Perturbation Training Improves Knee Kinematics and Reduces Muscle Co-contraction After Complete Unilateral Anterior Cruciate Ligament Rupture

Background and Purpose. Dynamic knee stabilization strategies of people who successfully compensate for the absence of an anterior cruciate ligament (ACL) ("copers") are different from those of people who do not compensate well for the injury ("noncopers"). Early after injury, certain patients ("potential copers") can increase the likelihood of successfully compensating for the injury by participating in 10 sessions of perturbation training. The purpose of this study was to determine how perturbation training alters muscle co-contraction and knee kinematics in potential copers. Subjects. Seventeen individuals with acute, unilateral ACL rupture who were categorized as potential copers and 17 subjects without injuries who were matched by age, sex, and activity level were recruited for this study. Methods. Motion analysis and electromyographic data were collected as subjects walked across a stationary or moving platform (horizontal translation) before and after perturbation training. Results. Before training, potential copers had higher co-contraction indexes and lower peak knee flexion angles than subjects without injuries. After training, potential copers' movement patterns more closely resembled those of subjects without injuries (ie, they showed reduced co-contraction indexes and increased peak knee flexion angles during stance). Discussion and Conclusion. Perturbation training reduced quadriceps femoris-hamstring muscle and quadriceps femoris-gastrocnemius muscle co-contractions and normalized knee kinematics in individuals with ACL rupture who were classified as potential copers. Findings from this study provide evidence for a mechanism by which perturbation training acts as an effective intervention for promoting coordinated muscle activity in a select population of people with ACL rupture. [Chmielewski TL, Hurd WJ, Rudolph KS, et al. Perturbation training improves knee kinematics and reduces muscle co-contraction after complete unilateral anterior cruciate ligament injuries. *Phys Ther*. 2005;85:740–754.]

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Although an estimated 100,000 to 200,000 anterior cruciate ligament (ACL) injuries occur in the United States annually, only approximately 60,000 individuals with ACL deficiency undergo reconstructive surgery each year.[1,2] Some individuals can stabilize their knees following ACL rupture, even during activities involving cutting and pivoting, but most experience instability with daily activities.[3]

Our data suggest that physiological responses and motor control strategies of people who successfully compensate for the absence of the ACL ("copers") are different from those of people who do not compensate well for the injury ("noncopers").[4] *Copers*, who we operationally define as people who have returned to full activity without symptoms of instability for at least 1 year, use strategies involving more coordinated muscle activation that stabilize the knee without compromising knee motion.[4,5] There is no single pattern adopted by the copers; individuals adopt idiosyncratic compensation patterns that are related to rate of muscle activation and unrelated to quadriceps femoris muscle force.[4] Conversely, noncopers adopt a remarkably limited strategy to stabilize their knees across activities with widely differing demands on the knee.[4–6] The pattern is a robust joint-stiffening strategy that includes reduced knee motion, reduced internal knee extension moment, distribution of support moment away from the knee, slower muscle activation, and generalized co-contraction of the muscles that cross the knee; and this pattern is present in activities ranging from walking to jumping.[4,6,7] The joint-stiffening strategy seen in the noncopers may reflect the early stages of motor skill acquisition. Vereijkin et al[8] demonstrated that individuals often freeze the degrees of freedom of a task via massive co-contraction of muscles during novel activities. As the skill level improves, joint stiffening gives way to a larger variety of movements and more selective motor responses during the activity. The muscle co-contraction strategy seen in the noncopers reflects an unsophisticated adaptation to the ACL rupture for which appropriate muscle activation strategies to dynamically stabilize the injured knee have not yet developed.

Compensation patterns appear to develop soon after injury in both copers and noncopers.[4,5] We have developed a screening examination that can be administered within 2 months of the ACL injury to identify those who have the potential to compensate well for the injury (potential copers).[9] We demonstrated in a randomized trial that a rehabilitation program that included pur-

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poseful perturbation of support surfaces (perturbation training) resulted in superior return to functional activity in potential copers compared with management with a standard rehabilitation program.[10] Ihara and Nakayama[11] and Beard et al[12] have similarly demonstrated improved dynamic knee stability in patients with ACL deficiency after rehabilitation that included perturbation training. An important question remains that affects the development of effective rehabilitation programs for patients after ACL rupture: *how* does the training promote dynamic knee stability? Our recent work demonstrated that potential copers possess slightly altered knee kinematics and abnormal muscle activity during walking, but develop small changes in muscle activity patterns (increased quadriceps femoris muscle activity) after perturbation training that are conducive to dynamic knee stability.[13,14]

Some researchers applied a perturbing force during walking and standing to elucidate dynamic knee stabilization patterns in subjects with a variety of pathologies, including those with chronic ACL deficiency.[15–18] Recently, we demonstrated that potential copers respond with knee kinematics much like subjects without injuries in response to a translation of the support surface while standing on the injured leg, whereas noncopers adopt a very different pattern.[19,20] The only negative adaptation shared by the potential copers and noncopers was high co-contraction of the knee extensors and flexors.

The purpose of this study was to elucidate the mechanism underlying the development of dynamic knee stability in patients with ACL deficiency as a result of perturbation training. A platform that translated in an anterior or lateral direction immediately after initial contact was used to destabilize the knee during walking. We hypothesized that the knees of both groups would flex less and have lower excursions when the platform moved compared with when the platform was stationary. We hypothesized that, prior to training, potential copers would have knee kinematics and muscle activity that are consistent with joint stiffening, including lower peak knee flexion angles, decreased knee flexion excursion, and greater co-contraction of the muscles that cross the knee. We also hypothesized that, after training, the potential copers would have normal peak knee flexion angles and joint excursions with reduced muscle co-contraction.

Methods

Subjects

Seventeen individuals with an acute, unilateral ACL injury were classified as potential copers through a screening process[9] and recruited for the study. Anterior cruciate ligament injury was confirmed with both magnetic resonance imaging and a KT-1000 test* of ≥ 3 mm compared with the contralateral knee.[1] Subjects without injuries (control subjects) who were matched by age, sex, and activity level were also recruited for study participation. All subjects were regular participants in level I or II sports[1] with no history of vestibular dysfunction or recent (within 6 months) low back injury. None of the subjects with ACL deficiency had concomitant ligamentous injury, articular cartilage damage, repairable meniscal tears, or bilateral knee involvement. None of the control subjects had a significant (more severe than mild sprain or strain) injury to either lower extremity. All participants signed an informed consent form before participating in the study.

Procedure

All subjects participated in a pretraining motion analysis data collection, 10 sessions of perturbation training[10] (Tab. 1), and a posttraining motion analysis data collection. Data collections were performed on the involved limb of all potential copers; the tested limb of the control subjects was randomly chosen prior to the study.

Motion analysis and muscle activity. Motion data were collected at 120 Hz with a 6-camera passive, 3-dimensional analysis system (VICON†). Retroreflective markers were used to determine joint centers and track limb motion. Marker data were low-pass filtered at 6 Hz with a fourth-order zero-lag Butterworth filter. Lower-extremity joint angles were calculated using rigid body analysis with Euler angles (Move3D‡).

Subjects performed self-paced walking trials along a 13-m walkway with a custom-built, movable platform located at its center and flush with the floor. The platform could be programmed to remain stationary (locked condition) or move 5.8 cm at a speed of 40 cm/s at initial contact. The speed and distance of the translation are similar to those of previous methods described in the literature for disturbing the gait of subjects with ACL deficiency.[21] Footswitches§ were affixed to the bottom of the subjects' shoes to assist with identification of heel-strike and toe-off on the platform. Walking speed was monitored by 2 photoelectric cells placed 2.86 m apart along the walkway. Subjects were allowed practice trials across the stationary platform until walking speed was consistent and platform contact could be achieved without targeting. Only trials within 5% of the subjects' mean speed were accepted. First, data were collected during 5 trials with the platform locked. Next, the platform was positioned and programmed to translate in

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† Oxford Metrics Ltd, Unit 8, 7 West Way, Botley, London, United Kingdom 0X2 0JB.

‡ IH Biomechanics Laboratory, Bethesda, MD 20894.

§ Motion Lab Systems Inc, 15045 Old Hammond Hwy, Baton Rouge, LA 70816.

Table 1.
Perturbation Training Protocol[10]

Technique	Sets/Duration	Direction of Board Movement[a]	Application
Rockerboard	2–3 sets/1 min each	A/P, M/L	Begin in bilateral stance for first session; perform in single-leg stance for remaining sessions
Rollerboard/platform	2–3 sets/1 min each, perform bilaterally	Initial: A/P, M/L Progression: diagonal, rotation	Subject force is counter-resistance opposite of rollerboard, matching intensity and speed of application so rollerboard movement is minimal; leg muscles should not be contracted in anticipation of perturbation, nor should response be rigid co-contraction
Rollerboard	2–3 sets/30 s–1 min each	Initial: A/P, M/L Progression: diagonal, rotation	Begin in bilateral stance for first session; perform in single-leg stance for remaining sessions; perturbation distances are 2.54–5.08 cm (1–2 in)

Early Phase (sessions 1–4)
Treatment goals:
- Expose athlete to perturbations in all directions
- Elicit an appropriate muscular response to applied perturbations (no rigid co-contraction)
- Minimize verbal cues

Middle Phase (sessions 5–7)
Treatment goals:
- Add light sport-specific activity during perturbation techniques
- Improve athlete accuracy in matching muscle responses to perturbation intensity, direction, and speed

Late Phase (sessions 8–10)
Treatment goals:
- Increase difficulty of perturbations by using sport-specific stances
- Obtain accurate, selective muscular responses to perturbations in any direction and of any intensity, magnitude, or speed

[a] A/P=anterior/posterior, M/L=medial/lateral.

an anterior or lateral direction (anterior and lateral conditions). Subjects were given 3 to 5 practice trials walking across the moving platform, after which data were collected during 5 trials. The order of presentation of the platform movement direction (anterior or lateral) was randomized prior to the data collection. The platform was then repositioned to collect data during trials in the untested direction. Lower-extremity kinematics for each subject were normalized to 100% of stance and averaged across trials. Peak knee flexion angle during stance and knee excursion (change in knee flexion angle measured, in degrees, from heel-strike to peak knee flexion) were the primary kinematic variables of interest.

Electromyographic (EMG) data were collected at a frequency of 960 Hz and band-pass filtered from 20 to 350 Hz. Surface electrodes[‡] were placed over the muscle bellies of the tibialis anterior (TA), vastus lateralis (VL), medial gastrocnemius (MG), soleus (SOL), medial hamstring (MH), and lateral hamstring (LH) muscles. Two seconds of resting and maximal voluntary isometric contraction (MVIC) EMG signals were collected from each muscle before the data collection.

All EMG data were post-processed and analyzed using custom-made software (LabVIEW[‖]). A linear envelope was created from the EMG signals by full-wave rectification and low-pass filtering with a second-order, phase-corrected Butterworth filter. The linear envelope was normalized to maximum muscle activity, identified either during MVIC testing or the walking trials, and integrated over the interval from 100 milliseconds prior to heel-strike to heel-strike (preparatory interval) and from heel-strike to the point of peak knee flexion (weight acceptance). *Muscle co-contraction*, defined as the simultaneous activation of antagonistic muscles (VL-MG and VL-LH), was calculated using the integrated EMG of each muscle and the formula: [(less active muscle/more active muscle) × (sum of the integrated activity of both muscles)].[5] This co-contraction calculation technique accounts for both the magnitude and timing of agonistic muscle groups and has been effective in identifying muscle activation strategies in patients with ACL deficiencies.[5] Muscle co-contraction

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[‖] National Instruments Inc, 11500 N Mopac Expwy, Austin, TX 78759.

was calculated over the preparatory and weight-acceptance intervals.

Perturbation training. Both groups underwent 10 sessions of perturbation training, which were performed under the supervision of 2 of the investigators (TLC and WJH) at the University of Delaware Physical Therapy Clinic according to the protocol described by Fitzgerald et al[10] (Tab. 1).

Data Analysis

For each condition, a 3-way analysis of variance (ANOVA) with 1 between factor (group) and 2 repeated factors (time and phase of gait) was used to identify differences between groups for VL-LH and VL-MG EMG co-contraction indexes. A 3-way ANOVA with one between factor (group) and 2 repeated factors (time and phase of gait) was used to identify differences between groups for kinematic variables (peak knee flexion angle and knee excursion) for each condition. When significant main effects were found, *post hoc* testing of EMG variables was performed with independent t tests to identify differences between groups before and after training, and paired t tests were used to identify pretraining-posttraining differences within groups. *Post hoc* testing of kinematic variables was performed using a 1-way ANOVA with one repeated measure (platform condition) to test the differences between trials when the platform was stationary and those when the platform translated anteriorly or laterally both before and after training. Statistical significance was set at $P<.05$ for kinematic variables and at $P<.1$ for co-contraction variables. A higher level of significance was established for EMG variables in an effort to avoid a type I error given the highly variable nature of EMG data.[22]

Results

Main effects were identified from the analysis of both peak knee flexion angle and knee flexion excursion. For peak knee flexion angle, main effects included platform condition ($P<.001$) and time × group × condition ($P=.028$). For knee flexion excursion, a main effect of condition was found ($P<.001$).

There were main effects for VL-LH and VL-MG co-contraction indexes during each platform condition. During the locked condition, there was a main effect of time for both VL-LH ($P<.001$) and VL-MG ($P<.001$). There was a main effect of time during the lateral condition for both VL-LH ($P<.001$) and VL-MG ($P<.001$). There also were main effects during the lateral condition for VL-LH co-contraction for time × group ($P=.045$), phase of gait ($P=.05$), and group ($P=.07$). During the anterior condition, there were main effects of time ($P<.001$), time × group ($P=.069$), phase of gait ($P=.019$), and time × phase of gait ($P=.043$) for VL-LH. There also was a main effect of time for VL-MG ($P<.001$) during the anterior condition.

Before Training

Effects of different conditions. There was less knee flexion excursion and lower peak knee flexion in the anterior and lateral conditions than in the locked condition for both groups (Fig. 1[A–C]).

Kinematics. The potential copers had lower peak knee flexion angles ($\overline{X}=19.81°$, SD=4.86°, $P=.016$) than the control subjects ($\overline{X}=24.28°$, SD=5.37°, $P=.016$) in the locked condition (Tab. 2, Fig. 1[A]). There were no differences between groups for peak knee flexion angle in the anterior condition (Tab. 2, Fig. 1[C]) ($P=.234$) or the lateral condition (Tab. 2, Fig. 1[B]) ($P=.067$). There were no differences in knee flexion excursion between groups for the locked condition ($P=.143$) (Tab. 2, Fig. 1[A]), the lateral condition ($P=.212$) (Tab. 2, Fig. 1[B]), or the anterior condition ($P=.429$) (Tab. 2, Fig. 1[C]).

Co-contraction. In the locked condition, group differences were found only in the VL-LH co-contraction index (Tab. 3, Fig. 2[A]). The VL-LH co-contraction index was higher in the potential copers than in the control subjects for both the preparatory interval (potential copers: $\overline{X}=28.83$, SD=14.55, $P=.062$; control subjects: $\overline{X}=20.44$, SD=10.39, $P=.062$) and the weight-acceptance interval (potential copers: $\overline{X}=41.69$, SD=17.34, $P=.034$; control subjects: $\overline{X}=30.40$, SD=11.87, $P=.034$). There were no differences between groups for VL-MG co-contraction during either the preparatory interval ($P=.113$) or the weight-acceptance interval ($P=.341$).

In the lateral condition, preparatory muscle co-contraction indexes were consistently larger in the potential copers (VL-LH: $\overline{X}=29.17$, SD=14.59, $P=.095$; VL-MG: $\overline{X}=16.35$, SD=7.27, $P=.018$) than the control subjects (VL-LH: $\overline{X}=21.38$, SD=11.69, $P=.095$; VL-MG: $\overline{X}=11.13$, SD=4.23, $P=.018$) (Tab. 3, Fig. 2[B]). In addition, the VL-LH co-contraction index was higher in potential copers ($\overline{X}=51.95$, SD=22.75, $P=.008$) than in the control subjects ($\overline{X}=34.70$, SD=11.15, $P=.008$) during the weight-acceptance interval. There was no difference between groups in the VL-MG co-contraction index ($P=.481$) during the weight-acceptance interval.

In the anterior condition, potential copers had a higher VL-MG co-contraction index in the preparatory interval ($\overline{X}=15.70$, SD=6.85, $P=.044$) compared with the control subjects ($\overline{X}=11.27$, SD=5.08, $P=.044$) (Tab. 3, Fig. 2[C]). Preparatory VL-LH co-contraction was not different between potential copers and control subjects ($P=.151$). The co-contraction index was larger in potential copers ($\overline{X}=53.45$, SD=25.00, $P=.022$) than in the control subjects

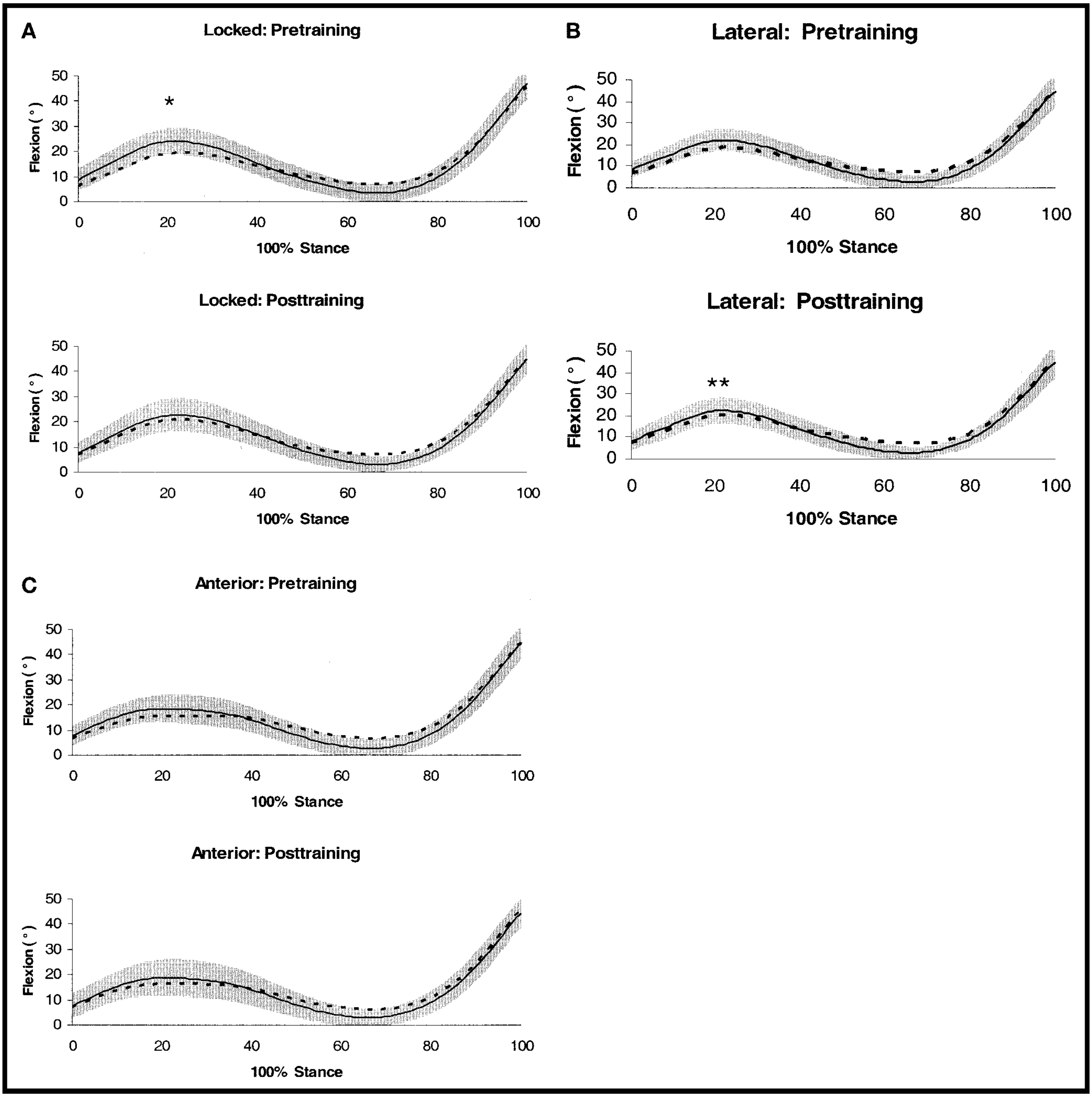

Figure 1.
Sagittal-plane knee kinematics in the locked (Fig. 1[A]), lateral (Fig. 1[B]), and anterior (Fig. 1[C]) conditions before and after perturbation-enhanced rehabilitation. The solid black line represents control subjects; the dashed black line represents potential copers. The gray region represents the standard deviation of the control subjects. Time is normalized to 100% of stance, with 0%=heel-strike and 100%=toe-off. Statistically significant differences between groups for peak knee flexion at a level of *P*<.05 are identified by a single asterisk (*); pretraining-posttraining differences for peak knee flexion in potential copers at a level of *P*<.05 is identified by a double asterisk (**).

($\overline{X}$=36.93, SD=13.25, *P*=.022) during the weight acceptance interval for VL-LH but not for VL-MG (*P*=.223).

After Training

Effects of different conditions. There was less knee flexion excursion and lower peak knee flexion in the anterior condition than in the locked condition for both groups. There was less knee flexion excursion in the lateral condition than in the locked condition for both groups.

Kinematics. After training, there were no differences in the peak knee flexion angle between groups in any of the conditions (Tab. 2, Fig. 1[A–C]). Potential copers demonstrated greater peak knee flexion angles after training in the lateral condition ($\overline{X}$=20.78, SD=5.51,

Table 2.
Knee Flexion Angle and Excursion (in Degrees) by Group and Condition Before and After Training[a]

	PKF				KEX			
	Potential Copers		Control Subjects		Potential Copers		Control Subjects	
Condition	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
Locked								
Pretraining	19.81	4.86*	24.28	5.37*	13.35	4.52	15.59	4.15
Posttraining	21.31	5.05	23.40	6.55	14.32	4.31	15.53	3.88
Lateral								
Pretraining	19.11	4.59	22.32	5.25	12.12	3.67	13.79	3.97
Posttraining	20.78	5.51**	22.57	5.93	13.22	4.20	14.34	2.89
Anterior								
Pretraining	16.71	5.18	18.92	5.44	9.88	4.70	11.18	4.74
Posttraining	17.04	5.80	19.08	7.23	9.83	4.20	11.63	4.02

[a] PKF=peak knee flexion angle during stance, KEX=knee excursion from heel-strike to peak knee flexion. Differences between groups at a level of $P<.05$ are denoted by a single asterisk (*), pretraining-posttraining differences within groups at a level of $P<.05$ are denoted by a double asterisk (**).

Table 3.
Co-contraction Values During Preparatory and Weight-Acceptance Phases of Gait Before and After Training for Potential Copers and Control Subjects[a]

	Preparatory				Weight Acceptance			
	VL-LH		VL-MG		VL-LH		VL-MG	
Condition	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
Locked								
Potential copers								
Pretraining	28.83	14.55*	13.17	5.45	41.69	17.34*	48.43	23.93
Posttraining	22.28	10.65	12.71	5.22	35.57	18.81	48.28	21.91
Control subjects								
Pretraining	20.44	10.39	10.44	4.23	30.40	11.87	41.27	18.91
Posttraining	23.49	13.91	10.19	3.63	32.87	20.46	38.62	18.94
Lateral								
Potential copers								
Pretraining	29.17	14.59*	16.35	7.27*	51.95	22.75*	56.73	30.00
Posttraining	21.25	10.71**	13.67	5.74	42.55	22.09**	51.53	31.35
Control subjects								
Pretraining	21.38	11.69	11.13	4.23	34.70	11.15	48.93	32.87
Posttraining	22.85	13.17	11.39	4.89	32.85	15.97	41.40	20.62
Anterior								
Potential copers								
Pretraining	27.22	13.60	15.70	6.85*	53.45	25.00*	57.73	25.23
Posttraining	20.90	11.28**	14.22	6.12	41.64	25.45**	50.67	28.02**
Control subjects								
Pretraining	20.86	11.51	11.27	5.08	36.93	13.25	46.61	25.28
Posttraining	21.41	9.69	11.73	4.80	32.33	14.60	42.22	13.70

[a] VL-LH=vastus lateralis-lateral hamstring muscle co-contraction, VL-MG=vastus lateralis-medial gastrocnemius muscle co-contraction. Significant differences at a level of $P<.10$ between groups before training are identified by a single asterisk (*), and significant pretraining-posttraining differences at a level of $P<.10$ within groups after training are identified by a double asterisk (**).

$P=.046$), but there was no change on the peak knee flexion angle in the anterior condition ($P=.688$) or the locked condition ($P=.072$). Training did not change the peak knee flexion angle of the control subjects. There also were no differences after training between groups for knee flexion excursion in any condition (Tab. 2, Fig. 1[A–C]). There was no effect of training within groups, for either potential copers or control subjects, in any of the conditions (Tab. 2, Fig. 1[A–C]).

Co-contraction. There were no longer group differences in co-contraction indexes in any condition (Tab. 3, Fig. 2[A–C]). Although there were generally lower mean co-contraction values for control subjects in each condition, these values were not different from pretraining values.

Although there were reductions in the potential copers' co-contraction indexes during the locked condition, the

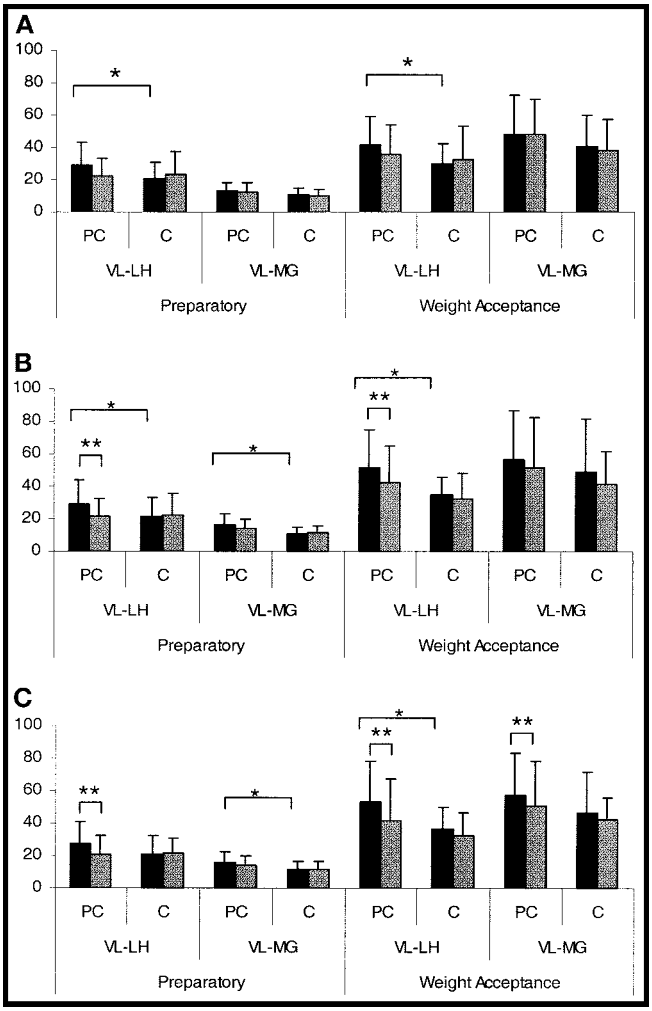

Figure 2.
Co-contraction for potential copers (PC) and control subjects (C) in the locked (Fig. 2[A]), lateral (Fig. 2[B]), and anterior (Fig. 2[C]) conditions. Pretraining values are represented by the solid black bars; posttraining values are represented by the black-and-white spotted bars. Statistically significant differences ($P<.10$) between groups are denoted by a single asterisk (*); differences within groups after training are denoted by a double asterisk (**). VL-LH=vastus lateralis-lateral hamstring muscle co-contraction; VL-MG=vastus lateralis-medial gastrocnemius muscle co-contraction.

change did not reach statistical significance. In the lateral condition, there were reductions in the potential copers' VL-LH co-contraction indexes after training in both the preparatory interval ($\overline{X}=21.25$, SD=10.71, $P=.073$) and the weight-acceptance interval ($\overline{X}=42.55$, SD=22.09, $P=.092$) (Fig. 2[B]). The lower VL-MG co-contraction indexes after training did not reach statistical significance. In the anterior condition, potential copers demonstrated reduced VL-LH co-contraction indexes in the preparatory interval ($\overline{X}=20.90$, SD=11.28, $P=.093$) and the weight-acceptance interval ($\overline{X}=41.64$, SD=25.45, $P=.052$). Decreases in VL-MG activity after training reached statistical significance only during the weight-acceptance interval ($\overline{X}=50.67$, SD=28.02, $P=.086$).

Discussion and Conclusions

The results of this study indicate that neuromuscular changes that occur in potential copers after perturbation training may explain the improved functional outcomes previously demonstrated by Fitzgerald et al.[10] As we hypothesized, prior to training, potential copers stiffened their knees with higher muscle co-contraction and slightly lower peak knee flexion angles, indicating an undeveloped knee stabilization strategy. Our hypothesis that platform translation would be destabilizing to both groups also was correct. Both groups demonstrated altered knee kinematics that included lower peak knee flexion angles and truncated knee flexion excursion during the conditions with platform movement compared with the locked condition. After perturbation training, the knee flexion angles increased and muscle co-contraction was generally lower in the potential copers, making their movement patterns similar to those of the control subjects. The effect of specialized training was to change the knee stabilization strategy from a joint-stiffening pattern to a pattern that may allow the potential copers to dynamically stabilize their knee in response to unexpected perturbations and perhaps preserve joint integrity over time.

Before the training, the potential copers stiffened their knees and co-contracted their muscles, which indicates an immature stabilization strategy. "Freezing degrees of freedom" has been described as a primitive strategy when mastering a new skill.[23] Potential copers must become skilled at stabilizing their knees in the absence of the passive restraint and afferent feedback provided by an intact ACL. Prior to training, they used a joint-stiffening strategy even while walking across a stationary platform when there was minimal threat to knee stability. The use of a joint-stiffening strategy in this case may be a response to potential instability brought on by an unopposed quadriceps femoris muscle contraction that can cause anterior tibial translation,[24,25] because a strong eccentric quadriceps femoris muscle contraction is present during weight acceptance of walking. Before training, there was a strong trend for the potential copers to flex less than control subjects in response to the lateral translation. Although the difference in knee angle was small, as we have previously demonstrated in potential copers,[13] it is consistent with an immature compensation strategy for ACL injury because people who can fully cope with the injury have peak knee flexion angles that are no different from those of people without injuries in a variety of tasks.[4,5]

During the anterior and lateral conditions, both potential copers and control subjects had less knee flexion than during locked conditions both before and after training, indicating that the activity was challenging to both groups. Similar results were obtained by Ferber et al,[21] who also demonstrated that people without injuries flexed the knee joint less in trials with anterior support surface translation than in trials when the platform was stationary. Despite comparable changes in knee motion, higher muscle co-contraction in potential copers reveals that they respond to a translation of the support surface differently than people without injuries. The change in muscle activity sheds light on the stabilization strategy used by individuals who are in the process of learning to stabilize the knee.

In the locked condition and in response to both anterior and lateral platform translations, the higher muscle co-contraction that was observed in the potential copers may have contributed to the observed joint stiffening. Higher VL-LH co-contraction prior to initial contact might be an attempt to preset the limb in a position of relative stability prior to heel-strike. The higher VL-LH co-contraction seen in the potential copers during weight acceptance was likely also related to stabilization through knee stiffening.

Higher VL-MG co-contraction values in preparation for heel-strike were observed in the potential copers before training only in the trials with platform movement. Co-contraction of the VL-MG may serve a direct role at the knee, similar to quadriceps femoris-hamstring muscle co-contraction. In preparation for a known disturbance, a biarticular muscle that acts at the knee and ankle may be in a unique position to provide stability as the foot contacts the moving platform.

After perturbation training, the potential copers flexed more during weight acceptance, and the degree of co-contraction was reduced; they became more similar to the control subjects. This change was particularly pronounced when the platform was stationary, where group differences prior to training were eliminated after training, and when the platform translated laterally, where potential copers had a pretraining-posttraining change in peak knee flexion angles. Although in both cases the magnitude of the change was small (1.5° for the stationary condition and 1.7° for the lateral condition), we believe the changes have clinical significance. The knee kinematics of potential copers are not typically very different from those of people without injuries, so the magnitude of change was not expected to be extreme in the potential copers. An increase in knee flexion indicates the adoption of a movement pattern that is consistent with clinical findings of improved dynamic knee stability after training.[10] Importantly, the results of our study suggest that muscle co-contraction is lessened after patients participate in a specialized training program that requires them to produce specific but varied muscle responses when reacting to random forces. Our findings are consistent with the work of Nichols,[26] who showed that force-feedback reflexively altered muscle-firing patterns to control both joint forces and torques in a decerebrate cat model. Recent work from the same group suggests that force feedback is organized to regulate coupling between joints.[27] Lower co-contraction reflects a change to a more selective pattern that helps explain increased knee flexion after training as well as the posttraining improvements in function found by other investigators.[10–12] Perturbation training provides the stimulus for reorganizing muscle responses that may ultimately lead to improved function.

We believe a key principle underlying perturbation training is that patients with ACL deficiencies should be exposed to carefully controlled forces that destabilize the knee joint enough to elicit appropriate responses without putting the knee joint at risk for further injury. Gradually adding more challenging forces allows them to learn more appropriate muscle responses to unexpected forces that release the tight control of the knee that manifests in reduced knee flexion. This premise is supported by our data. When learning and skill acquisition take place, rigid control over the degrees of freedom is released in 2 stages. In the first stage, restrictions are gradually lifted, and the degrees of freedom become incorporated into larger functional units (ie, groups of muscles are constrained to act as functional units).[23] In the second stage, the organization becomes more economical, enhancing the efficiency of muscular forces.[23] Compared with noncopers, who restrict joint motion to a larger extent, potential copers have only minor kinematic deviations during gait, suggesting that potential copers are in the first stage of learning to stabilize the ACL-deficient knee. Resolution of rigid muscle firing patterns in conjunction with normal gait kinematics after training is consistent with Bernstein's second stage of skill acquisition.[23] The posttraining adaptations observed in the potential copers in our study are thus indicative of a more mature and refined stabilization strategy.

Elimination of the joint-stiffening strategy used by people with ACL deficiencies is important. High co-contraction may help to stabilize the joint through joint stiffening; however, this strategy could be detrimental over time. Shear forces, such as those associated with episodes of giving way, and compression that may be associated with excessive muscle co-contraction, coupled with reduced shock absorption that accompanies limited knee flexion and decreased quadriceps femoris muscle force, can contribute to the biochemical and metabolic changes that characterize degeneration of articular cartilage.[28] The development of posttraumatic, unilateral knee osteoarthritis may be accelerated by the manner in which the potential copers attempted to stabilize the knee prior to training.[1,5,6]

Evidence supporting the use of perturbation-enhanced rehabilitation protocols for the management of patients with ACL deficiency and classified as potential copers is strong.[10] The response of patients with ACL deficiency and classified as noncopers who participate in perturbation-enhanced rehabilitation is unknown and warrants investigation. Nonoperative management of patients with ACL ruptures has resulted in limited success in returning individuals to physically active lifestyles without episodes of giving way.[1,29,30] Fitzgerald et al,[10] in a randomized trial of potential copers, found that perturbation training resulted in 93% of those subjects who completed the training successfully returning to high-level activity without episodes of giving way. Only 50% of those subjects in the traditional rehabilitation group returned to high-level activities.[10] The results of our study reveal a possible mechanism underlying the high success rate for return to sporting activities of potential copers who participate in perturbation training.

References

1 Daniel DM, Stone ML, Dobson BE, et al. Fate of the ACL-injured patient: a prospective outcome study. *Am J Sports Med.* 1994;22: 632–644.

2 *National Hospital Discharge Surveys.* Rosemont, Ill: Department of Research and Scientific Affairs, American Academy of Orthopedic Surgeons; 1990–1995.

3 Eastlack ME, Axe MJ, Snyder-Mackler L. Laxity, instability, and functional outcome after ACL injury: copers versus noncopers. *Med Sci Sports Exerc.* 1999;31:210–215.

4 Rudolph KS, Eastlack ME, Axe MJ, Snyder-Mackler L. 1998 Basmajian Student Award Paper: movement patterns after anterior cruciate ligament injury—a comparison of patients who compensate well for the injury and those who require operative stabilization. *J Electromyogr Kinesiol.* 1998;8:349–362.

5 Rudolph KS, Axe MJ, Buchanan TS, et al. Dynamic stability in the anterior cruciate ligament deficient knee. *Knee Surg Sports Traumatol Arthrosc.* 2001;9:62–71.

6 Rudolph KS, Axe MJ, Snyder-Mackler L. Dynamic stability after ACL injury: who can hop? *Knee Surg Sports Traumatol Arthrosc.* 2000;8:262–269.

7 Ramsey DK, Lamontagne M, Wretenberg PF, et al. Assessment of functional knee bracing: an in vivo three-dimensional kinematic analysis of the anterior cruciate deficient knee. *Clin Biomech (Bristol, Avon).* 2001;16:61–70.

8 Vereijkin B, van Emmerik REA, Whiting HTA, Newell KM. Freezing degrees of freedom in skill acquisition. *Journal of Motor Behavior.* 1992;24:133–142.

9 Fitzgerald GK, Axe MJ, Snyder-Mackler L. A decision-making scheme for returning patients to high-level activity with nonoperative treatment after anterior cruciate ligament rupture. *Knee Surg Sports Traumatol Arthrosc.* 2000;8:76–82.

10 Fitzgerald GK, Axe MJ, Snyder-Mackler L. The efficacy of perturbation training in nonoperative anterior cruciate ligament rehabilitation programs for physical active individuals. *Phys Ther.* 2000;80:128–140.

11 Ihara H, Nakayama A. Dynamic joint control training for knee ligament injuries. *Am J Sports Med.* 1986;14:309–315.

12 Beard DJ, Dodd CA, Trundle HR, Simpson AH. Proprioception enhancement for anterior cruciate ligament deficiency: a prospective randomised trial of two physiotherapy regimes. *J Bone Joint Surg Br.* 1994;76:654–659.

13 Chmielewski TL, Rudolph KS, Fitzgerald GK, et al. Biomechanical evidence supporting a differential response to acute ACL injury. *Clin Biomech (Bristol, Avon).* 2001;16:586–591.

14 Chmielewski TL, Rudolph KS, Snyder-Mackler L. Development of dynamic knee stability after acute ACL injury. *J Electromyogr Kinesiol.* 2002;12:267–274.

15 Ferber R, Osternig LR, Woollacott MH, et al. Gait perturbation response in chronic anterior cruciate ligament deficiency and repair. *Clin Biomech (Bristol, Avon).* 2003;18:132–141.

16 Nashner LM. Balance adjustments of humans perturbed while walking. *J Neurophysiol.* 1980;44:650–664.

17 Di Fabio RP, Graf B, Badke MB, et al. Effect of knee joint laxity on long-looped postural reflexes: evidence for a human capsular-hamstring reflex. *Exp Brain Res.* 1992;90:189–200.

18 Tang PF, Woollacott MH, Chong RK. Control of reactive balance adjustments in perturbed human walking: roles of proximal and distal postural muscle activity. *Exp Brain Res.* 1998;119:141–152.

19 Chmielewski TL, Hurd WJ, Snyder-Mackler L. Elucidation of a potentially destabilizing control strategy in ACL deficient non-copers. *J Electromyogr Kinesiol.* 2004;15:83–92.

20 Chmielewski TL, Ramsey DK, Snyder-Mackler L. Evidence for differential control of tibial position in pertrubed unilateral stance after acute ACL rupture. *J Orthop Res.* 2005;23:54–60.

21 Ferber R, Osternig LR, Woollacott MH, et al. Reactive balance adjustments to unexpected perturbations during human walking. *Gait Posture.* 2002;16:238–248.

22 Winter DA, Eng P. Kinetics: our window into the goals and strategies of the central nervous system. *Behav Brain Res.* 1995;67:111–120.

23 Bernstein N. *The Coordination and Regulation of Movements.* New York, NY: Pergamon Press; 1967.

24 Hirokawa S, Solomonow M, Lu Y, et al. Anterior-posterior and rotational displacement of the tibia elicited by quadriceps contraction. *Am J Sports Med.* 1992;20:299–306.

25 Grood ES, Suntay WJ, Noyes FR, Butler DL. Biomechanics of the knee-extension exercise: effect of cutting the anterior cruciate ligament. *J Bone Joint Surg Am.* 1984;66:725–734.

26 Nichols TR. A biomechanical perspective on spinal mechanisms of coordinated muscular action: an architecture principle. *Acta Anat (Basel).* 1994;151:1–13.

27 Wilmink RJH, Nichols TR. Distribution of heterogenic reflexes among the quadriceps and triceps surae muscles of the cat hind limb. *J Neurophysiol.* 2003;90:2310–2324.

28 Felson DT, Lawrence RC, Dieppe PA, et al. Osteoarthritis: new insights, part 1: the disease and its risk factors. *Ann Intern Med.* 2000;133:635–646.

29 Ciccotti MG, Lombardo SJ, Nonweiler B, Pink M. Non-operative treatment of ruptures of the anterior cruciate ligament in middle-aged patients: results after long-term follow-up. *J Bone Joint Surg Am.* 1994; 76:1315–1321.

30 Buss DD, Min R, Skyhar M, et al. Nonoperative treatment of acute anterior cruciate ligament injuries in a selected group of patients. *Am J Sports Med.* 1995;23:160–165.