The Efficacy of Perturbation Training in Nonoperative Anterior Cruciate Ligament Rehabilitation Programs for Physically Active Individuals

Background and Purpose. Treatment techniques involving perturbations of support surfaces may induce compensatory muscle activity that could improve knee stability and increase the likelihood of returning patients to high-level physical activity. The purpose of this study was to determine the efficacy of augmenting standard nonoperative anterior cruciate ligament (ACL) rehabilitation programs with a perturbation training program. Subjects. Twenty-six patients with an acute ACL injury or ruptures of ACL grafts participated in the study. Subjects had to have a unilateral ACL injury, be free of concomitant multiple ligament or meniscal damage requiring surgical repair, and pass a screening examination designed to identify patients who had the potential to return to high-level physical activity with nonoperative treatments. Subjects also had to be regular participants in level I activities (eg, soccer, football, basketball) or level II activities (eg, racquet sports, skiing, construction work). Methods. Subjects were randomly assigned to either a group that received a standard rehabilitation program (standard group) or a group that received the standard program augmented with a perturbation training program (perturbation group). Treatment outcome was determined from scores on the Knee Outcome Survey’s Activities of Daily Living Scale (ADLS) and Sports Activity Scale, a global rating of knee function, scores on a series of single-limb hop tests, measurements of maximum isometric quadriceps femoris muscle force output, and the group frequency of unsuccessful rehabilitation. Unsuccessful rehabilitation was defined as the occurrence of an episode of giving way of the knee or failure to maintain the functional status of a rehabilitation candidate on retesting. Results. More subjects had unsuccessful rehabilitation in the standard group compared with the perturbation group. There was a within-group \times time interaction for the ADLS, global rating of knee function, and crossover hop test scores. These scores decreased from posttraining to the 6-month follow-up for the standard group. Conclusion and Discussion. Although both the standard program and the perturbation training program may allow subjects to return to high-level physical activity, the perturbation training program appears to reduce the risk of continued episodes of giving way of the knee during athletic participation, and it allows subjects to maintain their functional status for longer periods. [Fitzgerald GK, Axe MJ, Snyder-Mackler L. The efficacy of perturbation training in nonoperative anterior cruciate ligament rehabilitation programs for physically active individuals. Phys Ther. 2000;80:128–140.]

Key Words: Anterior cruciate ligament, Knee, Rehabilitation.
Nonoperative treatment for anterior cruciate ligament (ACL) injury usually consists of rehabilitation that emphasizes joint mobility, increasing thigh muscle force production, endurance, agility training, functional activity modifications, and protective bracing.\textsuperscript{1–5} These appear to be successful only for those patients who are more sedentary or who are willing to modify their physical activities.\textsuperscript{1,2,6} Recent studies\textsuperscript{7–13} suggest that patients who achieve higher levels of functional recovery after ACL rupture alter their muscle activity in a manner that improves the stability of the knee. The success of rehabilitation programs for patients who want to participate in high-level activity, such as sports activities requiring cutting, jumping, and pivoting maneuvers of the lower extremity, should improve if treatment techniques that induce appropriate compensatory alterations in muscle activity are incorporated into treatment programs.

The challenge in designing treatments that induce compensatory muscle activity is that there appears to be no single proven compensatory pattern. Individuals who successfully compensate for a ruptured ACL appear to adopt idiosyncratic compensation patterns in several muscle groups of the lower extremities. Although there is consistency across studies with respect to the muscles that are altered to improve knee stability (eg, hamstring, gastrocnemius, quadriceps femoris muscles), the patterns of altered activity are remarkably varied.\textsuperscript{10,11} Successful training strategies, in our opinion, have to provide the opportunity for development of \textit{individualized} compensatory alterations in activity of several lower-extremity muscles.

Although there is limited understanding of the neuromuscular control mechanisms that play a role in maintaining knee stability, current theories regarding these mechanisms should be considered in the design of treatment. Johansson and Sjölander\textsuperscript{14} have suggested that stimulation of mechanoreceptors in joint structures increases gamma motor activity in a manner that may increase the sensitivity of muscle spindles in muscles associated with the joint. This increased sensitivity of the muscle spindles may result in a higher state of “readiness” of muscles to respond to perturbing forces applied to the joint, which may, in turn, improve joint stability.\textsuperscript{14}
The afferent mechanism in this response appears to respond to moderate levels of force and theoretically could be activated during perturbations that occur during functional activity. The implication for treatment may be that applying potentially destabilizing forces to the knee during treatment may enhance neuromuscular responses to destabilizing forces that may be encountered during function.

Nichols proposed a “force-feedback” hypothesis, based on a series of experiments in the decerebrate cat, that may also explain the coordinated response from muscles to perturbing forces applied to a joint. When a perturbing force is applied to a joint, muscles that would resist the perturbation are stretched and become activated to resist the perturbation. Simultaneously, there is a reflex inhibitory influence on muscles that would have a tendency to pull in the same direction as the perturbation. The inhibitory influence reduces, but does not entirely eliminate, the unwanted stretch reflex from muscles antagonistic to those that would resist the perturbing force. The net result is a coordinated coactivation of extremity muscles affected by the perturbation to stiffen the joint and maintain stability.

The proposed mechanisms for neuromuscular control of joint stability described by Johansson and Sjölander and Nichols have several implications for design of treatment programs. The force-dependent nature of the mechanisms suggests that exposing the joint to potentially destabilizing loads during training may be the necessary stimulus to encourage the development of effective neuromuscular compensatory patterns. Treatment techniques that attempt to promote the development of these protective compensatory patterns could be designed to encourage involuntary muscular responses to destabilizing forces.

Treatments that involve perturbing support surfaces (perturbation training) allow altered forces and torques to be applied to the lower extremity in multiple directions and in a controlled manner. These techniques may induce compensatory muscle activation patterns in patients with ACL deficiencies. The results of a randomized clinical trial indicated that subjects who received perturbation training combined with a standard nonoperative ACL rehabilitation program reported a greater increase in Lysholm Knee Rating Scale scores after training than subjects who received only the standard program. Although augmenting nonoperative ACL rehabilitation programs with perturbation training techniques appears to be a favorable treatment option, this approach has not been tested on highly active individuals who want to return to preinjury levels of function.

The purpose of our study was to compare treatment effectiveness between a standard nonoperative ACL rehabilitation program and one that is augmented with perturbation training techniques in returning physically active individuals to high levels of activity. We hypothesized that subjects receiving the perturbation training would be more successful in returning to high-level physical activities following rehabilitation than subjects who did not receive this treatment.

**Method**

**Subjects**

Patients referred by their physicians to the University of Delaware Physical Therapy Clinic (Newark, Del) with a diagnosis of ACL rupture or rupture of an ACL graft were potential subjects for the study. Individuals were excluded from the study if: (1) the onset of injury was longer than 6 months prior to referral, (2) there was concurrent multiple ligament injury or repairable meniscal damage associated with the ACL injury, (3) they did not participate in greater than 50 hours per year of level I physical activities (eg, football, basketball, soccer) or level II physical activities (eg, racquet sports, skiing, manual labor occupations), or (4) they exhibited less than 3 mm of side-to-side difference in passive anterior knee laxity, measured with maximum manual Lachman testing using a KT-2000 arthrometer.

A screening examination, which we had developed and tested in a previous study, was used in an effort to differentiate patients who had good potential to succeed with nonoperative treatment (rehabilitation candidates) from those who may be at high risk for reinjury. This screening examination consisted of a series of single-limb hop tests described by Noyes et al, the Knee Outcome Survey’s Activities of Daily Living Scale, a global rating of knee function, and the patient’s report of the frequency of episodes of the knee giving way from the time of injury to the time of the screening examination. The screening examination was administered when patients were free of knee pain and effusion, exhibited full knee joint range of motion, were able to perform a synchronous (smooth and sustained) isometric contraction of the quadriceps femoris muscles as determined by palpation and visual inspection, were able to perform a straight leg raise without the presence of a knee extension lag, and were able to tolerate hopping on the involved limb. In order to participate in the training study, patients had to meet all of the following criteria: (1) timed hop test score of ≥80%, (2) Activities of Daily Living Scale score of ≥80%, (3) global rating of knee function of ≥60%, and (4) no more than one episode of
the knee giving way from the time of injury to the time of the screening examination.

Twenty-eight subjects qualified for the training study. These subjects were randomly assigned to either a group that received a standard rehabilitation program (standard group) or a group that received the standard program combined with a perturbation training program (perturbation group). A computer-generated random number list was used to randomly assign subjects to groups (SYSTAT Design module, version 2.0†). All subjects signed an informed consent form, approved by the University of Delaware Human Subjects Review Board, prior to participating in the study. One subject in the standard group was dropped from the study because he was unable to maintain a regular treatment schedule. One subject in the perturbation group did not complete the study because she decided that time constraints made surgical treatment more convenient than undergoing nonoperative treatment. A total of 26 subjects (14 subjects in the standard group and 12 subjects in the perturbation group) completed the training. Group characteristics for age, height, weight, anterior knee laxity, and sex are shown in Table 1. Subject participation in level I and II activities is summarized in Table 2.

**Training Programs**

**Standard program.** The standard rehabilitation program consisted of resistive exercises for the quadriceps femoris and hamstring muscle groups, cardiovascular endurance training, agility skill training, and sports-specific skill training. The resistive exercises consisted of leg extensions, leg curls, and leg press progressive resistance exercises on a hydraulic resistance exercise device. A 1-repetition maximum was established at the beginning of the resistance exercise. The subject was instructed to perform 2 sets of 10 repetitions at 50% of the 1-repetition maximum, 2 sets of 8 repetitions at 75% of the 1-repetition maximum, and 2 sets of 5 repetitions using maximum effort. These guidelines were used for all 3 resistive exercises. The leg extension exercise was performed through a joint excursion from 90 to 45 degrees of flexion to minimize anterior tibial shearing during the exercise. Subjects whose maximum voluntary quadriceps femoris muscle isometric force for the involved limb was less than 80% of the uninvolved quadriceps femoris muscle force received a high-intensity electrical stimulation training protocol. The protocol consisted of 10 electrically stimulated isometric contractions of the quadriceps femoris muscles, 10 seconds on and 50 seconds off, with a 2,500-Hz stimulus delivered at 75 bursts per second and an amplitude equivalent to the current needed to produce 50% of maximum voluntary isometric torque of the injured limb’s quadriceps femoris muscle. The electrical stimulation protocol was continued until the maximum voluntary isometric force of the injured limb’s quadriceps femoris muscle was 80% of that of the uninvolved limb’s quadriceps femoris muscle.

Cardiovascular training techniques were selected based on each subject’s sports activities. A graded running program was used for subjects involved in running

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Table 1. Group Characteristics for Age, Height, Weight, Anterior Knee Laxity, and Sex

<table>
<thead>
<tr>
<th></th>
<th>Standard Group</th>
<th>Perturbation Group</th>
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<tr>
<td><strong>X</strong></td>
<td><strong>SD</strong></td>
<td><strong>Range</strong></td>
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<tr>
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<tr>
<td>Weight (kg)</td>
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<tr>
<td>Laxitya (mm)</td>
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<td>2.0</td>
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<tr>
<td>Sex</td>
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</tr>
</tbody>
</table>

*a Laxity measurement is the difference in passive anterior knee laxity between the involved and uninvolved knees.

Table 2. Group Characteristics for Activity Level

<table>
<thead>
<tr>
<th>Activity</th>
<th>Standard Group</th>
<th>Perturbation Group</th>
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<tbody>
<tr>
<td>Collegiate football</td>
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<td>2</td>
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<tr>
<td>Semiprofessional football</td>
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<td>1</td>
</tr>
<tr>
<td>Collegiate lacrosse</td>
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<td>1</td>
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<td>Collegiate field hockey</td>
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<td>1</td>
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<tr>
<td>Collegiate track/soccer</td>
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<td>1</td>
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<tr>
<td>High school basketball</td>
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<td>1</td>
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<tr>
<td>High school softball</td>
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<td>1</td>
</tr>
<tr>
<td>High school field hockey</td>
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<td>1</td>
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<tr>
<td>Semiprofessional baseball</td>
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<tr>
<td>Senior Olympic volleyball</td>
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<td>1</td>
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<td>Basketball</td>
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<td>1</td>
</tr>
<tr>
<td>Hockey</td>
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<td>1</td>
</tr>
<tr>
<td>Tennis</td>
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<td>1</td>
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<tr>
<td>Softball</td>
<td>1b</td>
<td>2</td>
</tr>
<tr>
<td>Volleyball</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

*b Two subjects also worked as construction workers (level II occupation).

b Subject was also a candidate for the local police academy (level II occupation).
Agility training techniques were used to improve lower-extremity coordination and the ability to quickly change movement direction. The techniques included side sliding (moving laterally in right and left directions, emphasizing quick change in direction every 4.5 m [5 yd]), cariocas (forward and backward leg crossovers while moving laterally in right and left directions, emphasizing quick change in direction every 9 m [10 yd]), forward and backward quick start-and-stop shuttle runs, multidirectional quick start-and-stop running, figure-eight running, and a 45-degree cutting-and-spinning drill. Agility training was initiated when subjects tolerated one half-effort agility training without pain or swelling.

Running activities were progressed based on subject tolerance for the activity. Tolerance was determined by monitoring complaints of pain during or following the activity or an increase in swelling after the activity. When subjects tolerated treadmill running for 10 to 15 minutes without inducing pain or swelling, they were progressed to level-surface running on a track or road. Subjects were instructed to add hill running when they were able to tolerate 20 to 30 minutes of level-surface running without pain or swelling. Sprinting and figure-eight running was added to the program when the subjects were able to perform the agility training techniques at maximum effort without pain or swelling.

The skating program was progressed in a manner similar to the running program. Tolerance was determined by monitoring complaints of pain during or following the activity or an increase in swelling after the activity. When subjects tolerated 10 to 15 minutes of the sliding board simulation, they were progressed to straight skating by doing laps around the rink. When they could tolerate 20 to 30 minutes of lap skating and they were able to tolerate maximum-effort agility training, quick stops and starts, cutting, and changing directions were added to the skating program.

For subjects who were not involved in running or skating, stationary cycling was used. The subjects were instructed to cycle 20 to 30 minutes per day at a cycling rate of 60 to 80 rpm, with moderate resistance, as determined by the subjects.

Sport-specific skills were initiated when subjects tolerated full-effort agility training without pain or swelling. Sport-specific tasks, such as ball catching, passing, and kicking, were added during the agility training phase. Sport-specific skills were also practiced in the context of playing situations. For example, basketball players would begin practicing dribbling skills, jump shots, and layups. Hockey players would perform stick handling, passing, and shooting drills during their skating workouts. These activities were initiated without an opponent and then progressed to practice with an opponent. All subjects wore a custom-made knee brace during the running, agility training, and sport-specific skill training activities.

Perturbation training program. The perturbation training techniques were: (1) anteroposterior and mediolateral perturbations on a Balance Master motorized force platform,\(^2\) (2) anteroposterior and mediolateral rotary perturbations on a tiltboard, (3) multidirectional perturbations while the subjects were standing with one lower extremity on a roller board and the contralateral lower extremity on a stationary platform, and (4) multidirectional perturbations while the subjects were standing in single-limb support on a roller board.

The motorized force platform was used for the first few training sessions to deliver the perturbations in a consistent manner with respect to speed and displacement, allowing the therapist to focus on each subject’s response rather than the stimulus. The platform, according to the manufacturer, delivered a 6.35-cm (2.5-in) translational displacement in approximately 0.5 second. The subject stood on the platform, and the therapist programmed the platform to be perturbed in anterior and posterior translations in a random manner. Medial and lateral translations were performed by having the subject stand on the platform, facing the lateral edge of the platform. The subject initially stood on the platform with bilateral lower-extremity support, with his or her hands supported on the crossbar for balance. The therapist informed the subject of the direction that the perturbation would occur so that the subject would be allowed to become familiar with the perturbations. As the subject became comfortable with the perturbations, arm support was eliminated and finally only single-limb support was used. This progression occurred within the first session. Once the subject could maintain balance during single-limb support, the translations were applied unannounced and in a random order with respect to direction and timing. Approximately 15 to 20 translations occurred per session.

When the subjects were able to maintain balance without difficulty during the motorized force platform transla-
tions (usually in 4 or 5 sessions), the motorized force platform was replaced with a roller board. The roller board was a 35×38-cm platform supported by 4 swivel rollers, with a roller placed on each corner of the platform’s underside. Each subject stood on the roller board in single-limb support while the therapist manually perturbed the roller board randomly in multiple directions, at varying speeds (Fig. 1). The displacement of the board during the perturbations varied between approximately 2.5 to 5 cm (1–2 in). The speed of the perturbations varied from quick displacements to slow, gradual displacements. A training bout lasted approximately 1 to 1.5 minutes. The activity was initially performed in parallel bars so that the subject would have arm support, if needed. When balance improved, the training was performed outside the parallel bars.

During the tiltboard perturbations, the subjects stood on the tiltboard with bilateral lower-extremity support and were asked to maintain a balanced position on the board (Fig. 2). Once a subject gained a balanced position on the board, the therapist manually applied anterior and posterior tilting perturbations at random to disturb the subject’s balanced position. The surface of the tiltboard was approximately 7.5 cm (3 in) in height from the surface of the floor. The amount of tilting during the perturbations varied from approximately 2.5 to 7.5 cm (1–3 in). The timing and speed of the perturbations were also randomly varied by the therapist. The timing between perturbations varied from approximately 1 to 5 seconds. The speed of tilting perturbations varied from a quick application to a slow, gradual application of tilting. Subjects were instructed to respond by regaining the balanced position on the board. The therapist provided standby assistance in the event that the subjects stepped off the board. The same process was repeated for medial and lateral tilting perturbations. Each bout lasted approximately 1 to 1.5 minutes. When subjects were able to perform this activity with minimal difficulty in double-limb support, the treatment was progressed to single-limb support.

During the roller board/stationary platform exercise, each subject stood with one limb on the roller board and the other limb on a box that was approximately the same height as the roller board (Fig. 3). The subject was instructed to maintain a steady position of the roller board when the therapist attempted to move the board. The subject attempted to resist the therapist’s force on
the board by pushing the lower extremity on the roller board in the opposite direction while matching the speed and magnitude of the therapist’s perturbation force. The therapist perturbed the roller board in varying directions, amplitudes, and speed. The subject’s ability to match the therapist’s perturbations was monitored by the therapist by observing the movement of the roller board. If the subject matched the therapist’s perturbations correctly, there should have been minimal movement of the roller board as the therapist applied and released forces or changed the direction and speed of forces on the roller board. This technique is similar to a proprioceptive neuromuscular facilitation–rhythmic stabilization technique.\textsuperscript{24} A training bout consisted of approximately 1 to 1.5 minutes of perturbations. Subjects performed one training bout with the involved limb on the roller board and a second bout with the involved limb on the stationary box. Training bouts were conducted with the subject assuming a straddle stance, a forward diagonal stance, and a backward diagonal stance. These stances were used because we believed they simulate stance positions used during many athletic activities. In addition, the diagonal stances increased the level of difficulty for the subject in controlling the roller board perturbations. The total treatment time was approximately 6 to 9 minutes for this activity.

The level of difficulty of the tiltboard, roller board with stationary platform, and single-limb roller board perturbation techniques was progressed by adding sport-specific tasks during the perturbations. These tasks were added to encourage carryover of possible learned compensatory responses to functional activity. Schmidt\textsuperscript{25} has suggested that practicing an acquired skill in the context of a functional task could enhance the carryover of the skill to functional performance. The sport-specific tasks were added during tiltboard perturbations when subjects were able to withstand the perturbations with minimal disturbance in their balance. Sport-specific activities were added to the roller board/stationary platform technique when subjects were exhibiting minimal co-contraction responses to the perturbations (determined by the therapist via visual inspection).

All subjects were treated for 10 sessions, at a frequency of 2 to 3 sessions per week, depending on scheduling constraints. All subjects completed the training program within 5 weeks. Subjects in both groups were encouraged to begin a partial return to their sport at the eighth treatment. Full return to athletic competition was allowed at the completion of the training program.

### Determination of Treatment Outcome

Unsuccessful rehabilitation was operationally defined as either the occurrence of an episode of the knee giving way or a subject’s reduction in status from being a candidate for rehabilitation to being at high risk for re-injury on retesting, based on the criterion measures of the screening examination. Recurrent episodes of the knee giving way have been associated with increased potential for doing further damage to knee structures.\textsuperscript{26,27} We believed, therefore, that the occurrence of an episode of the knee giving way would be a strong indicator that the subject would be unable to safely continue participation in high-level physical activity. Clinical tests of treatment outcome were: (1) measurement of maximum voluntary isometric force output of the quadriceps femoris muscles, (2) the ability to do a series of single-limb hop tests,\textsuperscript{21} and (3) measurement of passive anterior knee laxity using a KT-2000 knee arthrometer.\textsuperscript{19} Quadriceps femoris muscle maximum isometric force output was measured using a burst-superimposition method.\textsuperscript{28} The subject was seated on a Kin-Com II isokinetic dynamometer,\textsuperscript{8} and the dynamometer force arm was secured to the subject’s ankle. The knee was held in 90 degrees of flexion. Self-adhesive electrodes were applied to the quadriceps femoris muscle so that an electrical stimulus could be applied during muscle contraction. The subject was asked to exert as much force as possible while extending the knee against the force arm of the dynamometer. An electrical stimulus (amplitude=130 V, pulse duration=600 microseconds, pulse interval=10 microseconds, train duration=1 second) was applied during the contraction to ensure that the muscle was maximally activated during the test. The force test score was expressed as an index representing the injured limb’s quadriceps femoris muscle force divided by the uninjured limb’s quadriceps femoris muscle force and multiplied by 100.

The hop tests used in this study have been described by Noyes et al\textsuperscript{21} as performance-based measures of knee function, although they appear to reflect impairment. The tests are all single-limb hop tests and include: (1) a single hop for distance, (2) a crossover hop for distance in which the subject must cross over a 15.2-cm-wide (6-in-wide) tape with each consecutive hop, (3) a straight triple hop for distance, and (4) a timed hop in which the subject hops a distance of 6 m as fast as possible (Fig. 4). Subjects did 2 practice trials followed by 2 measurement trials of each hop test on both limbs. The hop test score for each limb was reported as the average of the 2 measurement trials. The single hop, crossover hop, and triple hop scores were expressed as a percentage of the injured extremity score divided by the uninjured extremity score and multiplied by 100. The timed hop score was expressed as a percentage of the uninjured extremity score divided by the injured extremity score and multiplied by 100.

\textsuperscript{8} Chattanooga Group Inc, 4717 Adams Rd, Hixson, TN 37343.
Passive anterior knee laxity measurements were taken to determine whether there was a change in laxity with participation in nonoperative management of the injury. The KT-2000 is an instrumented arthrometer that measures the degree of anterior tibial displacement (in millimeters) with respect to the femur when the examiner applies an anterior translational force to the posterior aspect of the subject’s leg. The instrument was strapped to the anterior aspect of the subject’s leg while the subject was positioned supine. The examiner pulled on the handle of the arthrometer with maximum manual force, creating an anterior translational force on the posterior aspect of the leg. The passive anterior knee laxity measurement is expressed as the difference in anterior displacements between the involved and uninjured knees. Results from a previous study performed at the University of Delaware involving 10 subjects with ACL injury indicated that measurements obtained with the KT 2000 were reliable.29

Self-report measures of knee function were: (1) the Knee Outcome Survey’s Activities of Daily Living Scale,22 (2) the Knee Outcome Survey’s Sports Activity Scale,22 and (3) a global rating of knee function. The Activities of Daily Living Scale of the Knee Outcome Survey assesses how a person’s knee condition affects daily activities such as ambulation, stair climbing, kneeling, sitting, and squatting. The Sports Activity Scale of the Knee Outcome Survey assesses how a person’s knee condition affects participation in sports activities and sports-related tasks such as running, jumping, cutting, and quick starting and stopping. Scores for both the Activities of Daily Living Scale and the Sports Activity Scale are reported as percentage scores, determined by dividing the subject’s score by the total possible score and multiplying by 100 for each scale. A global rating of knee function was used to assess the subjects’ overall knee function. Subjects rated knee function on a scale of 0% to 100%, with 100% representing preinjury function.

Data Management and Analysis
The number of subjects from each group classified as having unsuccessful rehabilitation was recorded. A chi-square analysis was used to determine whether there was a difference between groups in the number of subjects who were classified as having unsuccessful rehabilitation at the 6-month follow-up test session. Likelihood ratios30 were also calculated on these data to determine the probability of a successful outcome when receiving perturbation training or the standard treatment. The formula for a positive likelihood ratio is: (sensitivity/1−specificity).30 The formula was applied to the frequency data in this study in the following manner. Based on the results of the chi-square analysis, we expected that subjects in the perturbation group would be more likely to have successful rehabilitation and subjects in the standard group would be more likely to have unsuccessful rehabilitation. Therefore, sensitivity would equal the number of subjects in the perturbation group who successfully completed the study divided by the number of subjects in both groups who successfully completed the study. Specificity would equal the number of subjects in the standard group who had unsuccessful rehabilitation divided by the number of subjects in both groups who had unsuccessful rehabilitation.

Group means and standard deviations were calculated for each of the clinical tests and for self-report scores for pretraining, immediately posttraining, and 6-month postinjury testing sessions. A 2-way, group × time, repeated-measures multivariate analysis of variance was used to determine whether there were group differences in the test variables. The level of statistical significance for all analyses was $P < .05$.

Results

Frequency of Success Versus Failure
Table 3 is a contingency table of the frequency of success or failure of rehabilitation in each group at the time of the 6-month postinjury follow-up test session. One subject in the perturbation group had an episode of the knee giving way while playing football prior to the end of

Table 3. Contingency Table of Frequency Data for Successful and Unsuccessful Rehabilitation Between Groups

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<thead>
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<th>Successful Rehabilitation</th>
<th>Unsuccessful Rehabilitation</th>
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<tr>
<td>Perturbation group</td>
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<tr>
<td>Standard group</td>
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<tr>
<td>Total</td>
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<td>26</td>
</tr>
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</table>

Figure 4. Diagram of single-limb hop test series. Redrawn with permission from Noyes et al.21

the training period. All other subjects in this group had not experienced an episode of the knee giving way on return to full activity. Seven subjects in the standard group were classified as having unsuccessful rehabilitation. One of these subjects experienced an episode of the knee giving way during training. Five subjects reported an episode of the knee giving way on return to full activity, and 1 subject regressed to being at high risk for reinjury based on test scores at the 6-month postinjury follow-up test session. The chi-square analysis indicated that a greater number of subjects in the standard group had unsuccessful rehabilitation ($\chi^2=5.27$, critical value=3.84, $P<.05$). The positive likelihood ratio was 4.88 ((11/18)/1-(7/8)). This finding indicates that subjects who received the perturbation training were 4.88 times more likely to succeed have a successful outcome with nonoperative treatment than subjects who did not receive the perturbation training.

**Self-Report Surveys**

The scores of 3 subjects were not included in the analysis. One subject from the standard group was lost to follow-up because he received surgery prior to the follow-up test session. Two subjects, one from each group, had an unsuccessful outcome before the end of the training program and did not receive a posttreatment examination, resulting in incomplete data for this analysis. The analyses, therefore, were based on data for 11 subjects from the perturbation group and 12 subjects from the standard group. There were no differences in group means for pretreatment, posttreatment, and follow-up test sessions ($P>.05$). Interactions were present for the Activities of Daily Living Scale and global rating of knee function scores ($P<.03$) (Figs. 5 and 6). There was a reduction in the Activities of Daily Living Scale and global rating of knee function score means from the posttreatment test session to the follow-up test session in the standard group, whereas no change in these means occurred during this time frame for the perturbation group. A similar trend was observed in post-treatment and follow-up Sports Activity Scale scores; however, the interaction was not statistically significant (Fig. 7).

**Hop Tests**

The 2 subjects who had an unsuccessful outcome prior to the end of training did not have a posttreatment examination. One subject in the standard group was lost to follow-up because he had surgery prior to the follow-up examination. A second subject in the standard group was unable to perform the hop tests at the time of follow-up due to a back injury. A third subject was unable
to perform the hop tests at the time of follow-up due to leg cramps. The analysis was performed on data from the remaining subjects (11 subjects in the perturbation group and 10 subjects in the standard group). Subjects who refused to perform the hop tests on retesting because of pain or fear of reinjury were given a score of 0 for the hop tests (4 subjects in the standard group refused to hop). There were no differences between groups for pretreatment and posttreatment hop test scores. The perturbation group scored higher on the follow-up single and triple hop test for distance scores (single hop test: $X=101\%, SD=14\%$; triple hop test: $X=99\%, SD=12\%$) than did the standard group (single hop test: $X=68\%, SD=48\%$; triple hop test: $X=59\%, SD=51\%$) ($P<.05$). There were no differences in group means for follow-up crossover test ($P=.07$) and timed hop test ($P=.09$). There was an interaction for the crossover hop test scores ($P<.05$). Standard group crossover scores decreased from the posttreatment test session ($X=100\%, SD=15\%$) to the follow-up test session ($X=64\%, SD=55\%$), whereas perturbation group scores were maintained during this time period (posttreatment test session: $X=105\%, SD=13\%$; follow-up test session: $X=104\%, SD=16\%$) (Fig. 8).

Quadriceps Femoris Muscle Force Index and Anterior Knee Laxity

Data were not obtained for 4 subjects (1 subject in the standard group and 3 subjects in the perturbation group) at the posttreatment test session. One subject from each group had an unsuccessful outcome before the end of training and did not receive a posttreatment examination. The Kin-Com II dynamometer was in repair at the time of posttreatment examination for 2 other subjects from the perturbation group, and the examinations were not rescheduled. Data were not obtained for 5 subjects (3 subjects in the standard group and 2 subjects in the perturbation group) at the follow-up test session. Three subjects in the standard group and 1 subject in the perturbation group could not be scheduled for force testing prior to their surgeries. One subject in the perturbation group had a scheduling conflict for the follow-up testing session and was never rescheduled. Therefore, a meaningful group × time repeated-measures analysis could not be conducted. Standard $t$ tests were used to compare group mean differences at each testing session for the available data. There were no differences between groups for quadriceps femoris muscle isometric force indexes at the pretreatment testing session (perturbation group: $X=91\%, SD=17\%$; standard group: $X=86\%, SD=8\%$), the posttreatment testing session (perturbation group: $X=94\%, SD=15\%$; standard group: $X=90\%, SD=13\%$), or the follow-up testing session (perturbation group: $X=96\%, SD=15\%$; standard group: $X=92\%, SD=10\%$). Pretraining group means for anterior knee laxity (reported as differences between involved and uninjured knees) are provided in Table 1. Follow-up examination mean anterior knee laxity was 4.9 mm (SD=1.7) the perturbation group and 5.4 mm (SD=2.3) for the standard group. There were no differences between groups in anterior knee laxity, and there was no change in laxity from the pretreatment test session to the follow-up test session within either group ($P>.05$).

Discussion

The results of the chi-square analysis indicate that more subjects in the standard group had unsuccessful rehabilitation compared with the perturbation group. The subjects either experienced an episode of the knee giving way or regressed to being at high risk for reinjury during the follow-up period. The likelihood ratio calculated for the frequency data for success or failure of rehabilitation suggests that patients would be almost 5 times more likely to successfully return to high-level physical activity if they receive the perturbation training than if they receive only the standard training program. Adding the perturbation training to current standard nonoperative ACL rehabilitation programs more predictably returns patients to level I and II activities. The higher scores for the perturbation group for follow-up single and triple hop tests further support this finding.

Interactions were found for the Activities of Daily Living Scale, global rating of knee function, and crossover hop test scores. Subjects in both groups improved their scores from the pretreatment test session to the posttreatment test session. Subjects in the perturbation group maintained their scores on these measures from the posttreatment test session to the follow-up test session, whereas the scores of the subjects in the stan-
dard group fell. Both treatment programs were capable of returning subjects to level I and II activities; however, the perturbation program allowed for longer-term success of rehabilitation.

There were no differences in passive anterior knee laxity between groups prior to training and at the follow-up examination. There was also no change in mean laxity measurements from the pretreatment test session to the follow-up test session for either group. It should be noted, however, that follow-up laxity measurements were not obtained for 1 subject in the perturbation group and 4 subjects in the standard group. All 5 subjects had had an episode of the knee giving way between the pretreatment and follow-up examination periods. It is possible that anterior knee laxity measurements could have increased in these subjects as a result of the episode of the knee giving way. However, of the remaining 2 subjects in the study who had an episode of the knee giving way, passive anterior knee laxity was unchanged in 1 subject and was reduced in the other subject from the pretreatment test session to the follow-up test session. Several studies have indicated that passive anterior knee laxity is not correlated with functional outcome following ACL injury. Therefore, we believe that even if a difference in passive anterior knee laxity existed between groups, it would probably not explain differences in treatment outcomes between groups.

The perturbation training may provide some protective effect for continued participation in high-level physical activities following nonoperative ACL rehabilitation. Although the mechanism for this protective effect cannot be determined from the results of this study, it could be related to adaptations in neuromuscular control of knee stability. Subjects in the perturbation program were given additional exposure to potentially destabilizing forces about the knee in a controlled, yet progressive, manner. This additional exposure may have provided an additional opportunity for the neuromuscular system to adapt to these forces by developing successful compensatory muscle activity patterns. Future studies are needed to compare pretraining and posttraining changes in muscle activity during functional activities. These studies may be useful in describing the underlying mechanisms for the success of the perturbation training program.

The method of application of the perturbation training techniques may also have contributed to the success of the perturbation training program. As individuals acquire new motor skills, muscle activity responses will progress from strong co-contraction patterns to more selective muscle activity and movement patterns. During the roller board and stationary platform perturbation, most subjects appeared to respond with strong co-contractions of lower-extremity muscles during early treatment sessions (based on visual inspection and palpation). Subjects were asked not to overcome the forces applied by the therapist, but rather to match the forces as they were applied and released. This method of instruction resulted in more selective lower-extremity muscle contractions in response to the applied loads. This method of instruction during the roller board and platform technique may have better prepared the subjects for higher-skilled muscular responses to destabilizing forces when they returned to full athletic competition.

Applying the perturbation techniques during performance of sport-specific tasks may have added to the success of this treatment. If the perturbation techniques allowed subjects to acquire protective compensatory neuromuscular adaptations, application of these techniques during sport-specific tasks may have provided for carryover of the protective responses to functional situations. Practicing learned motor skills in the context of functional tasks has been suggested to ensure carryover during functional activities.

Subjects were treated for 10 sessions, at a frequency of 2 to 3 times per week. Although this treatment dosage seemed to be adequate over a 6-month period from the time of injury, the optimal dosage for extended participation in level I and II activities cannot be determined from the results of this study. Future investigations that use varied numbers and frequencies of training sessions may be useful in identifying an optimal dose-response relationship for the perturbation training program.

We were the first researchers to use a screening examination to select patients with good potential to succeed with nonoperative management for participation in a study of this type. In previous studies, subjects self-elected nonoperative management for their injuries. Many subjects in these studies experienced continued episodes of instability and had reduced their activity levels as a result of their knee condition, even after undergoing rehabilitation. Engström et al reported that only 23% of their subjects were able to return to preinjury activity levels with nonoperative management. Andersson reported that only 30% of subjects electing nonoperative management were able to return to preinjury activity levels within 1 year of injury.

The best success rate for returning patients to high-level physical activity was reported by Shelton et al. Subjects in their study self-elected nonoperative treatment and were excluded only if multiple ligament or repairable meniscal damage was associated with the ACL injury. Thirty-one of the 43 subjects in Shelton and colleagues’ study returned to athletic competition. Only 12 (39%) of the 31 subjects who returned to athletic competition were able to do so without experiencing an episode of...
giving way at the knee. Comparing this result with ours, 69% (18/26) of all subjects in our study returned to full activity and did not report an episode of giving way at the knee at the time of the follow-up examination. The success rate was 92% (11/12) in the perturbation group and 50% (7/14) in the standard group. The success rates for subjects in our study were superior to that of the study by Shelton et al, regardless of treatment group assignment. The evidence suggests that use of the screening examination to select appropriate patients for nonoperative management of ACL rupture improves the probability of successful return to high-level activity in this patient population.

Conclusions
Augmenting nonoperative ACL rehabilitation programs with the perturbation training techniques described in this report enhances the probability of successful return to high-level physical activity. Although both training programs used in this study allowed subjects with isolated ACL ruptures to return to high-level physical activities, subjects who received the perturbation training demonstrated greater long-term success than subjects who did not receive this training. The greater proportion of successful return to activity in both treatment groups compared with previously reported success rates indicates the screening examination enhanced treatment outcome by identifying patients with good potential to succeed with nonoperative management.

References


