an effort to monitor progress. The daily log data were also used to measure compliance, which was calculated as the percentage of prescribed exercises that were completed each day and averaged over the duration of each program. A compliance of 100% indicated the patient completed every exercise (sets and repetitions) over the duration of interest (ie, the time interval that was considered—weeks, months, or the entire program). A compliance greater than 100% indicated that patients completed more than what was prescribed and, conversely, a value less than 100% indicated they did less. These compliance data were also used as covariates in the statistical analysis.

Follow-up Evaluations

Participants were evaluated preoperatively and then at 3, 6, 12, and 24 months by the same independent observer who was blinded to the treatment groups to which the participants were assigned. These evaluations included the primary outcome measure of knee laxity (also measured immediately after surgery in an effort to establish that baseline laxity was restored to the value of the contralateral, normal, knee), and the outcome measures of clinical assessment (International Knee Documentation Committee [IKDC]), patient outcome (Knee Injury and Osteoarthritis Outcome Score [KOOS]), function (one-legged hop), activity level (Tegner score), proprioception (threshold to detection of passive knee motion), and thigh muscle strength (isokinetic strength).

The primary outcome, the 6 degrees of freedom displacements of the tibia relative to the femur, was measured with RSA using the methods that have been described and validated.[5,13] Roentgen stereophotogrammetric analysis provided an accurate evaluation of the entire envelope of knee laxity by measuring the A-P, medial-lateral, proximal-distal, internal-external, varus-valgus, and flexion-extension displacements of the tibia relative to the femur that were produced by the anterior (130 N) to posterior (90 N)–directed loads applied to the knee. These measurements were obtained immediately after ACL reconstruction (while the patient remained under anesthesia) and then at the follow-up intervals (performed without anesthesia) using the approach described in Appendix C (available online). The KT-1000 arthrometer was used by the same investigator to provide a single degree of freedom measurement of displacement of the tibia relative to the femur prior to the surgery (to evaluate the effect of joint injuries on knee biomechanics), at the time of surgery during tensioning of the graft (to allow us to confirm that A-P laxity of the normal knee joint was restored to within the limits of the contralateral side), and then postoperatively at all follow-up intervals (to allow comparisons with the RSA).

The IKDC rating system has been validated for investigations of ACL reconstruction and was used to evaluate clinical outcome.[19] Eight different categories were evaluated and the final score was based on 4 of them: (1) the patient's assessment of function, (2) symptoms, (3) range of knee motion, and (4) clinical examination. Each category was rated on a 4-point scale. The worst rating of any item in a category determined the final category rating and the final IKDC rating was then based on the score of the worst category.[19]

The KOOS was self-administered by the study participant and assessed 5 outcomes: pain, symptoms, activities of daily living, sport and recreation function, and knee-related quality of life.[33,34] Previous work has validated the KOOS for the study of ACL injury, demonstrating that it is responsive to ACL reconstruction and rehabilitation, and has shown that it is a reliable instrument for patients undergoing ACL reconstruction and rehabilitation.[34]

Knee function was evaluated with the one-legged hop test. This was chosen because it is well correlated with power, it has the advantage of evaluating each leg in isolation, and it is a highly reproducible test.[1] At each visit, participants were instructed to hop as far as possible with their arms free while taking off and landing on the same limb. They performed 3 trials on each limb, alternating normal and reconstructed limbs, and the hop distance was measured from toe to toe. The maximum value of the 3 trials obtained from each limb was recorded as the jump length.

Activity level was measured with the Tegner activity scale before surgery and at all follow-up visits. The Tegner scale measured activity level based on participation in sports and work and has been validated for the study of individuals after ACL injury, reconstruction, and rehabilitation.[11]

Knee proprioception was evaluated by measuring the threshold to detection of passive knee motion with a device that had established reliability and precision[9] (see Appendix D, available online). Participants sat blindfolded on an adjustable, padded chair, such that the popliteal region of the knee did not contact the seat bottom when the leg rested in a flexed position. The threshold to detection of passive knee motion of the normal and ACL-reconstructed limbs was evaluated with movement of the knee into flexion (3 times on both sides) or extension (3 times on both sides). Data from each set of the 3 trials were averaged and used for statistical analysis.

Strength of the knee extensors and flexors were evaluated at 60 deg/sec using gravity correction with the Biodex System 3 isokinetic dynamometer (Biodex Medical Systems, Shirley, New York). After the participants were properly positioned and given instructions, they performed a series of submaximal repetitions to familiarize themselves with the test. They then performed 5 maximal test repetitions and the repetitions with the greatest peak torque values were recorded and normalized to the participant's body weight for statistical analysis.

Statistical Analysis

The objective was to compare the 2 treatment groups on multiple clinical tests evaluated 5 times over the 2-year follow-up interval. Roentgen stereophotogrammetric analysis measurement of knee laxity was the primary measure of efficacy. The significance level was .05 for all analyses. This provided the greatest power for detecting a group difference given an expectation that the 2 treatments would be equally effective.

Nearly all of the outcomes were continuous data. Change scores (follow-up measurement minus baseline) were found to be normally distributed as assessed using normality plots. For the one-legged hop and muscle strength tests, the ratio of injured/normal knee measurements was used in the analysis. SAS Proc Mixed (SAS Institute Inc, Cary, North Carolina) was used for the repeated-measures analyses of variance (ANCOVA). Time was treated as a categorical variable. Sex, age, and compliance with the rehabilitation programs were evaluated to see whether they decreased between-subject variability; they were retained in the final statistical model as covariates if their respective P value was $< .10$.

Proc Mixed treats missing data as missing at random. The within-subject covariance matrix was calculated with the available data and its structure was not defined. The influence of outliers was evaluated by rerunning the analyses without them and they were not found to have influenced the statistical significance for all comparisons.

A log linear analysis (SAS Proc Catmod) was used for the IKDC assessment, a clinical test with categorical outcomes. This analysis evaluated time and treatment but did not include covariates.

Comparison of participant characteristics (Table 1) was performed using the t test for age and surgical delay, Fisher exact test for graft failure, and the χ^2 test for the remaining categorical data. The Wilcoxon rank-sum test was used to evaluate group differences in compliance measured as percentages.

RESULTS

Forty-two patients were enrolled with 24 and 18 randomized to the accelerated and nonaccelerated groups, respectively (Table 1). Follow-up through 2 years included 85% of those enrolled. Two patients chose to discontinue participation immediately after surgery when they arrived in the recovery room (1 each in the accelerated and nonaccelerated groups), 2 in the accelerated group dropped out after the 3-month follow-up, 1 after 6 months (accelerated group), and 1 after 12 months (accelerated group). Thirty-six patients completed the 2-year follow-up with complete data. One participant in the nonaccelerated group suffered a retear of their graft detected at the 6-month follow-up and this was produced during the same sport (cheerleading) that produced the index injury. This patient's data were included in the analyses and were not found to be outliers. Throughout the study, there were no protocol deviations.

Comparison of Participant Characteristics, Intraoperative Findings, and Concomitant Operations at Baseline

The time interval between index injury and surgery, sex, age, height, weight, and activity level of participants in the treatment groups were similar (Table 1). As well, there was no difference in the proportion of tears of the menisci, and damage to the articular cartilage was similar between the treatment groups (Table 1). The medial collateral, lateral collateral, and posterior cruciate ligaments were clinically normal in all participants.

TABLE 1
Patient Data for Participants in Accelerated and Nonaccelerated Rehabilitation Programs[a]

	Accelerated	Nonaccelerated	Comparison (P Value)
Number of patients enrolled in investigation	24	18	
Number of dropouts	5	1	
Number of patients studied >2 years and retained for analyses	19	17	
Suspected ACL graft failure, n (%)	0 (0)	1(6)	.47
Age in years, mean (range; SD)	29.7 (16-48; 10.1)	30.2 (16-46; 9.9)	.89
Weight in kg, mean (range)	75.3 (49-98)	71.8 (55-97)	
Gender			
Males, no. (%)	13 (68)	9 (53)	
Females, no. (%)	6 (32)	8 (47)	.34
Days between index injury and surgery, mean (range; SD)	56 (13-102; 23.5)	66 (29-134; 31.6)	.30
Meniscal lesion identified at surgery			
Medial	7 (37)	7 (41)	.79
Lateral	5 (26)	6 (35)	.56
Meniscal debridement/resection			
Medial	3 (16)	3 (18)	.88
Lateral	5 (26)	3 (18)	.53

[a]ACL, anterior cruciate ligament; SD, standard deviation.

Compliance With Accelerated and Nonaccelerated Rehabilitation Programs

Over the first 3 months of rehabilitation, both groups had similar compliance with the rehabilitation programs (P = .47). For those in the accelerated group, an average of 114% (range, 30%-316%) of the rehabilitation exercises were completed while 99% (range, 19%-219%) of the exercises were completed for those in the nonaccelerated group. Over the first 3 months, 74% of the patients in the accelerated group completed at least 75% of the exercises, while 65% of those in the nonaccelerated group met this same level of compliance (P = .56).

The findings were different for the overall compliance with the entire rehabilitation programs. Over the entire 19-week accelerated program, participants completed 94% (range, 25%-292%) of the exercises on average, while those in the 32-week nonaccelerated program finished an average of 53% (range, 13%-108%) by the end of their program (P = .04). Forty-seven percent and 29% of those in the accelerated and nonaccelerated groups, respectively, completed at least 75% of the exercises over the course of each program (P = .27).

Laxity in Response to A-P–Directed Loading of the Knee

Intraoperative, prereconstruction KT-1000 arthrometer measurements of A-P laxity of the injured knees were similar between patients in the accelerated and nonaccelerated groups (P = .91, Appendix E [available online]). Immediately after ACL graft fixation, while the patient was under anesthesia, KT-1000S arthrometer measurements of A-P laxity were restored to within 1 mm of the normal knee in all participants, and there was no difference in A-P laxity between the groups (P = .38, Appendix E).

The RSA of each degree of freedom of knee displacement produced by the A-P loading revealed no difference between the accelerated and nonaccelerated rehabilitation programs (Table 2). This was the case for A-P, medial-lateral, and proximal-distal displacements of the tibia relative to the femur (ANCOVA; all $P \geq .26$ for the group effect, all $P \geq .19$ for the group-time interactions) and the coupled internal-external, varus-valgus, and flexion-extension rotations (ANCOVA; all $P \geq .12$ for group effect, all $P \geq .10$ for the group-time interactions). There was a similar pattern of change of knee kinematics during graft healing produced by the A-P loading that was consistent for patients in both treatment groups. Between the baseline (immediately after surgery) and the 2-year follow-up interval, there was a significant increase of A-P displacement ($P < .0001$) and the coupled internal-external and varus-valgus rotations of the tibia relative to the femur (P = .03; Table 2). Over this time interval, A-P displacement and the coupled internal-external and varus-valgus rotations of the tibia relative to the femur increased 3.2 mm, 2.6°, and 2.3° for patients in the accelerated group and similar increases of 4.5 mm, 1.9°, and 2.5° were observed for patients in the nonaccelerated group (Table 2).

Clinical Assessment

There was no difference in the overall IKDC grade between the 2 rehabilitation programs (log-linear analysis, P = .13 for group, P =.91 for group-time interaction; Table 3). There was a significant improvement of the IKDC grade for both groups over time ($P < .0001$). At baseline, 95% of the patients in the accelerated group and 100% of those in the nonaccelerated group were categorized as an IKDC grade C or D. At the 2-year follow-up interval, the IKDC group grade improved to an A or B in 78% of the accelerated and 88% of the nonaccelerated patients.

TABLE 2
Roentgen Stereophotogrammetric Analysis Measurements of the 6 Degrees of Freedom Laxity Data of the Tibiofemoral Joint for Patients Enrolled in the Accelerated and Nonaccelerated Rehabilitation Programs[a]

	Immediately After Surgery (Postop)	3 Mo After Surgery	6 Mo After Surgery	12 Mo After Surgery	24 Mo After Surgery	Change Over 24 Mo of Healing (24 Mo – Postop)
Accelerated rehabilitation						
A-P displacement, mm						
Mean	8.3	9.7	11.3	11.3	11.5	3.2
SE	0.69	0.68	0.87	0.67	0.77	
M-L displacement, mm						
Mean	1.6	0.7	0.34	−0.2	0.7	−0.9
SE	0.48	0.69	0.74	0.65	0.53	
P-D displacement, mm						
Mean	1.2	1.5	1.5	1.4	1.6	0.4
SE	0.23	0.29	0.29	0.34	0.34	
Absolute displacement, mm						
Mean	8.7	10.3	12.0	11.6	11.9	3.2
SE	0.75	0.68	0.89	0.72	0.79	
External rotation, deg						
Mean	10.7	12.4	13.3	14.5	13.3	2.6
SD	4.9	4.9	4.3	3.3	4.1	
Varus rotation, deg						
Mean	0.9	3.4	3.6	4.4	3.2	2.3
SD	2.7	5.5	4.3	3.8	3.3	
Extension rotation, deg						
Mean	10.7	15.5	12.9	15.3	14.2	3.5
SD	5.1	7.3	4.7	5.6	4.3	
Nonaccelerated rehabilitation						
A-P displacement, mm						
Mean	8.3	10.0	11.7	11.9	12.8	4.5
SE	0.73	0.73	0.91	0.71	0.82	
M-L displacement, mm						
Mean	2.1	0.4	−0.2	0.1	−0.6	−2.7
SE	0.51	0.74	0.77	0.69	0.57	
P-D displacement, mm						
Mean	1.6	1.4	1.9	1.9	2.0	0.4
SE	0.25	0.32	0.30	0.36	0.36	
Absolute displacement, mm						
Mean	8.9	10.5	12.2	12.3	13.2	4.3
SE	0.8	0.73	0.93	0.76	0.84	
External rotation, deg						
Mean	12.7	11.4	12.9	13.3	14.6	1.9
SD	3.9	2.7	4.0	2.8	2.3	
Varus rotation, deg						
Mean	2.2	2.1	4.4	4.8	4.7	2.5
SD	1.6	1.8	3.2	3.2	3.3	
Extension rotation, deg						
Mean	13.8	10.7	13.7	13.7	13.7	0.1
SD	4.6	3.6	4.1	3.7	3.2	

[a]The data were obtained from the patient's injured knee and are presented as the change in position of the tibia relative to the femur in response to the release of the anterior (130-N) load and application of the posterior (90-N) directed load. Included are the mean values for displacements in the anterior-posterior (A-P), medial-lateral (M-L), and proximal-distal (P-D) directions. The coupled external, varus, and extension rotations of the tibia relative to the femur produced by the loading are also presented. SE, standard error; SD, standard deviation.

Activity Level

For patients in the accelerated treatment group, the Tegner scores were, on average, 5.0, 4.1, 5.4, 6.5, and 6.5 at the baseline, 3, 6, 12, and 24-month follow-up time points, respectively. Patients in the nonaccelerated treatment group had Tegner scores that were 5.4, 3.9, 5.3, 5.7, and 5.6 at these same intervals. There was a small (approximately 0.4) but statistically significantly greater change from baseline in the Tegner activity scores for patients in the accelerated program ($P = .002$), but the group-time interaction was not found to be significant ($P = .43$). In clinical terms, however, the

TABLE 3
Data From the Clinical Assessment With the IKDC Outcome[a]

	Accelerated	Nonaccelerated
Preoperative		
A	0 (0)	0 (0)
B	1 (5)	0 (0)
C	12 (63)	9 (53)
D	6 (32)	8 (47)
3 mo		
A	0 (0)	0 (0)
B	6 (32)	4 (24)
C	11 (58)	9 (53)
D	2 (11)	4 (24)
6 mo		
A	0 (0)	1 (7)
B	10 (53)	4 (27)
C	8 (42)	4 (27)
D	1 (5)	6 (40)
12 mo		
A	5 (28)	2 (12)
B	9 (50)	10 (59)
C	3 (17)	4 (24)
D	1 (6)	1 (6)
24 mo		
A	7 (39)	4 (25)
B	7 (39)	10 (63)
C	3 (17)	0 (0)
D	1 (6)	2 (13)

[a]Included are the overall group grades for the accelerated and nonaccelerated rehabilitation programs at the preoperative and 3, 6, 12, and 24 month follow-up intervals. Shown are the number of patients, with the percentage in parentheses. IKDC, International Knee Documentation Committee.

activity levels were similar between groups.[11] Age was also a significant covariate (P = .008). Younger patients were more likely to report a greater increase in activity level from preoperative levels. This difference was greatest at the 6-month follow-up: the younger half of the participants underwent an increase of 2.5 in the Tegner score from the baseline visit in comparison with the older half; however, by the 2-year follow-up, the difference was negligible.

Patient Satisfaction

There were no significant differences between the treatments and no treatment–time interactions for the KOOS outcomes of pain (ANCOVA; treatment group: P = .60, treatment group–time interaction: P = .13,), symptoms (P = .13, .23), activities of daily living (P = .42, .13), sports and recreation participation (P = .21, .71), and knee-related quality of life (P = .53, .54) (Table 4). Patient sex was found to be a significant covariate in 4 of the 5 KOOS subscales, the exception being the activities of daily living scale, with male patients demonstrating less change from baseline than females. Patient age was significant in 2 subscales, namely symptoms and quality of life, with older patients reporting greater improvements from baseline in comparison to the younger patients.

The patients in each rehabilitation group recorded a significant improvement in their KOOS scores between the baseline and 2-year follow-up interval ($P < .0001$). The temporal response of the scores of 4 out of the 5 subscales (pain, symptoms, activity of daily living, and sports and recreation participation) were nearly identical for both treatment groups: these scores approached a value of 100 by the 2-year follow-up, indicating a return to normal, or preinjury, status. In contrast, the knee-related quality of life score plateaued at values below 90 for patients in both groups, indicating that the index injury, surgery, and rehabilitation with either program had a long-term effect on how patients perceived their quality of life.

Functional Assessment

The patients' ability to perform the one-legged hop was similar between treatment groups. There was significant improvement over time ($P < .0001$) and the participants in each program improved their function in a similar manner during healing (group effect; P = .17; treatment-time interaction, P = .63). Patients in the accelerated group had mean differences in jump distance between uninjured and injured limbs that were 36.9 cm (standard deviation, ±31.9 cm), 52.2 ± 30.3 cm, 23.6 ± 20.3 cm, 11.3 ± 14.3 cm, and 4.0 ± 13.2 cm at the preoperative and 3, 6, 12, and 24-month follow-up intervals, respectively. Those in the nonaccelerated group had values that were 34.7 ± 30.7 cm, 57.4 ± 39.7 cm, 38.9 ± 39.6 cm, 4.8 ± 20.3 cm, and 9.6 ± 18.5 cm at the same follow-up intervals.

Knee Proprioception

The threshold to detection of passive knee motion was similar between the accelerated (Figure 2A) and nonaccelerated (Figure 2B) groups. Comparison of the threshold to detection of passive extension motion (the detection of knee motion as the joint was moved into extension) revealed no effect of treatment group (P = .79), no treatment group–time interaction (P = .37), and no change over time (P = .31). There were similar findings for comparison of the threshold to detection of passive flexion motion between the groups. There was no effect of treatment group (P = .54), no treatment group–time interaction (P = .15), and no change over time (P = .32).

Additional post hoc analysis was performed on the data collected after ACL disruption but prior to ACL reconstruction in an effort to gain insight into the effect of the injury on knee proprioception. This revealed that the ACL injury did not produce a change in the threshold to detection of passive knee extension and passive knee flexion motion values in comparison to the contralateral, normal knee (P = .70 and P = .56, respectively).

Strength of the Extensors and Flexors of the Knee

Strength of the knee extensors was similar between the rehabilitation treatments (Figure 3). Participants in both groups regained extensor strength in similar manner over time ($P < .0001$), there was no difference between

TABLE 4
Knee Injury and Osteoarthritis Outcome Score Used to Evaluate the Patients' Perspective of Pain, Symptoms, Activities of Daily Living, Sports and Recreation Participation, and Quality of Life[a]

		Accelerated Program		Nonaccelerated Program	
		Mean	SD	Mean	SD
Pain					
	Before surgery	78	14	77	15
	3 mo	88	9	83	10
	6 mo	88	14	87	10
	12 mo	92	12	91	10
	24 mo	93	12	95	6
Symptoms					
	Before surgery	67	19	68	22
	3 mo	77	12	71	14
	6 mo	86	7	80	13
	12 mo	92	8	83	16
	24 mo	93	6	90	12
Activities of daily living					
	Before surgery	88	13	86	14
	3 mo	87	17	91	9
	6 mo	95	13	94	6
	12 mo	96	13	98	4
	24 mo	97	10	98	3
Sports and recreation					
	Before surgery	57	28	60	31
	3 mo	67	21	60	24
	6 mo	74	21	70	24
	12 mo	87	21	88	13
	24 mo	92	17	93	9
Quality of life					
	Before surgery	40	19	36	27
	3 mo	54	14	48	25
	6 mo	67	18	63	27
	12 mo	81	18	75	17
	24 mo	86	14	80	18

[a]The scale ranged from 0 (anchored as the absolute worse condition) to 100 (completely normal). Average values are shown, with corresponding standard deviations (SD) for patients in the accelerated and nonaccelerated rehabilitation programs.

treatments ($P = .11$), and no treatment group–time interaction ($P = .30$). As well, strength of the knee flexors was similar between the treatments. There was no difference between the treatments ($P = 0.57$), no treatment group–time interaction ($P = .51$), and patients in both groups demonstrated the same temporal improvement of flexion strength during healing ($P < .0001$).

Post hoc analysis found that the strength of the extensors was significantly greater for patients in the accelerated group compared with those in the nonaccelerated group at 3 months ($P = .03$); however, no differences were observed between the groups at the 6-month ($P = .09$) and later follow-up intervals (all $P > .45$).

DISCUSSION

This investigation demonstrated that rehabilitation with either accelerated or nonaccelerated programs after ACL reconstruction with a bone–patellar tendon–bone autograft produces the same effect on the primary outcome (the envelope of knee laxity) and a majority of the secondary outcomes (clinical outcome, patient satisfaction, patient function, and proprioception) over intermediate and 2-year follow-up intervals. There was a small, but not clinically significant, improvement of the Tegner activity scores for the patients who underwent accelerated versus nonaccelerated rehabilitation, and significant improvements in thigh muscle strength at the 3-month follow-up but not at the subsequent follow-up intervals. The RSA measurements revealed that A-P displacement of the tibia relative to the femur increased an average of 3.2 mm and 4.5 mm over the 2-year follow-up period for patients in the accelerated and nonaccelerated programs, respectively, and there was a corresponding increase in the coupled internal-external (2.6° and 1.9°) and varus-valgus (2.3° and 2.5°) rotations (Table 2).

The temporal change in the envelope of knee laxity is of considerable interest. The use of a prospective study design combined with accurate RSA measurements of displacement of the tibia relative to the femur revealed a similar pattern of increase in the envelope of knee laxity over time for all study participants that occurred when the

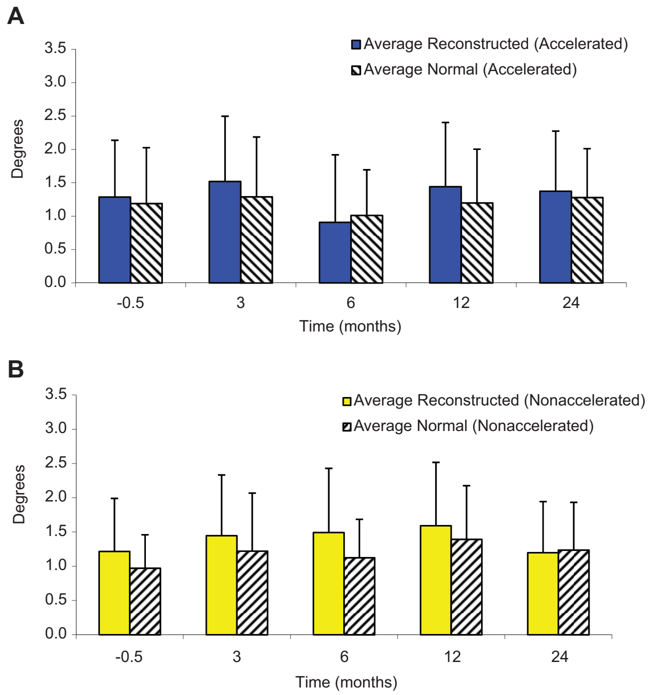

Figure 2. Threshold to detection of passive knee motion: (A) accelerated group; (B) nonaccelerated group.

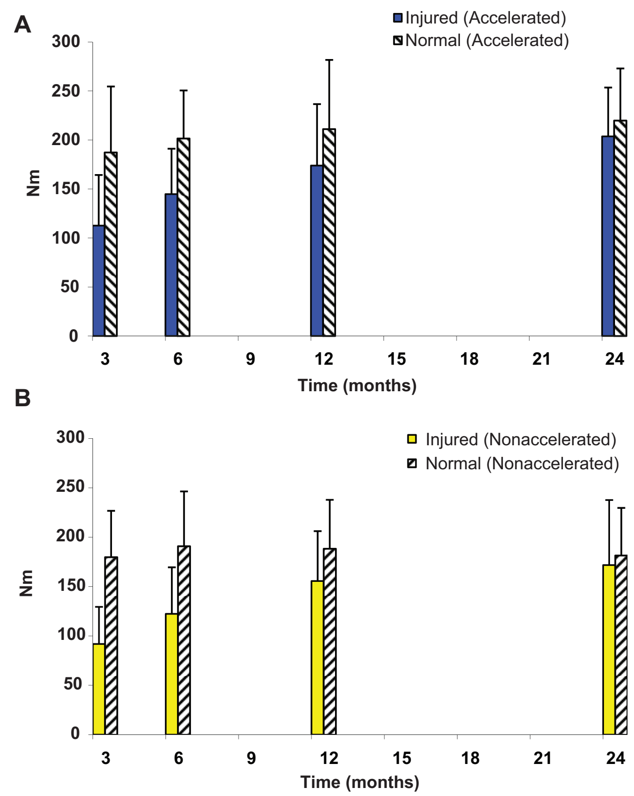

Figure 3. Quadriceps peak torque at 60 deg/sec: (A) accelerated group; (B) nonaccelerated group.

rehabilitation treatments were administered. There was a similar increase of A-P displacements combined with an increase of the coupled internal-external and varus-valgus rotations during the first 6 months of healing and very little change thereafter for participants in both rehabilitation groups (Table 2). Between the baseline and the 3-month follow-up interval, the increases of anterior displacement were 39% and 56% of the total 2-year changes for patients in the accelerated and nonaccelerated programs, respectively, and from the same baseline through the 6-month follow-up interval, these increases were 87% and 98.5% of the total change for patients in these same programs. Similar increases were observed over these time spans for the coupled internal-external and varus-valgus rotations of the tibia relative to the femur. The magnitude of these increases in anterior displacement were less than half the baseline values and were substantially less than the 2.7-fold increase reported for ACL-deficient knees relative to normal, uninjured knees by Karrholm et al.[25] These findings demonstrate that during graft healing, the entire envelope of knee laxity increases for participants in both rehabilitation programs, not simply an increase in a single degree of freedom such as A-P displacement, and that a majority of this increase occurs during the initial 6 months of graft healing when exercises are advanced and patients begin to return to preinjury activity levels. The increases from baseline and absolute magnitudes of knee laxity that we observed with RSA at follow-up were evaluated with fixed, or static, loads applied to the knee as boundary conditions; however, similar changes have been observed with the use of dynamic RSA measurements of ACL-reconstructed patients during downhill running on a treadmill. For example, Tashman et al[39,40] reported increased anterior laxity and external and adduction rotations during the first 12 months of healing after ACL reconstruction. Whether measured statically or dynamically, the increases in the envelope of knee motion are a concern when one considers the work of Andriacchi et al,[4] which suggests the progression of osteoarthritis after an ACL tear is related to changes in the normal articular contact conditions of the tibiofemoral joint and that these are produced by abnormal rotational kinematics about this joint during motion. Anderst and Tashman[3] recently used a canine ACL transection model in combination with dynamic RSA to demonstrate that increased damage of articular surfaces was associated with increased velocity of the femoral articular surface relative to the tibial articular surface during treadmill gait. The authors hypothesized that this was associated with increased shear loading at the cartilage contact region during gait and noted that this may create a “plowing” mechanism that is responsible for the initial onset and subsequent progression of osteoarthritis.[3]

The exact site at which the graft-fixation construct changed and produced increased anterior and coupled rotational laxity of the tibia relative to the femur during healing is uncertain, and review of the temporal response of the envelope of knee laxity provides important insight into the underlying mechanism. A large proportion of the increase of A-P displacement occurred at a time significantly greater than when graft fixation was considered secured by bone block–to–bone tunnel healing (eg, >6 weeks). This suggests that only a small proportion of the slippage occurred at the bone block–bone tunnel fixation sites and that a majority of the change was produced by the midsubstance portion of the graft permanently elongating during healing as rehabilitation was advanced. This observation is supported by the work of Friden et al,[14] who used RSA to study a bone–patellar tendon–bone autograft fixed with interference screws in a manner similar to what was used in our study. They revealed the displacement between the bone blocks and bone tunnel over a 1-year follow-up interval was never greater than 0.7 mm. A change in the position of a bone block of this magnitude, when considered in combination with a graft orientation of 45° relative to the tibial plateau, explains less than 10% of the total increase of anterior knee laxity that we observed. This analysis suggested that at least 90% of the increase of joint laxity that we observed was produced by permanent elongation of the midsubstance of the graft during healing.

This investigation was designed to improve upon the prior comparison[10] of the same rehabilitation programs by restoring the normal (contralateral) A-P knee laxity values at the time of graft fixation (baseline) with the KT-1000S arthrometer such that they were within 1 mm of the contralateral knee, and by using the highly accurate RSA to measure the entire envelope of knee laxity at baseline and throughout all follow-up intervals. The A-P laxity of the contralateral knee was restored to the reconstructed knee at baseline (immediately after graft fixation) in a controlled manner and we demonstrated no difference in knee laxity (for all degrees of freedom) between the programs during the 2-year follow-up interval. Participants in both programs underwent substantial increases in the envelope of knee laxity when the rehabilitation exercises were advanced and the magnitude of the RSA measurements of increased A-P laxity were larger than the previous investigation of the same programs and may be attributed, at least in part, to the different approaches that were used to measure knee laxity. These details are presented in Appendix E. There was 90% power to detect a 2.0-mm difference in the change of A-P laxity from the baseline through the 2-year follow-up interval between the accelerated and nonaccelerated programs. The mean difference in the change of A-P laxity from the baseline through the 2-year follow-up interval between the treatments was 1.3 mm. This difference was not statistically significant; however, it was unclear if this value was significant from biomechanical and clinical perspectives because the relationship between the increase of A-P laxity and coupled rotations and subsequent injury or reinjury to menisci and articular cartilage are unknown. Further, the current study expanded on prior work[10] by including a comprehensive selection of secondary outcome measures obtained from a larger sample of patients. There was a significantly greater improvement in thigh muscle strength for participants in the accelerated compared with the nonaccelerated program at the 3-month follow-up, but no differences between the programs thereafter. This demonstrates that our intervention, advancement of exercises, produced a treatment effect during healing and that this was not maintained at longer term follow-up. Further, we found proprioception was not affected by the ACL injury and was similar between the programs over the entire follow-up interval. This finding is in contrast to prior studies that have shown worsened knee proprioception in patients with chronic ACL injury, and may be attributed to the focus of our study, which was on patients with acute, isolated ACL injury who did not have significant additional injuries and had not experienced multiple giving-way episodes, in contrast to those with chronic ACL injury who may have other articular injury, pathologic changes, and altered secondary restraints.

During the first 3 months of healing, compliance with the 2 rehabilitation programs was similar and well controlled with 75% or more of the exercises performed by 74% and 65% of the participants in the accelerated and nonaccelerated programs, correspondingly. This resulted in greater improvements of thigh muscle strength for patients in the accelerated program as presented above. Measuring compliance over the duration of the entire rehabilitation programs is unique because it demonstrated that similar control of the 2 treatments was obtained and allowed us to use these data as covariates in the statistical analysis. The temporal response of compliance was very similar between rehabilitation programs and comparable with the prior study.[10] For both programs, compliance with rehabilitation decreased over time; however, this should not lead to the interpretation that the study participants were inactive. Instead, after 3 months of rehabilitation, as compliance with the prescribed programs slowly decreased, patients became more active and participated in different sport-specific exercises and activities that either interested them or were more challenging. This transition from the structured ACL rehabilitation programs that were the focus of the current study to sport-specific training exists for all studies of ACL injuries; however, to our knowledge, there is very little quantitative data published that characterize compliance with specific programs and identify at what point in time the transition begins to occur. The transition between structured rehabilitation and return to sport-specific exercises and activity is complex because it is dependent on many variables (eg, concomitant injuries, pain, swelling, age, activity level, fitness level, motivation level, time to the next sports season, expectations).

A majority of the prior randomized controlled trials of ACL autograft rehabilitation have compared different types of exercise programs (eg, open kinetic chain versus closed kinetic chainexercises[12,18,27-29]); however, our study compared the same rehabilitation exercises administered over 2 different time intervals in an effort to understand how the biomechanical dose of exercises administered during rehabilitation effects the temporal healing response of the bone–patellar tendon–bone autograft and knee. Our finding of no difference in the envelope of knee laxity between accelerated rehabilitation (early unrestricted weightbearing and early use of quadriceps-dominated exercises that strain the healing graft) and nonaccelerated rehabilitation (delayed application of these same exercises) is similar to the randomized controlled trial performed by Shaw et al,[36] who found no difference between a rehabilitation program that initiated straight-leg raises and isometric quadriceps contractions after ACL reconstruction in comparison with a program that delayed these exercises for 2 weeks. Likewise, our findings are similar to the randomized controlled trial conducted by Isberg et al,[20] who found no difference in knee laxity and clinical outcome between a rehabilitation program that did not allow exercises with the knee in extension during the first 4 weeks of recovery in comparison with the same program that allowed muscle contraction with active and passive extension exercises immediately after reconstruction with a bone–patellar tendon–bone graft. As well, our finding of no difference in knee laxity between accelerated and nonaccelerated rehabilitation is similar to the study by Heijne and Werner,[16] who found no difference in knee laxity between rehabilitation programs that started open kinetic chain exercises for the quadriceps at 4 weeks compared with 12 weeks after reconstruction. While these comparisons suggest that after ACL reconstruction with a bone–patellar tendon–bone autograft, rehabilitation that includes early unrestricted weightbearing and early use of quadriceps-dominated exercises is safe and effective, it is important to highlight that it remains unclear how quickly the frequency and magnitude of quadriceps activity can be increased and weightbearing activities advanced without producing an increase in knee laxity greater than that observed in this study. It is also unclear how the rehabilitation programs that we studied and the changes in knee laxity that were observed can be generalized to the healing response of hamstring tendon grafts, quadriceps tendon grafts, allografts, or knees with significant injuries to the articular cartilage and menisci.

When designing this study, an effort was made to minimize potential sources of bias and confounding (these details are presented in Appendix F [available online]); however, application of the findings from our study to the clinical environment must be done with care. For example, we do not know how the rehabilitation exercises that the patients completed compared with the overall biomechanical dose that was delivered to the graft as a result of participation in common activities of daily living (eg, walking, ascending/descending stairs, rising from a chair) and return to sport-specific exercises. Initially, the rehabilitation programs delivered a majority of the loading to the healing graft and over the course of the rehabilitation programs, there was a transition from this structured rehabilitation to rehabilitation combined with activities of daily living delivering loads to the healing graft. We do not know how the relative contributions from these different sources of loading associated with activities of daily living changed over time; however, randomization created 2 rehabilitation treatments that had similar contributions of loading from activities of daily living during healing and return to preinjury activity. Further, we do not know what effect that rehabilitation with programs less aggressive than the traditional programs would have on the outcomes evaluated in our study. It may be that the programs compared in this investigation were too accelerated, as both produced similar increases in the envelope of knee laxity, and that rehabilitation programs less accelerated than those compared in this investigation may have produced a smaller increase in the envelope of knee laxity. Another limitation of our study is that different mechanisms of administering rehabilitation may have affected the outcome. In an effort to provide control of our rehabilitation interventions, the same individual administered the rehabilitation program and monitored compliance in a carefully controlled setting. Grant et al[15] demonstrated that recreational athletes can undergo successful rehabilitation with either a home-based program that involves limited supervision or a physical therapy–supervised program, and this finding suggests that delivery of accelerated versus nonaccelerated rehabilitation programs with a home-based approach may result in outcomes similar to our current study of supervised rehabilitation. The approach of measuring knee laxity while the patient was under anesthesia (done immediately postoperatively, just after the wounds were closed in an effort to characterize baseline), combined with subsequent measurements obtained while the patient was not under anesthesia (follow-ups conducted at 3, 6, 12, and 24 months postoperatively), did not introduce confounding into the study because all participants underwent the same measurement conditions at baseline and the subsequent follow-up visits, measurements were made in an identical manner at all time points, and the statistical analysis compared change in laxity value from the baseline condition. This was done for each degree of freedom of knee motion. With this approach, the influence of anesthesia on knee laxity magnitude at the baseline visit had the same effect on all participants. Consequently, we did not introduce confounding into the comparison between the treatment programs because the data were analyzed as the change in laxity relative to a common baseline condition.

In conclusion, this investigation demonstrated that accelerated rehabilitation produces the same increase of the envelope of knee laxity compared with nonaccelerated rehabilitation, and that the increase occurs as rehabilitation is advanced and patients return to preinjury activity. Likewise, both rehabilitation programs have the same apparent effect on clinical outcome, proprioception, and the patient's perspective of the outcome (evaluated in terms of pain, symptoms, quality of life, ability to participate in activities of daily living, and ability to participate in sports and recreation activity). Participants in the accelerated program had an increase of thigh muscle strength at the 3-month follow-up compared with those in the nonaccelerated program, but there were no differences between the programs at the longer follow-up intervals. These findings of similar biomechanical, clinical, and patient-oriented outcomes, combined with improved thigh muscle strength for those in the accelerated program, leads us to recommend its use for rehabilitation after ACL reconstruction with a bone–patellar tendon–bone autograft.

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