Published in final edited form as:

J Appl Biomech. 2012 August ; 28(4): 374–386.

Unilateral Stance Strategies of Athletes With ACL Deficiency

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Abstract

Aberrant movement strategies are characteristic of ACL-deficient athletes with recurrent knee instability (non-copers), and may instigate premature or accelerate joint degradation. Biomechanical evaluation of kinematic changes over time may elucidate noncopers' responses to neuromuscular intervention and ACL reconstruction (ACLR). Forty noncopers were randomized into a perturbation group or a strength training only group. We evaluated the effects of perturbation training, and then gender on knee angle and tibial position during a unilateral standing task before and after ACLR. No statistically significant interactions were found. Before surgery, the strength training only group demonstrated knee angle asymmetry, but 6 months after ACLR, both groups presented with similar knee flexion between limbs. Aberrant and asymmetrical tibial position was found only in females following injury and ACLR. Neither treatment group showed distinct unilateral standing strategies following intervention; however, males and female noncopers appear to respond uniquely to physical therapy and surgery.

Keywords

anterior cruciate ligament injury; perturbation training; gait analysis

Every year, well over 100,000 anterior cruciate ligament (ACL) tears occur during football, basketball, soccer, skiing, and other sports that demand unanticipated cutting, jumping, and pivoting (Feagin et al., 1987; Majewski et al., 2006; Silvers & Mandelbaum, 2007). Not all individuals respond similarly acutely after ACL rupture, and these athletes can be categorized into two groups (potential copers or noncopers) based on functional status and compensatory strategies (Fitzgerald et al., 2000a). Potential copers present with few functional deficits (Fitzgerald et al., 2000a) and gait deviations early after injury (Chmielewski et al., 2001, 2005b). Athletes with ACL deficiency without effective dynamic knee stability are known as noncopers (Eastlack et al., 1999). In addition to limited functional abilities, noncopers demonstrate constrained knee positioning and movement compared with uninjured athletes (Chmielewski et al., 2005b; Rudolph et al., 1998, 2001). Determining how to remediate these aberrant and unsuccessful compensatory strategies in noncopers may decrease the risk of further joint damage and improve the prognosis after ACL rupture. Whether aberrant patterns are modifiable in noncopers after preoperative physical therapy and reconstruction is unknown.

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Many studies have evaluated the biomechanical characteristics and clinical performance of athletes after ACL injury, but identifying common movement patterns and functional characteristics of a population that responds differently after injury is challenging. A clinical classification scheme used to differentiate individuals with ACL deficiency soon after injury (Fitzgerald et al., 2000a) showed that the majority of athletes with ACL deficiency are noncopers (Hurd et al., 2008). Noncopers demonstrate a knee stiffening strategy that consists of over-constraining the knee during a variety of functional tasks. For example, noncopers position their tibia more posteriorly, relative to the femur, during unilateral standing tasks (Chmielewski et al., 2005b, 2005c) and hopping tasks (Ramsey et al., 2001). These strategies appear to be unsuccessful, as noncopers experience recurrent knee instability and limited function during daily activities (Fitzgerald et al., 2000a).

Specialized neuromuscular training called *perturbation training* is an effective intervention for enhancing functional performance (Fitzgerald et al., 2000a, 2000b) and improving gait mechanics in potential copers (Chmielewski et al., 2005a). Perturbation training involves systematic translations and rotations of support surfaces by a physical therapist to elicit specific muscular responses from the injured athlete (Fitzgerald et al., 2000b). More recently, the effects of this preoperative paradigm have been evaluated on noncopers (Hartigan et al., 2009). When compared with progressive strength training alone, the addition of perturbation training to preoperative rehabilitation improved the involved knee kinematics of noncopers six months after ACL reconstruction (Hartigan et al., 2009). The functional outcomes of noncopers who received perturbation training, however, were not superior to those who received strength training only (Hartigan et al., 2010). These data suggest that noncopers may not be a homogeneous group of ACL-deficient individuals, and that other patient factors may contribute to the outcomes of noncopers.

Gender may play a meaningful role in the recovery of function and normal limb mechanics following ACL injury. Female athletes have a significantly greater risk for ACL injury than males (Arendt & Dick, 1995) and are also more likely to be classified as noncopers following ligament rupture (Hurd et al., 2008). Earlier studies have reported minimal differences between the outcomes of men and women following injury and ACL reconstruction (Barber-Westin et al., 1997; Ott et al., 2003). In contrast, a large cohort study of over 10,000 ACL-injured individuals (Ageberg et al., 2010) showed that females reported worse outcomes on the Knee injury and Osteoarthritis Outcome Score (KOOS) than males both before and after ACL reconstruction. While these studies provided some initial insight into purported gender differences, findings were limited to self-report outcomes. There is a need, therefore, to investigate the role of gender in the postinjury knee mechanics of noncopers.

The generalized stiffening strategy seen in noncopers during gait carries over to their single limb standing posture, where abnormal constraint of the knee joint has been noted (Chmielewski et al., 2005c). The posterior tibial positioning characteristic of the noncoper cohort may be a crude effort to stabilize the knee and avoid pathological tibial translation (Chmielewski et al., 2005c). Other work has shown similar preferential posterior joint contact positioning in people with ACL-deficiency when compared with their uninjured knee, particularly near full knee extension (Li et al., 2006). During more dynamic movements, the measurement of discrete tibiofemoral mechanics is challenging (Cappozzo et al., 1996; Ramsey & Wretenberg, 1999) and may be particularly difficult for noncopers who experience knee instability during the simplest functional tasks. Basic single limb activities, therefore, have become important biomechanical tasks used to evaluate knee strategies in noncopers (Chmielewski et al., 2005c; Rudolph et al., 2000; Rudolph & Snyder-Mackler, 2004).

Attempting to address the abnormal tibiofemoral positioning during unilateral standing by way of perturbation training could have important implications on normal joint movement and joint health. Determining whether male and female noncopers respond differently after ACL injury and reconstruction may further explain the variable outcomes of this unique cohort. Finally, our data will help to elucidate the neuromuscular strategies and malleability of noncopers. Therefore, the purpose of this study was twofold: (a) we wanted to evaluate changes in the arthrokinematics and osteokinematics of the knee joint in noncopers during a unilateral standing task after perturbation training and after ACL reconstruction, and (b) to compare the unilateral stance strategies of male and female noncopers over time. First, we hypothesized that following preoperative perturbation training, non-copers will demonstrate symmetrical knee position between limbs and this symmetry will persist 6 months after ACL reconstruction, whereas those who receive strength training only would demonstrate asymmetrical knee positions both before and after surgery. Second, we hypothesized that, independent of treatment group, only women would demonstrate abnormal knee kinematics after ACL reconstruction.

Methods

A priori power analysis was performed using previously published data from our laboratory (Chmielewski et al., 2005c). The knee angles and tibial positions of noncopers and potential copers in the unperturbed condition were used to calculate effect sizes between groups (knee angle: 0.76, tibial position: 1.34) because the knee kinematics of these individuals represent a clinically meaningful disparity in functional abilities and neuromuscular adaptation following ACL injury. Sample size ($N = 21$ for each group based on knee angle data, $N = 8$ for each group based on tibial position data) was determined using an online power calculator (http://www.dssresearch.com/toolkit/sscalc/size_a2.asp), with a one-tailed test, α of 0.05, and a desired power ($1 - \beta$) of 0.8. Eligible participants were between the ages of 13 and 55 who participated in Level I/II sports or activities (those that include cutting, pivoting, jumping, and/or lateral movements) more than 50 hr per year (Hefti et al., 1993). Activities varied from high school and collegiate athletes, to recreational sports participants, to highly active manual laborers. Each individual had suffered a unilateral ACL rupture by a contact or noncontact mechanism without concomitant Grade III knee ligament injuries or osteochondral lesions greater than 1 cm² were eligible.

Fifty-five athletes with ACL deficiency were identified as noncopers by the ACL clinical classification scheme administered at the University of Delaware Physical Therapy Clinic. The screening examination classified noncopers based on quadriceps strength values as measured by a burst superimposition technique (Snyder-Mackler et al., 1993), unilateral hop symmetry (Noyes et al., 1991), and two self-report questionnaire scores. Those who experienced more than one episode of giving way during activities of daily living were automatically classified as noncopers. This study was approved by the University's Human Subjects Review Board and each individual provided written informed consent before their participation.

Noncopers who consented to study participation were randomized into one of two pretreatment groups: progressive strength training only (STR = 28) or progressive strength training supplemented with perturbation training (PERT = 27). Randomization order was determined a priori using a random number generator, and was applied chronologically to incoming participants. Study authors were not blinded to group assignment because of their active involvement in the rehabilitation of these individuals. Perturbation training was implemented and progressed according to University of Delaware protocol (at the end of this article, see Appendix: UDPT Perturbation Training Program). Athletes were instructed on proper initial positioning on each board configuration, and their responses were guided with

instruction and feedback cueing from the physical therapist. As the athlete progressed through successive sessions, speed and amplitude of the perturbations increased, and feedback from the therapist was gradually withdrawn. Sport-specific tasks were introduced in the late phase of training. This included, but was not limited to, catching and throwing tasks (baseball, basketball, football), stick skills (hockey and lacrosse), kicking and heading a ball (soccer), and other drills pertinent to the individual's sport. The criterion-based strengthening protocol consisted of the same exercises for both groups. The PERT group performed the strength training after perturbation training to avoid the effects of fatigue on muscular responsiveness. Strengthening activities included closed and open kinetic chain exercises, including isokinetics and neuromuscular electrical stimulation to the quadriceps muscle (T. J. Manal & Snyder-Mackler, 1996).

Both groups received 10 preoperative physical therapy sessions (training time: 3.7 weeks $\pm$ 1.5), after which subjects underwent ACL reconstruction with either a quadruple bundle semitendinosus/gracilis autograft or allograft within 2 weeks of completing preoperative training. Three participants also had a partial meniscectomy (PERT = 1, STR = 2). Both groups received the same criterion-based postoperative physical therapy (T. J. Manal & Snyder-Mackler, 1996) which included impairment resolution and functional training, progressive strengthening, and neuromuscular electrical stimulation to the quadriceps muscle per the University of Delaware ACL protocol (Snyder-Mackler et al., 1994). Fifteen of the 55 participants dropped out of the study due to non-compliance with our physical therapy protocol, deferred surgery, or missed one of the three testing sessions (Figure 1). Therefore, statistical analysis was performed on the remaining forty noncopers (Table 1).

Unilateral stance analysis was performed at three time points: before preoperative intervention, after the preoperative intervention, and 6 months after ACL reconstruction. Collections of unilateral stance data were performed in the Motion Analysis Laboratory at the University of Delaware within one week of functional testing. ViconMX Workstation software (Vicon Motion Systems, Oxford, UK) with a passive, eight-camera system was used to collect three-dimensional kinematic data at 60 Hz for a collection volume of 0.62 m³. Retro-reflective markers were affixed to anatomical landmarks of both lower extremities (medial and lateral metatarsal heads, medial and lateral malleoli, medial and lateral femoral condyles, and the greater trochanters of the hips) to determine segment lengths and joint centers. Interrater and intrarater intraclass correlation coefficients (ICCs) were calculated as part of the larger RCT. Marker position data were collected on two separate days during standing calibration trials and fixed joint angles at 60° of knee flexion to ensure between-day reliability with marker placement. The ICCs for marker placement between three physical therapists, each with more than 5 years of orthopedic clinical experience, ranged from 0.94 to 0.975, with camera residuals (system error) of less than 0.5 mm. Measurement error between days was less than 1°. Five tracking shells with marker clusters were secured to the subjects' proximal antero-lateral shank and distal antero-lateral thigh with elastic wraps (Superwrap, FabriFoam, Inc., Exton, PA) to measure joint angles and tibial position. Subjects were directed to "stand comfortably on one leg while holding still." Trials were excluded if the subject visibly swayed or changed position, touched the non-weight-bearing leg to the floor or stance limb, or lost their balance. Ten usable 4-s unilateral stance trials were collected on both legs.

A custom LabVIEW program (LabVIEW, National Instruments, Austin, TX) was used to streamline the writing of scripts for postprocessing of kinematic data in Visual3D (C-Motion, Inc, Bethesda, MD). The middle 2 s of each of the 10, 4-s trials were time normalized and smoothed with a low-pass fourth-order, bidirectional phase-corrected Butterworth filter at a frequency of 6 Hz. Subject-specific models were created from anthropometric measurements and marker locations from a standing calibration trial.

Kinematic knee data during the unilateral standing task were referenced to the segments' position in the calibration trial, where the individuals' knees were placed, by the examiner, in zero degrees of knee extension using a standard goniometer, confirmed by the motion capture system. Knee angle and tibial position was then calculated by referencing the shank's local coordinate system to the local coordinate system of the femur. Posterior tibial positioning and knee flexion were represented by values equal to or less than zero. Variables of interest included tibial position relative to the femur and knee rotation in the sagittal plane before and after presurgical treatment and six months after ACL reconstruction.

Minimal clinically important differences (MCIDs) for this study were defined a priori based on both clinical and biomechanical data. Our pilot work evaluating the variance in tibial position and knee angle between the limbs of 10 uninjured controls during unilateral standing suggests using 3 mm and 3.5° for MCIDs for tibial position and knee flexion angles, respectively (Table 2). Our control subjects were young (age: 21 years $\pm$ 2), active individuals who participated in Level I/II activity at least 50 hr each year. The loss of 3–5 degrees of knee extension adversely affected self-report and objective postsurgical outcomes in a cohort of over 500 ACL-reconstructed individuals (Shelbourne & Gray, 2009). During biomechanical analysis of perturbed unilateral standing, a 3 mm difference in tibial position discriminated ACL-deficient athletes with successful (potential copers) and unsuccessful (noncopers) neuromuscular strategies (Chmielewski et al., 2005c). Clinically, a difference of 3 mm between limb is used to confirm the presence of pathological ligament laxity after injury (Daniel et al., 1985). Current literature suggests that an MCID should be (1) larger than the calculated standard error of the measurement (*SEM*), and (2) relatable to the patient's perception of meaningful clinical change (Copay et al., 2008). Using a minimal detectable change (MDC) value has also been suggested as way to ensure that a change in outcome measure represents true change (Copay et al., 2007). Based on this literature and data from our uninjured control subjects, we propose that MCIDs of 3.5° of knee flexion and a 3 mm change in tibial position during unilateral standing is not only clinically meaningful, but also surpasses the advocated MCID and MDC criteria. In addition to statistical differences, changes and asymmetries in knee angle and tibial position equal to that of the MCIDs will also be reported.

A mixed model analysis of variance (ANOVA) test was used to compare tibial and knee joint position in the sagittal plane with a between subjects factor of treatment group and within subject factors of limb and time. A second mixed model analysis of variance (ANOVA) test was used to compare tibial and knee joint position in the sagittal plane with a between subjects factor of gender and within subject factors of limb and time. Post hoc paired *t* tests were used to analyze knee angle and tibial position differences between limbs and independent *t* tests were used to clarify where treatment group and gender differences existed. Frequency counts and chi-squared tests of independence were used to further explain group and gender differences at each testing session. A priori alpha significance level was set at $p = .05$.

Results

Average tibial position between treatment groups (PERT vs. STR) and limbs were not statistically different over the three testing sessions ($p = .270$). Similarly, there were no differences between the perturbation and strength groups regarding clinically meaningful change in tibial position between any of the testing sessions (Table 3). Preoperative and postoperative adaptations were varied between individuals within both treatment groups (Figure 2).

No significant differences or MCIDs in knee angle over time between treatment groups were found (Table 4). There was a main effect of limb ($p = .001$) and a time $\times$ limb interaction ($p = .036$). Post hoc paired t tests showed initial differences between the limbs of the strength group only ($p = .004$; Involved: $9.5^\circ \pm 5.6$, Uninvolved: $4.8^\circ \pm 6.7$) that persisted after preoperative intervention ($p = .001$; Involved: $7.9^\circ \pm 5.5$, Uninvolved: $3.7^\circ \pm 5.9$) (Figure 3). For both the PERT and STR groups, knee flexion angles between limbs were similar six months after ACL reconstruction ($p = .275$).

There were no statistically significant differences or MCIDs in tibial position or knee flexion angle between males and females (Tables 5 and 6). With regard to clinically meaningful differences at the initial pretreatment evaluation, posterior tibial positioning was found only in the involved limb of the females (Figure 4). After preoperative physical therapy, both men and women demonstrated anterior tibial positioning in the involved limb, similar to that of their uninvolved limb. Six months after surgery, while males maintained anterior positioning, females again demonstrated clinically meaningful asymmetry, and resumed the acutely injured posterior positioning of their involved limb (Involved: $0 \text{ mm} \pm 3$; Uninvolved: $3 \text{ mm} \pm 5$). Before presurgical intervention, both males and females had clinically meaningful differences in knee angle between their involved and uninvolved limbs (Females—Involved: $10.4^\circ \pm 7.4$, Uninvolved: $6.5^\circ \pm 6.6$; Males—Involved: $9.3^\circ \pm 4.9$, Uninvolved: $5.4^\circ \pm 6.6$). This asymmetry resolved by the 6 month follow-up for both genders (Females—Involved: $10.8^\circ \pm 7.5$, Uninvolved: $9.5^\circ \pm 8.6$; Males—Involved: $7.7^\circ \pm 5.4$, Uninvolved: $6.5^\circ \pm 7.3$) (Figure 5).

Discussion

Neither the perturbation nor the strength group demonstrated a clear pattern of adaptation to the presurgical treatment or surgery. Our predefined MCIDs were used in an attempt to better capture a trend in individual responses. This did not, however, clarify distinct behaviors based on group assignment. Tibial position at each of the three testing sessions was highly variable and did not follow an identifiable trend. Initial limb differences in knee angle were identified only in the strength group and persisted following preoperative rehabilitation. Six months after ACL reconstruction, both treatment groups had similar unilateral standing strategies. The involved limb of our noncopers was predictably more flexed than the knees of uninjured controls and the involved knees of potential copers (Chmielewski et al., 2005c) but did not change in response to preoperative treatment or surgery, regardless of group assignment. Unexpectedly, postoperative knee angle symmetry was achieved primarily by a more flexed knee posture adopted by the uninvolved limb. Our hypothesis that abnormal knee and tibial positioning of noncopers would resolve only with perturbation training was not supported by these data, but preintervention limb asymmetries of only the strength group may have masked any treatment effect.

In contrast, males and females appeared to have unique unilateral standing strategies. The posterior tibial positioning characteristic of noncopers was found only in our females early after injury and 6 months after surgery. Interestingly, it was the females who appeared most responsive to the preoperative physical therapy, as knee angle asymmetry and posterior tibial positioning of the involved limb did resolve before surgery. Following ACL reconstruction, both males and females demonstrated knee flexion angle symmetry during the unilateral stance task. Our findings suggest the presence of variable stance strategies within the noncoper cohort based on gender.

Noncopers are characterized by their limited ability to perform activities of daily living with adequate knee stability (Fitzgerald et al., 2000a). Several studies have reported the aberrant and insufficient neuromuscular strategies in the noncoper cohort (Button et al., 2008;

Chmielewski et al., 2005c; Rudolph et al., 2001; Rudolph et al., 1998). The aberrant “stiffening” compensations noncopers use during basic single limb tasks predominate in other more dynamic tasks, like walking, running (Rudolph et al., 2001), and hopping (Ramsey et al., 2001). So while unilateral stance may not be overtly physically demanding, it does represent a challenging task for individuals following ACL injury who experience recurrent knee instability, and which findings may translate to more dynamic activities.

Previous work has detailed the unique neuro-muscular strategies of ACL-deficient athletes with a variety of functional capabilities. The unilateral stance behaviors of noncopers, potential copers, and uninjured participants were compared using a 3 *df* perturbation platform (Chmielewski et al., 2005c). Noncopers held their tibias in a more posterior position with greater knee flexion compared with potential copers and uninjured controls, regardless of direction of platform translation (Chmielewski et al., 2005c). Other work (Ramsey et al., 2001) evaluated tibial position during single leg hopping in four noncopers and found a similarly constrained, posterior positioning of the tibia. Protective knee strategies, including reduced knee excursions, were also found in noncopers during unperturbed gait, which supports the concept of the noncopers’ knee stiffening behavior (Rudolph et al., 2001). These restrictive and ineffective knee stabilization strategies may be a behavior adopted by noncopers as an attempt to minimize the pathological joint subluxation. Furthermore, potential copers do not demonstrate a single strategy for successful dynamic knee stabilization following injury (Rudolph et al., 1998), suggesting that variable strategies may also exist within the noncoper cohort.

For ACL-deficient athletes with recurrent knee instability, ligament reconstruction is the preferred treatment of many orthopedic surgeons in the United States (Marx et al., 2003), as research has shown poor outcomes with nonoperative management (Daniel et al., 1994; Hurd et al., 2008; Marx et al., 2003). While ACL reconstruction is successful in restoring normal anterior knee laxity, under more dynamic conditions, surgery does not fully arrest abnormal joint kinematics (Tashman et al., 2004; Woo et al., 2002), providing an impetus to develop interventions that may resolve these aberrant movement patterns.

Abnormal motion and altered joint loading patterns have been implicated as mechanisms of degenerative joint changes after ACL injury (Anderson & Lipscomb, 1989; Andriacchi & Dyrby, 2005; Andriacchi & Mundermann, 2006; Andriacchi et al., 2004; Kvist & Gillquist, 2001; Wu et al., 2000). Investigators have identified a correlation between a more posterior tibial position as the knee flexion moment increased during the weight acceptance period of gait (Andriacchi & Dyrby, 2005). Others described an earlier and longer lasting anterior tibial displacement in the injured limb of ACL-deficient athletes when compared with the uninjured limb and control limbs (Kvist & Gillquist, 2001). Disagreement in findings regarding tibial position could be related to disparities in experimental methodologies, and the chronicity of the subject pools involved in each of these studies. Evaluation of ACL-deficient athletes without functional classification and regardless of gender may have obscured the distinct strategies within these subject groups.

Building upon previous work, we examined how perturbation training may affect the abnormal knee strategies of noncopers. In contrast to Chmielewski’s study (Chmielewski et al., 2005c), however, we found the mean tibial position during unilateral stance to be slightly anterior. However, our gender comparison showed that this positioning may be more characteristic of our male noncopers, who made up the majority of our cohort. Chmielewski and colleagues (Chmielewski et al., 2005c) also used a perturbed stance paradigm, where subjects were aware that extrinsic movement to the support surface would occur. Our study allowed athletes to maintain a self-selected, comfortable unilateral standing position without perturbing forces. Differences in identified strategies between these

investigations could be attributed to the subjects' anticipation of an extrinsic disturbance to their balance.

Perhaps most importantly, athletes who have ruptured the ACL demonstrate a higher rate of osteoarthritis development than their uninjured counterparts, regardless of whether the ligament was surgically reconstructed (Kessler et al., 2008; Lohmander et al., 2004, 2009). Mitigating aberrant motion via neuromuscular intervention appears paramount in attempting to influence the development of osteoarthritis following ACL injury. Gathering insight into the limb behaviors of noncopers in response to injury, training, and rehabilitation may be a key step to informing efficacious clinical practice for these individuals.

Accurate and valid measurement of joint arthrokinematics poses some challenges during motion analysis (Cappozzo et al., 1996; K. Manal et al., 2003; Ramsey & Wretenberg, 1999). Precise, reliable marker placement, a small capture volume, and small residual errors during camera calibration for a quasi-static task like unilateral standing can, however, minimize experimental artifact (Cappozzo et al., 1996; Chmielewski et al., 2005c). Using a unilateral standing task to discern adaptations in movement strategies over time can also be difficult. Although knee flexion angles and tibial position measured during perturbed unilateral stance discriminates differences between noncopers, potential copers and uninjured subjects (Chmielewski et al., 2005c), our unperturbed standing task may not be provocative enough to identify neuromuscular responses to treatment.

Conclusion

The results of our study suggest that the effects of gender must be considered when evaluating changes in neuromuscular behaviors of noncopers following rehabilitation or surgery. Noncopers are clearly a more diverse group of ACL-deficient athletes than previously thought, and possess variable capacities for adaptation. Our current work suggests gender-specific kinematic responses to preoperative intervention and ACL reconstruction. Noncopers who demonstrate normal unilateral standing strategies early after injury may also represent the more malleable group within this cohort. Determining whether specific unilateral standing strategies are correlated to functional outcomes and more dynamic tasks may support future interventional studies aimed to alter aberrant movement patterns in this population. Furthermore, observing changes in neuromuscular patterns can elucidate the effects of different interventions on the knee stabilization strategies of noncopers. Additional stratification of the noncoper cohort by gender appears necessary to isolate different neuromuscular behaviors related to single limb postural control.

Acknowledgments

Funding for this study was provided by the National Institutes of Health (R01AR048212 and S10RR022396-01) and the Foundation for Physical Therapy (PODS I Scholarship) awarded to Stephanie Di Stasi. The authors acknowledge Sarah Trager for her support with software programming; Wendy Hurd, Kyle Fennemore, Greg Seymour, and Emily Gardinier for their assistance with data collection and processing; and Martha Callahan for her help with subject retention and data organization. We would also like to thank the physical therapists at the University of Delaware Physical Therapy Clinic for assistance with subject training, and Michael Axe for his patient referrals for study participation.

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Appendix: UDPT Perturbation Training Program

UDPT Perturbation Training Program			
	Early (Estimated Treatment 1–3)	Middle (Estimated Treatment 4–7)	Late (Estimated Treatment 8–10)
Date Completed			
Anterior/Posterior and Medial/Lateral Roller Board	Position: Patient on board (bilateral 1st treatment, progress to unilateral)	Position: Unilateral (avoid forefoot abduction/adduction) Application: Unexpected forces	Position: Unilateral Application: Increased magnitude of force application

UDPT Perturbation Training Program			
	Early (Estimated Treatment 1–3)	Middle (Estimated Treatment 4–7)	Late (Estimated Treatment 8–10)
	<ul style="list-style-type: none"> Eyes straight ahead <p>Application: Inform the patient of direction and timing of rollerboard movement</p> <ul style="list-style-type: none"> Slow application of force, Low magnitude. Straight plane of movement (do all A/P reps before you begin ML) <p>Observe: Cue patient to avoid massive co-contraction at knee. Do not overstress beyond limit of stability (don't induce fall)</p>	<ul style="list-style-type: none"> Rapid increasing magnitude force application Add rotation and diagonal motions Alternate plane of movement (start A/P, then M/L, progress to A/L/IR) Short delay between subsequent force applications <p>Distraction: May begin to add distraction (ball toss, stick work)</p> <p>Observe: Observe difficulty with recovery but few to no falls</p>	<p>Random direction movements Little to no delay between applications</p> <p>Distraction: Increase speed and magnitude of distraction Consider sport specific positions</p> <p>Observe: Look for disassociation of hip, knee, and ankle</p>
Date Completed			
Anterior/posterior and Medial/Lateral Tilt Board	<p>Position: Begin bilateral, progress to unilateral Eyes straight ahead</p> <p>Application: Inform patient of direction and timing of tilting Slow application of force, Low magnitude Less force medial than lateral</p> <p>Observe: Cue patient to maintain equal weight bearing bilaterally</p> <ul style="list-style-type: none"> Cue patient to avoid massive co-contraction at the knee 	<p>Position: Unilateral (avoid forefoot abduction/adduction)</p> <p>Application: Unexpected forces</p> <ul style="list-style-type: none"> Rapid, increasing magnitude force application Hold the board to the floor in one direction and unexpectedly release <p>Distraction: May begin to add distraction (ball toss, stick work)</p> <p>Observe: Look for a rapid return to a stable base after perturbation</p> <ul style="list-style-type: none"> Look for dissociation of hip, knee and ankle 	<p>Position: Begin to place foot at a diagonal</p> <p>Application: Increased magnitude force application</p> <ul style="list-style-type: none"> Random direction movements Little to no delay between applications <p>Distraction: Increase speed and magnitude of distraction</p> <ul style="list-style-type: none"> Consider sport specific positions <p>Observe: Look for minimal sway from stable stance at rest or following any perturbation</p>
Date Completed			
Rollerboard and Stationary Platform	<p>Position: One foot on the rollerboard, one on the platform</p> <ul style="list-style-type: none"> Eyes straight ahead, equal weightbearing on both lower extremities <p>Application: Inform patient of direction and timing of movement</p> <ul style="list-style-type: none"> Slow application of force, low magnitude 	<p>Position: One foot on the rollerboard, one on the platform</p> <ul style="list-style-type: none"> Eyes straight ahead, equal weightbearing on both lower extremities <p>Application: Unexpected forces</p> <ul style="list-style-type: none"> Rapid, increasing magnitude force application 	<p>Position: One foot on the rollerboard, one on the platform</p> <ul style="list-style-type: none"> Eyes straight ahead, equal weightbearing on both lower extremities <p>Application: Increased magnitude force application</p> <ul style="list-style-type: none"> Random direction movements

UDPT Perturbation Training Program			
	Early (Estimated Treatment 1–3)	Middle (Estimated Treatment 4–7)	Late (Estimated Treatment 8–10)
	<ul style="list-style-type: none"> All directions A/P, M/L, IR/ER, diagonals <p>Observe: Cue patient to maintain equal weightbearing bilaterally (watch for unweighting of the involved limb as level of difficulty increases)</p> <ul style="list-style-type: none"> Do not overpower the patient board should not move > 1 or 2 inches Match therapist's forces w/o excessive movement of roller board 	<ul style="list-style-type: none"> Begin combining directional movements (Ant with IR) <p>Distraction: May begin to add distraction (ball toss, stick work)</p> <p>Observe: Cue patient to maintain equal weightbearing bilaterally (watch for unweighting of the involved limb as difficulty level increases)</p> <ul style="list-style-type: none"> Do not overpower the patient, board should not move > 1 or 2 inches <p>Cue patient to react as you remove force (avoid rebound board movement)</p>	<ul style="list-style-type: none"> Little to no delay between applications <p>Distraction: Increase speed and magnitude of distraction</p> <ul style="list-style-type: none"> Consider diagonal/sport specific stance (forward split, backward split) <p>Observe: Cue patient to maintain equal weight bearing bilaterally (watch for unweighting of the involved limb as difficulty level increases)</p> <ul style="list-style-type: none"> Cue patient to react as you remove force (avoid rebound board movement)

Rollerboard and Stationary Platform instructions:

Setup: The involved leg is placed on either the rollerboard or the stationary platform and after 3 sets of 1 minute, the legs are alternated and the treatment is repeated

Instructions: *Meet my force. Don't beat my force.*

"When I push the rollerboard, resist the exact movement in speed and magnitude. The board should remain in the same place Do not overpower me and move the rollerboard away and do not let me overpower you."

COMMON THEMES IN PERTURBATION TRAINING			
Tools: Roller Board, Tilt Board, Stationary Platform, Sport Specific Equipment Time: 3 sets of 1 minute of each, rest time for calf stretching as needed Phases: 10 treatments total Progressions: Vary by individual, estimates are noted above			
<p>Application to Surface - As the therapist increases the stress to the patient in one area (i.e. change force application from expected to unexpected), the therapist may need to decrease the intensity of another application variable (i.e. magnitude of speed). Once the patient is successful, progress toward resumption of altered variable (magnitude or speed)</p> <p>Distraction of Patient - When progressing a patient in difficulty level or progressing to the next phase of training, a therapist may need to decrease the distraction level for 1 or 2 treatments until the patient's skill level has improved. Once the patient is successful, progress toward resumption of the previous level of distraction and progress.</p> <p>Observation of Patient - Each time a therapist adds stress to the training program (by application or distraction) you may see a decrease in performance level. This will require more cueing and feedback until the new skill is acquired and more stress can be incorporated.</p>			
	Early (Estimated Treatment 1–3)	Middle (Estimated Treatment 4–7)	Late (Estimated Treatment 8–10)
Date Completed			
Resistive Quadriceps/ Hamstrings Training <ul style="list-style-type: none"> Weights Isokinetics 			
Date Completed			

COMMON THEMES IN PERTURBATION TRAINING			
Tools: Roller Board, Tilt Board, Stationary Platform, Sport Specific Equipment Time: 3 sets of 1 minute of each, rest time for calf stretching as needed Phases: 10 treatments total Progressions: Vary by individual, estimates are noted above			
<p>Application to Surface - As the therapist increases the stress to the patient in one area (i.e. change force application from expected to unexpected), the therapist may need to decrease the intensity of another application variable (i.e. magnitude of speed). Once the patient is successful, progress toward resumption of altered variable (magnitude or speed)</p> <p>Distraction of Patient - When progressing a patient in difficulty level or progressing to the next phase of training, a therapist may need to decrease the distraction level for 1 or 2 treatments until the patient's skill level has improved. Once the patient is successful, progress toward resumption of the previous level of distraction and progress.</p> <p>Observation of Patient - Each time a therapist adds stress to the training program (by application or distraction) you may see a decrease in performance level. This will require more cueing and feedback until the new skill is acquired and more stress can be incorporated.</p>			
	Early (Estimated Treatment 1–3)	Middle (Estimated Treatment 4–7)	Late (Estimated Treatment 8–10)
Agility Program (5 reps of each: begin 3–6 feet progressing to 1D feet) Forward/backward running (plant on involved leg) Side shuffle Carioca/Braiding Corner Turn/Pivot On Command Drill	Progression: Increase speed/distance/unexpected direction change Observe: Willingness to rely on involved lower limb Sport Specific: Addition of equipment (i.e. dribble basketball while performing agility) Modify Drills: i.e. Run ahead and take pass to extreme right or left	Progression: Increase speed/distance/unexpected direction change Observe: Willingness to rely on involved lower limb Sport Specific: Addition of equipment (i.e. dribble basketball while performing agility) Modify Drills: i.e. Run ahead and take pass to extreme right or left	Progression: Increase speed/distance/unexpected direction change Observe: Willingness to rely on involved lower limb Sport Specific: Addition of equipment (i.e. dribble basketball while performing agility) Modify Drills: i.e. Run ahead and take pass to extreme right or left
Date Completed			
Return to Sport Specific Activity	If return to sport before surgery: Start sport specific activities immediately If no return to sport before surgery: Sports specific activities not to be completed	Begin sports specific skills: Dribble basketball, straight shots (no jumping) Backboard tennis within arms' reach Low level soccer ball handling Stroking for skaters Progression: Patient specific based on performance in perturbation skills	Transition to Play: <ul style="list-style-type: none"> One on one basketball (time limit) Tennis with partner (easy on pivots) Begin soccer drills Begin skating spins and glides Progression: Patient specific based on middle phase progression and perturbation skills <ul style="list-style-type: none"> Goal to begin modified play by sessions 8–10

Goal: The goal of the return to sports specific activity phase is to return patients with acute ACL ruptures to high level activities. This must include progressive return to activities themselves. The time frame for return to sport specific activities is variable and patient dependent.

Figure 1.
Algorithm for noncopper randomization and testing procedures.

Figure 2. Tibial position (m) of each subject before pre-operative intervention, after preoperative intervention, and 6 months post anterior cruciate ligament reconstruction (ACLR).

Figure 3. Knee flexion angle (degrees) of the involved (solid lines) and uninvolved (dashed) limbs of the PERT and STR before preoperative intervention, after preoperative intervention, and 6 months post ACLR.

Figure 4. Tibial position of males (top graph) and females (bottom graph) before preoperative intervention, after preoperative intervention, and 6 months post ACLR.

Figure 5. Knee flexion angle (degrees) of males and females before preoperative intervention, after preoperative intervention, and 6 months post ACLR.

Table 1

Subject demographics

Subjects (N)	Graft Type	Treatment Group Composition by Gender	Age (Years)	Time from Injury (Weeks)
40	Autograft = 16	P = 19 (M = 12; F = 7)	P = 30.0 ± 12.5 S = 29.0 ± 10.8	P = 9.7 ± 8.2 S = 12.5 ± 11.7
	Allograft = 24	S = 21 (M = 16; F = 5)	F = 31.7 ± 12.3 M = 28.5 ± 11.3	F = 8.5 ± 9.9 M = 12.3 ± 10.3

Note. P = perturbation group, S = strength group, M = males, F = females.

Table 2

Calculation of standard error of the measurement (*SEM*) and minimal detectable change (MDC) for tibial position and knee angle during unilateral stance in uninjured controls

Gait Data	Tibial Position (m)			Knee Angle (°)		
	Left	Right	Limb Difference	Left	Right	Limb Difference
Subject 1	-0.004	-0.003	0.002	-5.8	-8.4	2.6
Subject 2	0.004	-0.003	0.007	7.2	0.5	6.7
Subject 3	-0.003	0.006	0.009	-8.3	-2.1	6.2
Subject 4	0.003	0.003	0.000	-6.3	-6.5	0.2
Subject 5	0.003	0.003	0.000	6.2	-8.2	14.4
Subject 6	0.003	0.005	0.002	-7.4	-6.4	1.0
Subject 7	0.006	0.004	0.002	-14.2	-22.8	8.6
Subject 8	0.002	0.002	0.001	-1.3	-6.7	5.3
Subject 9	0.005	0.002	0.003	-13.4	-12.4	1.0
Subject 10	0.004	0.004	0.000	1.2	0.3	0.9
Mean $\pm$ <i>SD</i>	0.003 m $\pm$ 0.003			4.7° $\pm$ 4.5		
<i>SEM</i>	0.001 m			1.1°		
MDC	0.002 m			3.1°		

Table 3

Meaningful changes in involved limb tibial position over time

	Treatment Group		
Time Period and Change	Perturbation	Strength	χ^2 test <i>p</i> value
Pre- to Postintervention			
(+)	4	6	0.784
(−)	3	4	
(∅)	12	11	
Preintervention to 6 months post ACLR			
(+)	4	7	0.593
(−)	3	4	
(∅)	12	10	
Postintervention to 6 months post ACLR			
(+)	5	5	0.971
(−)	4	5	
(∅)	10	11	

(+), 3 mm decrease in posterior position or change from posterior to anterior position.

(-), 3 mm increase in posterior positioning or change from anterior to posterior position.

(Ø), < 3 mm change or maintenance of anterior positioning.

Table 4

Meaningful changes in involved limb knee flexion angles over time

	Treatment Group		
Time Period and Change	Perturbation	Strength	χ^2 test <i>p</i> value
Pre- to Postintervention			
(+)	6	7	0.584
(−)	4	2	
(∅)	9	12	
Preintervention to 6 months post ACLR			
(+)	7	4	0.442
(−)	4	5	
(∅)	8	12	
Postintervention to 6 months post ACLR			
(+)	4	2	0.236
(−)	3	8	
(∅)	12	11	

(+) 3.5° decrease in knee flexion.

(-) 3.5° increase in knee flexion.

(Ø) < 3.5° change.

Table 5

Meaningful changes in involved limb tibial position over time

	Gender		
Time Period and Change	Males	Females	χ^2 test <i>p</i> value
Pre- to Postintervention			
(+)	6	4	0.722
(−)	5	2	
(Ø)	17	6	
Preintervention to 6 months post ACLR			
(+)	7	4	0.586
(−)	6	1	
(Ø)	15	7	
Postintervention to 6 months post ACLR			
(+)	6	4	0.635
(−)	6	3	
(Ø)	16	5	

(+), 3 mm decrease in posterior position or change from posterior to anterior position.

(-), 3 mm increase in posterior positioning or change from anterior to posterior position.

(Ø), < 3 mm change or maintenance of anterior positioning.

Table 6

Meaningful changes in involved limb knee flexion angles over time

Time Period and Change	Gender		χ^2 test <i>p</i> value
	Males	Females	
Pre- to Postintervention			
(+)	10	3	0.803
(−)	4	2	
(Ø)	14	7	
Preintervention to 6 months post ACLR			
(+)	8	3	0.557
(−)	5	4	
(Ø)	15	5	
Postintervention to 6 months post ACLR			
(+)	4	2	0.814
(−)	7	4	
(Ø)	17	6	

(+), 3.5° decrease in knee flexion.

(-), = .5° increase in knee flexion.

(Ø), < 3.5° change.