Development of dynamic knee stability after acute ACL injury

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Abstract

Recently, a training program that includes perturbation of support surfaces has been shown to allow most active individuals with ACL injury who pass a screening examination to successfully return to high level activities. The purpose of this study was to identify the effect of this rehabilitation program on involved side muscle activation during walking in subjects with acute ACL rupture and to determine if the activation changes were coincident with improved function. Nine subjects with an acute, unilateral ACL injury or rupture of an ACL graft, who met the screening examination criteria, received ten sessions of rehabilitation that included perturbation training. Motion analysis of five self-paced walking trials were performed before and after training. Electromyographic (EMG) data were collected during stance. After training during walking, the vastus lateralis (VL) integral of activity increased, and relationships between muscles were significantly altered. During walking, VL activation variables were dependent on lateral hamstrings (LH) and/or the soleus (SOL) activation, while no relationships were found before training. Function improved after training, and all subjects returned to their pre-injury activities without experiencing instability. The relationships formed between muscles post-training suggests that perturbation training enhances dynamic knee stability by inducing a well-coordinated strategy among muscles that affect tibial translation. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Anterior cruciate ligament; Rehabilitation; Perturbation

1. Introduction

Individuals have different abilities to compensate for complete anterior cruciate ligament (ACL) rupture. More than half of those with ACL rupture who regularly participated in high-level activities such as jumping, pivoting and cutting sports before injury have significant knee instability, even during daily activities (“non-copers”) [1]. There are some individuals, though, who are able to return to these high level activities without episodic episodes of giving way (“copers”) [2,3]. Copers have been shown to have stance phase knee kinematics and kinetics during walking and jogging that are virtually identical to uninjured subjects, however their quadriceps and hamstrings muscle activity are altered [3]. Non-copers, on the other hand, decrease the injured knee motion and internal extensor moment, have higher soleus activity, altered gastrocnemius and hamstring timing and use significantly more muscle co-contraction [3]. Other investigators have reported changes in quadriceps, hamstrings, gastrocnemius, soleus and tibialis anterior activity during walking after ACL injury, but the relationship to knee stability is unclear since the subjects were not sub-classified [4–6]. Muscle activity alterations after ACL rupture are reasonable since dynamic mechanisms are required to compensate for the loss of a static restraint; however, only those muscle activity alterations that improve knee stability and function can be considered successful.

Theoretically, successful muscle activation compensations after ACL injury reduce anterior translational forces on the tibio-femoral joint, resulting in improved dynamic knee stability. The specific compensation for each muscle is likely dependent on the role the muscle plays in knee stability. The quadriceps can contribute to knee instability by drawing the tibia anteriorly in relationship to the femur. Isolated contraction of the quadriceps has been found to increase ACL strain [7–9]. Conversely, the hamstrings are a potential knee stabilizer because of the ability to draw the tibia posterior in relationship to the femur. Contraction of the hamstrings
has been found to reduce strain on the ACL [7,8] and decrease anterior tibial translation [10]. The gastrocnemius may aid knee stability by increasing knee stiffness. The soleus, although it does not cross the knee joint, has the potential to stabilize the knee during gait through an indirect effect. The soleus is typically activated near the completion of the loading response, controlling forward progression of the tibia [11]. In this way, the soleus aids the quadriceps in extending the knee and may counter the destabilizing effect of the quadriceps. A variety of muscle activity alterations, through altered timing or magnitude, are therefore possible to produce dynamic knee stability. It is not surprising, then, that no single activation strategy has been shown to be optimal to produce dynamic knee stability in all patients [19,20]. Consequently, rehabilitation to induce dynamic knee stability should focus on activities that challenge knee stability, allowing individuals to develop their own compensation strategies to maintain knee stability during destabilizing activities [3].

Developing strategies to elicit appropriate muscle responses is challenging, but the proposed “force feedback” hypothesis of Nichols [13], based on a series of experiments in decerebrate cats, suggests one mechanism by which appropriate muscle strategies may be trained. They found that when a perturbing force is applied to a joint, muscles that resist the perturbation are stretched and activated to resist the perturbation. Simultaneously, muscles that act in the same direction as the perturbation are reflexly inhibited to reduce the unwanted motion [13]. The net result is a coordinated co-activation of muscles to stiffen the joint and maintain dynamic stability. Force-dependent reflex inhibitory neural pathways are linked to muscles that directly influence torques produced at a given joint. Force-dependent inhibitory pathways are also linked to muscles whose mechanical actions influence torques about adjacent joints [14–16]. Coordinated, compensatory muscle activity patterns that provide dynamic knee stability in patients with ACL rupture involve several muscle groups in the lower extremity that could be mediated by these pathways. Repeated movement experiences during treatment may refine the protective neuromuscular responses because spinal mediated pathways are influenced by input from higher motor control centers in the central nervous system [17,18]. In addition, treatment programs should provide practice in the context of functional and sport specific tasks.

Fitzgerald and colleagues developed a “perturbation training program” based on the force-feedback principle. Perturbation training involves activities that challenge knee stability in a safe and progressively more difficult manner [19,20]. Patients with unilateral, acute ACL rupture who were previously active in high-level sports and who were classified as being good candidates for non-operative treatment by a screening exam [1] were randomly assigned to receive either strength and agility training or the same treatment with the addition of perturbation training. Fitzgerald found that 93% of subjects who received the additional perturbation training were able to return to high-level activity without episodes of giving way [19]. Only 50% of those treated with strength and agility training alone returned to high-level activities [19]. The mechanism underlying the success of rehabilitation with perturbation training was not studied.

The purpose of this study was to determine if rehabilitation augmented with perturbation training results in predictable changes in lower extremity muscle activity during walking and if the changes are coincident with improved function. Subjects were individuals with acute ACL rupture who had passed a screening examination designed to identify those with good potential for non-operative management. We hypothesized that rehabilitation that included perturbation training would result in a change in muscular responses. Specifically, we expected that muscles that can mitigate anterior tibial translation on the femur (i.e., hamstring, gastrocnemius and soleus) would change activity to allow for greater quadriceps activation during walking.

2. Materials and methods

2.1. Subjects

Nine subjects (seven males, two females) with an acute, unilateral ACL tear who were regular participants (≥50 h/year) in level I or II activities (e.g., jumping, pivoting and cutting sports) [21] prior to injury and who passed an ACL screening examination [1], participated in this study. These subjects represented consecutive subjects over 18 months (comprising five athletic seasons) who both passed the screening examination and elected to participate in the training and testing in an effort to delay or avoid surgery and attempt to return to activity. The mean age of the subjects was 23.3 years (range 17–34 years), the mean time from injury to screening was 22.3 days (range 5–63 days), and all subjects returned to play within 1 week of the last perturbation training session. All patients had a grade III Lachman test. Confirmation of the ACL tear was provided by both MRI and a KT 1000 test of ≥3 mm side-to-side difference with a manual maximum pull [21]. No subject had other ligamentous injury, repairable meniscal damage, full thickness articular cartilage defects or bilateral involvement. All subjects consented to participate in the study by signing an informed consent form approved by the University of Delaware Institutional Review Board.

Quadriceps strength testing, the screening examination and data collection (see description below) were performed by the subjects before and after rehabilitation with perturbation training. A quadriceps index, a com-
comparison of quadriceps strength on the injured side to the uninjured side, was calculated from the results of maximal voluntary isometric contraction (MVIC) testing with burst-superimposition Quadriceps Index = 3D [(involved maximal voluntary isometric force/uninvolved maximal voluntary isometric force) × 100] [22]. Scores from the pre- and post-rehabilitation screening examination tests [1] (timed 6 m one-legged hop test [23]; Knee Outcome Survey-Activities of Daily Living Scale (KOS-ADLS) and Global Rating self-report of function questionnaires [24]) were used to assess changes in function. The timed hop test score was calculated by [(uninjured side score/injured side score) × 100]. A timed hop test score less than 85% is indicative of disability [25]. The KOS-ADLS is a questionnaire that assesses the patient’s ability to perform daily activities that involve their knee, and symptoms during these activities [24]. A score of 100% equates to no difficulty or symptoms in performing daily activities. The Global Rating is a verbal analog scale in which the patient rates the current level of function in comparison to the pre-injury level [24]. A Global Rating score of 100% means that the patient is functioning at the pre-injury level.

All subjects returned to their pre-injury sports without episodes of giving way (Table 1). Five of the nine subjects underwent ACL reconstruction at the completion of their competitive seasons. The four subjects who did not undergo reconstruction continue to participate in their respective sports without episodes of giving way.

### 2.2. Data collection

EMG data were collected with active surface electrodes and the MA-300 EMG System (Motion Lab Systems, Baton Rouge, LA). Electrodes had parallel detection surfaces 1.03 cm in diameter, located 1.74 cm apart. EMG data were sampled at 960 Hz, band pass filtered from 20 to 350 Hz.

Electrodes were placed bilaterally over the muscle bellies of the vastus lateralis (VL), lateral hamstrings (LH), medial gastrocnemius (MG) and soleus (SOL) muscles according to the guidelines of Perotto [26]. The skin overlying the muscles was lightly abraded and cleaned with isopropyl alcohol prior to electrode placement. The electrodes were held in place with adhesive tape (Transpore, 3M Health Care, St Paul, MN) and elastic overwrap (Superwrap, Fabriform, Inc., Exton, PA).

At both the pre- and post-training data collections, maximal voluntary isometric contraction and resting EMG signals were obtained from each muscle group prior to the dynamic trials. Subjects were stabilized on a table, with padded cuffs providing resistance, in the following testing positions: prone with the knees in 15° of flexion (LH); seated with the knees in 60° of flexion and the hips in 90° of flexion (VL); prone with the hips, knees and ankles in neutral (MG); and in quadruped with the hips and knees in 90° of flexion and the ankle in neutral (SOL). Four seconds of resting data and 2 s of maximal contraction data were collected for each muscle group.

Subjects performed five self-paced walking trials on a 13 m walkway. Movement speed was calculated from the time measured by photoelectric beams located 286.5 cm apart along the walkway. Trials where movement speed was within 5% of a mean speed were accepted. Practice trials were given until the movement speed was consistent, and the subject was able to contact the force plate without altering their stride. Total number of trials for a subject never exceeded ten.

A linear envelope was created using full wave rectification and low-pass filtering by a second order, phase-corrected, Butterworth filter using a cut-off frequency of 20 Hz. The threshold used to determine the timing of muscle activation was 2.5 times the resting signal for more than 50 ms. EMG data were saved across the stance phase, normalized to 100% of stance and averaged for each subject. For the pre- and post-training data collections separately, MVIC and dynamic (walking) trials were analyzed for the highest muscle activity, averaged over a 50 ms window, and this peak was used for normalizing the EMG signals of the respective data collection. Peak muscle activity during dynamic trials therefore never exceeded 100%.

Muscle timing variables are reported in percentage stance and included onset, termination of activity, duration of muscle activity, and time to peak amplitude. Muscle EMG magnitude variables included peak amplitude (in percentage maximum EMG) and the integral of muscle activity during loading response during walking (100 ms prior to initial contact to the point of peak knee flexion).

### 2.3. Perturbation training augmented rehabilitation

Perturbation training was administered by two physical therapists at the University of Delaware Physical
Therapy Clinic according to the protocol of Fitzgerald et al. [19]. Subjects participated in 10 sessions of perturbation training, each lasting approximately 1 h, delivered two to six times per week (average duration of treatment was 20 days). Treatment frequency was decreased if a patient’s knee developed an effusion after a session, or if the patient had difficulty meeting the goals of a treatment session.

Perturbation training involves the application of support surface perturbations through three techniques: rollerboard, rockerboard, and rollerboard with stationary platform (Figs. 1–3). Depending on the technique, subjects either resist the force of the perturbation or regain a balanced position after the perturbation application. In each technique, perturbations are initially administered along the sagittal plane, in a predictable fashion, with verbal cues given for the perturbation onset. During the first five treatments, perturbations are progressively introduced in all planes, the application of perturbations moves from predictable to random and from light force to greater intensity, and verbal cues are decreased. During the last five treatments, perturbations are applied while the subject performs a sport-specific task. Because the sport-specific task distracts the subject’s attention to the perturbations, perturbation difficulty must decrease to the initial level and gradually increase as previously described. Perturbation training in our study followed this general format for all subjects; however, the rate of progression was individualized and was determined by the subject’s ability to counter the direction and force of perturbations without rigid co-contraction of the lower extremity muscles, and to demonstrate infrequent loss of balance. By the 10th session, all subjects were able to perform sport-specific tasks simultaneously with the application of random, forceful and fast perturbations.

Rehabilitation also included agility and strength training. Agility training for all subjects included: side shuffles, cariocas (i.e. braiding), shuttle runs and cutting drills, in addition to drills specific to the subject’s primary sport. Strength training consisted of open and closed chain exercises for the quadriceps, hamstrings and gastrocnemius muscles (e.g. squatting, leg curls, knee extensions, and calf raises).

2.4. Data analysis

Statistical analysis (Systat, Evanston, IL) included paired t-tests to analyze changes in the quadriceps index, and KOS-ADLS, Global Rating and timed hop scores. Paired t-tests were also used to determine significant changes in VL EMG variables. The level of significance for paired t-tests was set at $p < 0.05$.

Stepwise forward regression analysis was used to study pre- and post-training relationships between the VL, a muscle that can destabilize the knee, and the lateral hamstrings, medial gastrocnemius and soleus muscles, muscles which can counter the destabilizing effects of the VL. Regression analyses were performed with each VL variable as the dependent variable, and, based on normal gait, only those variables which were likely to coincide with the VL variable were entered into the regression as the independent variables (Table 2). An alpha level of 0.05 was used as the criteria to enter the regression and the level of significance for the regression analyses was set at $P < 0.01$ to account for multiple comparisons.

3. Results

3.1. Screening examination

The quadriceps index was high prior to training ($90.9 \pm 12.5\%$) and was unchanged at the end of training ($91.3 \pm 5.8\%$). The mean timed hop test score also showed no change after training ($97.3 \pm 7.9\%$ pre-training, $96.0 \pm 4.9\%$ post-training). The pre-training mean Knee Outcome Survey-Activities of Daily Living Scale score was $91.8 \pm 6.6\%$ and significantly increased to $97.3 \pm 2.3\%$ after training ($p = 0.037$). The Global Rat-
ing, which measures overall function, significantly increased from 83.7 ± 13.6% to 94.3 ± 4.3% post-training ($p = 0.022$).

### 3.2. Data collection

The involved VL integral during walking significantly increased after perturbation training ($p = 0.037$) (Figs. 4 and 5), but no changes occurred in the peak magnitude or timing of VL muscle activity during walking. The regression analysis demonstrated no significant relationship between the VL variables and any of the tested variables prior to training. After training, the VL peak magnitude and integrated VL activity were both modeled by the SOL onset ($R^2 = 0.70$, $p = 0.005$ and $R^2 = 0.73$, $p = 0.003$, respectively). Time-to-peak activity of the VL was modeled by both the SOL onset and the integrated activity of the LH ($R^2 = 0.87$, $p = 0.006$). The termination of VL activity was significantly modeled by a linear combination of integrated LH activity.

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**Fig. 2.** Rollerboard technique for perturbation training.

**Fig. 3.** Rollerboard and stationary platform technique for perturbation training.
Table 2
Regression analysis variables

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Independent variables</th>
</tr>
</thead>
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<tr>
<td>VL onset</td>
<td>LH onset and time-to-peak</td>
</tr>
<tr>
<td>VL time-to-peak amplitude</td>
<td>All LH variables except termination SOL onset</td>
</tr>
<tr>
<td>VL peak</td>
<td>All LH variables</td>
</tr>
<tr>
<td>VL integral</td>
<td>All LH variables</td>
</tr>
<tr>
<td>VL termination</td>
<td>All LH variables except onset</td>
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and the time to peak activation of the SOL ($R^2 = 0.94, p = 0.001$). These relationships were not present on the uninjured side either before or after training.

4. Discussion

We investigated the effect of rehabilitation with perturbation training on lower extremity muscle activity and function in ACL deficient individuals who pass a screening examination. We specifically chose this subject population because they have previously been shown to successfully compensate for their injury and return to high level activities short-term after completing training [19]. This investigation was undertaken to help explain the mechanism which allows for improved dynamic knee stabilization after training, information that can be beneficial to rehabilitation protocols for ACL injury.

The integral of quadriceps activity, normalized to the post-training maximum activity, increased after training. Other researchers have found or hypothesized decreased quadriceps activity after ACL injury [5,27]. The capability of the quadriceps to destabilize the ACL deficient knee is a reasonable explanation for the decrease in quadriceps activity. The finding of higher quadriceps activity after training in our study, without concomitant knee instability, suggests concurrent compensation by muscles which act as ACL agonists.

The integral of quadriceps activity, along with other quadriceps magnitude and timing variables, were predicted by hamstrings and soleus activation variables after training. These relationships were not present prior to training, which suggests these compensations are not a result of the injury; rather the relationships were influenced by the training program. Contraction of the hamstrings has been shown to counter anterior tibial translation [10], thus coupling between the quadriceps and hamstrings is not surprising. The importance of coupling between the quadriceps and soleus is less obvious, unless one considers the role of the soleus in controlling tibial progression during walking, and the overlap in soleus and quadriceps activity (Fig. 6). We did not find any relationships between the quadriceps activity variables and those of the gastrocnemius. This does not mean that gastrocnemius activity may not play a role in dynamic
knee stability; rather, gastrocnemius activity does not counter the destabilizing effects of quadriceps activity during walking.

Recent research has shown that reflexive hamstring activation may be important in knee stabilization after ACL injury [28,29] and that training with support surface perturbations may improve the reaction time of hamstring activation [28,30]. In contrast, our results suggest that a coupling between quadriceps activity and activity of the hamstrings and soleus occurs after training to improve dynamic knee stability during walking. By providing controlled opportunities to dynamically stabilize the knee via support surface perturbations, reflex pathways are modulated to allow these relationships to be formed.

Unless muscle activity changes are accompanied by improved function, it is questionable whether the changes are successful compensations. Prior to beginning the training program, the subjects in our study had a high functional level, in part due to the requirement of meeting the screening examination criteria. Because of this high initial level, scores on the timed hop test did not improve. The KOS-ADLS and Global Rating scores, which account for a variety of activities, did improve, and the subjects returned to high level activities without knee instability, confirming our hypothesis that the muscle activity alterations we found were evidence of successful compensations.

While this discussion assumes that the addition of the perturbation training was responsible for the post-training muscle activity alterations, subjects also participated in strength and agility training which may have contributed to the post-training alterations. We believe, however, that improved dynamic knee stability in those who receive the addition of perturbation training to rehabilitation, compared to those who participate in strength and agility training alone [19], provides evidence that perturbation training is largely responsible for alterations which improve dynamic knee stability.

The present investigation offers insight into the mechanism by which training alters muscle activity to improve dynamic knee stability. Additional work is necessary to measure the effect of the induced muscle activity alterations on anterior tibial translation, as control of tibial translation is only inferred in this work through absence of knee instability. Further research is also needed to determine the mechanism involved in stabilizing the knee during more demanding tasks.

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References


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