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original research

Time to Stabilization of Anterior Cruciate Ligament–Reconstructed Versus Healthy Knees in National Collegiate Athletic Association Division I Female Athletes

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Context: Jump landing is a common activity in collegiate activities, such as women's basketball, volleyball, and soccer, and is a common mechanism for anterior cruciate ligament (ACL) injury. It is important to better understand how athletes returning to competition after ACL reconstruction are able to maintain dynamic postural control during a jump landing.

Objective: To use time to stabilization (TTS) to measure differences in dynamic postural control during jump landing in ACL-reconstructed (ACLR) knees compared with healthy knees among National Collegiate Athletic Association Division I female athletes.

Design: Case-control study.

Setting: University athletic training research laboratory.

Patients or Other Participants: Twenty-four Division I female basketball, volleyball, and soccer players volunteered and were assigned to the healthy control group (n = 12) or the ACLR knee group (n = 12). Participants with ACLR knees were matched to participants with healthy knees by sport and by similar age, height, and mass.

Intervention(s): At 1 session, participants performed a single-leg landing task for both limbs. They were instructed to stabilize as quickly as possible in a single-limb stance and remain as motionless as possible for 10 seconds.

Main Outcome Measure(s): The anterior-posterior TTS and medial-lateral TTS ground reaction force data were used to calculate resultant vector of the TTS (RVTTS) during a jump landing. A 1-way analysis of variance was used to determine group differences on RVTTS. The means and SDs from the participants' 10 trials in each leg were used for the analyses.

Results: The ACLR group (2.01 ± 0.15 seconds, 95% confidence interval [CI] = 1.91, 2.10) took longer to stabilize than the control group (1.90 ± 0.07 seconds, 95% CI = 1.86, 1.95) ($F_{1,22} = 4.28$, $P = .05$). This result was associated with a large effect size and a 95% CI that did not cross zero (Cohen d = 1.0, 95% CI = 0.91, 1.09).

Conclusions: Although they were Division I female athletes at an average of 2.5 years after ACL reconstruction, participants with ACLR knees demonstrated dynamic postural-control deficits as evidenced by their difficulty in controlling ground reaction forces. This increased TTS measurement might contribute to the established literature reflecting differences in single-limb dynamic control. Clinicians might need to focus rehabilitation efforts on stabilization after jump landing. Further research is needed to determine if TTS is a contributing factor in future injury.

Key Words: postural control, jump landings, dynamic stability

Key Points

- The resultant vector time to stabilization demonstrated that participants with anterior cruciate ligament–reconstructed knees took longer to stabilize during a single-leg jump-landing task than participants in the control group.
- Dynamic postural-control deficits and difficulties in controlling ground reaction forces during landing might be present in women with anterior cruciate ligament–reconstructed knees even after clearance by a physician and return to play.
- Clinicians might focus rehabilitation on dynamic stabilization following jump landing in patients after anterior cruciate ligament reconstruction.

Many health care professionals face the challenge of preventing anterior cruciate ligament (ACL) injuries in female collegiate athletes and rehabilitating those who have ACL injuries. In 1995, using injury surveillance, Arendt and Dick[1] published the first study establishing greater risk for ACL injury in women than men in basketball and soccer. In a more recent study, Mihata et al[2] updated the male-female ACL injury comparison by adding men's and women's lacrosse and using information from the National Collegiate Athletic Association (NCAA) Injury Surveillance System. Despite increased levels of fitness and years of participation for women and the introduction of ACL injury–prevention programs in many women's athletics programs over 15 years, they found that female collegiate athletes continued to injure their ACLs at greater rates than their male counterparts. They also found that, between 1989 and 2004, the rate of ACL injury in women was 3 times greater than in men for soccer and 4 times greater than in men for basketball.

Differences in dynamic postural control during landing have been proposed as contributing factors to ACL injuries in women compared with men. Women tend to land with greater knee extension,[3–5] knee abduction,[6–9] and hip internal rotation[3,10] than men; the latter 2 recently have

Table 1. Participant Demographics, Mean ± SD

Group	Age, y	Height, cm	Mass, kg	Sport		
				Basketball	Volleyball	Soccer
Anterior cruciate ligament reconstructed (n = 12)	20.50 ± 1.24	167.85 ± 7.92	65.11 ± 3.84	3	1	8
Control (n = 12)	19.25 ± 1.13	167.64 ± 4.84	62.61 ± 61.00	3	1	8

been associated with weak hip musculature.[3,11] Specific to sporting activity, Salci et al[5] found that, when landing from a 40-cm spike, 60-cm spike, or block, female collegiate volleyball players displayed less knee and hip flexion and greater vertical ground reaction forces (GRFs) than male volleyball players. These positions have been linked to mechanisms for ACL injury,[2,10,12] substantiating the higher incidences of ACL injury in women than in men.

In addition to kinematic and kinetic differences, structural and proprioceptive differences between men and women also have been documented. Rozzi et al[13] reported that, among male and female collegiate soccer and basketball players, female athletes demonstrated excessive knee joint laxity and longer time to detect knee joint motion in passive extension. They suggested that these deficits might make female athletes more susceptible to ligament injuries because their knees have decreased kinesthesia and are less likely to detect potentially damaging forces.

When considering these mechanisms prospectively, Hewett et al[14] demonstrated that female athletes who ruptured their ACLs demonstrated higher GRFs and shorter stance times during jump landing, allowing motion, force, and moments to occur more quickly. Some of these deficits not only have been demonstrated with first-time injuries but also might contribute to repeated ACL injuries. Of individuals with previously ACL-reconstructed (ACLR) knees, 10% to 25% have reported recurrent laxity.[15] Salmon et al[16] followed 612 patients with ACLR knees and found that 74 (12%) either ruptured the grafts or ruptured their contralateral ACLs.

These studies showed that highly competitive female athletes might possess neuromuscular deficits that put them at a higher risk of ACL injury than male athletes. Often, neuromuscular deficits of the lower extremity are measured using static single-leg–stance positions.[17–23] Colby et al[24] suggested that a static position does not sufficiently challenge the neuromuscular system in recreating athletic activity or even activities of daily living. More dynamic types of activities, such as jump-landing tasks, might be a more accurate tool for assessment of the lower extremity neuromuscular system during single-limb activities. The time-to-stabilization (TTS) measurement technique is used to assess the time that participants take to attain a stable position after a jump-landing task, giving an indication of dynamic postural stability. Colby et al,[24] who were the first to study this technique, compared the stabilization times of unilateral ACL-deficient and ACLR knees with the contralateral healthy knees in recreationally active patients. They found that TTS was a reliable means for identifying a deficit in dynamic postural stability in those with ACL injury while performing a step-down task. Since that initial study, other investigators have used TTS when studying participants with chronic ankle instability (CAI).[25–34] New techniques in collecting these measurements of dynamic postural stability have combined the 2-directional GRFs that make up the traditional reporting of the frontal-plane and sagittal-plane TTS measurements into a single dependent variable: the resultant vector TTS (RVTTS).[34] These more recent studies of ankle conditions consistently have demonstrated longer TTS, and therefore a deficit in dynamic postural stability, in individuals with CAI than in healthy participants.

Because jump landing is the core of TTS and because this method repeatedly has revealed dynamic postural changes in individuals with CAI, we were interested in using this functional task to help determine if similar findings would occur in individuals with ACL reconstructions. Jump landing is a common athletic activity and a well-known mechanism for injury to the ACL, so investigation into stabilization of jump landing might help clinicians and researchers understand more clearly if deficits in dynamic stability might persist even after successful reconstruction and rehabilitation. Female athletes who have had an ACL injury, have undergone reconstructive surgery, and have returned to competition can provide important information on the effects of ACL injury. Because of the greater likelihood of ACL injury in women and the unique characteristics displayed in landing, it is critical to investigate women, especially those who have had an ACL injury, to help understand deficits in dynamic postural control and stability that might exist. Although studying women with ACLR knees might not tell us if these deficits existed before injury, it might establish that dynamic postural control differs between women with ACLR knees and women with healthy knees, thus laying the groundwork for future prospective research into whether these differences exist before injury.

Competing as a Division I athlete demands significant neuromuscular control, and neuromuscular control is greater for these athletes than for nonathletes. Furthermore, because female athletes participating in soccer, basketball, and volleyball are at greater risk for ACL injury than male athletes in the same sports and male or female athletes in other sports,[1,2] we believed that this population would be optimal for study in the area of dynamic postural control through TTS measurements. Although ACL injuries are common in these athletes during noncontact landings,[1,2] the TTS method has not been used to investigate the dynamic postural control of this population. Therefore, the purpose of our study was to use TTS to measure differences in dynamic postural control during jump landings in ACLR knees compared with healthy knees among Division I female athletes.

METHODS

Participants

Twenty-four NCAA Division I female basketball, volleyball, and soccer players volunteered for the study (Table 1). Participants were assigned to 1 of 2 groups based on whether they had healthy knees or ACLR knees. Participants with ACLR knees were matched to participants with healthy knees by the same sport and by similar age, height, and mass. When participants had sustained bilateral ACL tears (n = 5), the knee with the shortest time since surgery was used for statistical analysis. This knee was chosen because the dynamic postural control of the knee with the older injury might have been influenced by a more recent injury on the contralateral side.

All participants reported choosing the right leg with which to kick a ball. Participants with ACLR knees had undergone surgery at least 1 year (mean = 2.50 ± 1.18 years) before the study. Of the 12 participants with ACLR knees, 7 (58%) reported a noncontact mechanism of injury, and 2 (22%) reported contact mechanisms; the mechanisms of injury were not available for 3 (25%). Of the 2 participants who had sustained contact injuries, both later had torn their contralateral ACLs through noncontact mechanisms. All participants in the ACLR knee group had been cleared by the team physician for full participation in their sports. Participants provided written informed consent, and the study was approved by the University of Toledo Institutional Review Board.

Instrumentation

A strain-gauge force platform (model 4060 NC; Bertec Inc, Columbus, OH) and MotionMonitor software (version 7.0; Innovative Sports Technologies Inc, Chicago, IL) were used to measure and record GRFs. A Vertec (Sports Imports, Columbus, OH) was used to assess the vertical jumping height and to establish the target or the jump height during the jump-landing procedures. LabVIEW software (version 8.2; National Instruments, Austin, TX) was used to calculate TTS.

Procedures

The participants wore athletic clothing and athletic shoes of their choice and reported for testing at the Athletic Training Research Laboratory, where the study was explained. Before beginning the testing procedures, the maximal vertical jumping heights of the participants were established. Standing-reach heights were collected from the participants by instructing them to stand beneath the Vertec, reach up with 1 hand as far as they could without their heels leaving the ground, and touch the highest tab possible on the Vertec. While standing directly under the Vertec on 2 feet, participants were instructed to complete a maximal vertical jump, hit the highest tab they could reach on the Vertec, and land on 2 feet. No restrictions were placed on the jump for takeoff or landing technique. The best of 3 trials was recorded.

Next, the tab on the Vertec was set at 50% of the maximal jump height, which was the tab that measured halfway between the standing reach and maximal jump height. Participants were instructed to stand behind a mark on the floor that was 70 cm away from the center of the force platform.[35] They were instructed to jump off anteriorly from 2 feet, hit the target on the Vertec with their fingers, and land on the force platform on the designated foot. All participants were right-hand dominant and used the right hand to hit the Vertec. They were instructed to "stick the landing," place their hands on their hips as soon as possible, and hold the position as motionless as possible for 10 seconds.[36] These were the only restrictions placed on the technique of the jump and landing. If a participant hopped on the landing, missed the target, or touched her other foot on the ground, the trial was discarded. Participants were allowed to practice until they felt comfortable with the task. Although this was a somewhat novel task, the participants typically required only 2 to 4 attempts before they reported feeling comfortable to begin testing. Ten trials were completed on each limb.[24] Although these athletes were exposed regularly to strenuous activity, including jumping, a 1-minute rest was given between trials to avoid fatigue.

Data Processing

The GRFs of the anterior-posterior and medial-lateral components were sampled at 180 Hz[24,29–32] with the MotionMonitor software from the force plate and were processed in LabVIEW. A Butterworth filter at 12 Hz was applied to the GRF data.[31] Anterior-posterior TTS (APTTS) and medial-lateral TTS (MLTTS) were calculated using the range-of-variation method described by Ross et al.[31] A range of variation was calculated from the smallest absolute GRF during the final portion of the single-leg stance of the landing for the anterior-posterior and medial-lateral elements. The range of variation of the GRF ± 3 SDs was multiplied by the participant's body mass and was used as a reference variable. An unbounded third-order polynomial curve-fit line was applied to the GRF to determine the decay of the data. The time at which the data corresponding to the unbounded polynomial were equal to or less than the range of variation was identified as the time to gain stability and was designated as the variable calculated in both anterior-posterior (APTTS) and medial-lateral (MLTTS) directions. After APTTS and MLTTS values were calculated, the RVTTS was calculated using the following formula:

$$\mathrm{RVTTS} = \sqrt{\mathrm{APTTS}^2 + \mathrm{MLTTS}^2}$$

Although APTTS and MLTTS commonly are reported separately, the RVTTS variable has been developed recently and has been recommended to provide a single stability assessment of both planes of movement.[34] The average RVTTS value of the 10 trials for each participant was used for data analysis.

Statistical Analysis

The means and SDs were used for all analyses. The RVTTS values for each participant were averaged across the 10 trials in each leg. A 1-way analysis of variance was used to examine group differences for RVTTS.

Based on the means and SDs, effect sizes were calculated for the post hoc pairwise comparisons according to the Cohen d.[37] The interpretation of the calculated values followed the scale provided by Cohen[37] of small (0.20), moderate (0.50), and large (0.80) effect sizes. In addition, 95% confidence intervals (CIs) were calculated around the mean values. We used SPSS (version 14.0; SPSS Inc, Chicago, IL) to analyze the data. The α level was set a priori at .05.

Table 2. Resultant Vector Time to Stabilization

Group	Mean ± SD	*P* value	Cohen d	95% Confidence Interval	Observed Power
Anterior cruciate ligament reconstructed	2.01 ± 0.15	.05	1.0	0.91, 1.09	0.55
Control	1.90 ± 0.07				

RESULTS

The ACLR group took longer to stabilize (2.01 ± 0.15 seconds, 95% CI = 1.91, 2.10) than the control group (1.90 ± 0.07 seconds, 95% CI = 1.86, 1.95, $F_{1,22} = 4.28$, $P = .05$; Table 2). This result was associated with a large effect size and a 95% CI that did not cross zero (Cohen d = 1.0, 95% CI = 0.91, 1.09; Table 2).

DISCUSSION

The ACLR group had an observable deficit of 0.11 seconds in the time it took to stabilize after a jump landing compared with the control group. The strong effect size suggests that this difference was clinically important and leads us to believe that Division I athletes who have had successful ACL reconstruction and have been cleared for full sport participation might still possess deficits in dynamic stability during a task that mimics a common sport activity.

Proper dynamic postural control is essential for performing not only high levels of athletic activity but also activities of daily living. Schutte et al[38] established the neurologic composition of the ACL, specifically the direct connections from the ACL to the spinal cord and to supraspinal areas. If attention is not given to restoring proper functioning in this system, deficits in dynamic postural control might persist after rehabilitation and return to activity. Anterior cruciate ligament injuries have been linked to changes in landing patterns for kinetic and kinematic variables in participants with ACLR knees compared with healthy participants,[39–41] as well as in the contralateral limbs of participants with ACLR knees.[39,41] Hewett et al[14] found that higher GRFs and shorter stance times during jump landing, which allow motion, force, and moments to occur more quickly, are predispositions to ACL injury.

The nature of the TTS task requires participants to control GRFs and to stabilize quickly after both horizontal and vertical displacements. The alterations seen in women with ACLR knees might have been due to the participants' trying to control vertical forces from landing, as well as anterior tibial translation. The ability to stabilize quickly also requires good muscular strength and firing patterns; insufficiencies might have contributed to difficulty in stabilizing as quickly as the healthy controls. As noted, neuromuscular kinetic and kinematic differences have been demonstrated in individuals with ACLR knees. Specifically, changes include GRFs[41,42]; peak flexion angles of the hip, knee, and ankle[41]; increased valgus knee moments[43]; increased anterior-posterior shear forces at the tibia[40]; increased rotation of the tibia[43]; and changes in muscle-firing patterns.[40,41] All of these deficits might have contributed to differing landing patterns in the athletes with ACLR knees. Increased TTS might have been another contributing factor in landing alterations in athletes with ACLR knees compared with athletes with healthy knees. Our findings might help clinicians and researchers to understand and recognize a potential additional contribution to lingering deficits and injury risk associated with ACL injury.[14]

Using TTS, Colby et al[24] also studied the effect of ACL injuries on stabilization times by comparing the injured and uninjured legs of those with ACLR or ACL-deficient knees against those with healthy knees while performing a hop test and a step-down task. In a within-subjects comparison, their results demonstrated that the ACLR knees had greater vertical TTS than the uninjured knees during the step-down task. Although we and Colby et al[24] found longer stabilization times in ACLR knees compared with healthy knees and used variations of TTS, a direct comparison of means is difficult because of differences in the task goals and how TTS was calculated in our study.[34] Nonetheless, in both studies, a deficit was noted in the injured groups, even in the Division I female athletes whom we studied.

Recently, Ross et al[34] studied CAI participants as a pathologic group, and the same calculations of RVTTS as in our study demonstrated longer TTS in the CAI group than in the healthy control group. Their reported means and group differences (CAI group = 1.80 ± 0.53, healthy group = 1.50 ± 0.32) were similar to our results. Although CAI has a multifactorial cause, researchers have documented that deficits in dynamic postural control might contribute to the recurrent nature of the condition.[44] This might be important to consider when comparing the results from our study and the reinjury rates[15,16] reported for those with ACLR knees. Because ACL injury also has a multifactorial mechanism, future investigators who examine the numerous contributions to recurrent ACL injury risk might need to consider dynamic postural-control deficits after reconstruction.

Clinical Implications

Longer TTSs indicate that participants have more difficulty controlling GRFs at landing, which might be related to impaired neuromuscular control. In recent years, ACL injury–prevention programs that focus on improving neuromuscular control by having participants perform jump-landing tasks have been implemented. These practiced movements have similar task goals to the testing technique implemented in our study: obtain and maintain stable positions after dynamic movement. Authors[45–49] of many prospective studies have reported positive results when studying groups of female athletes performing neuromuscular intervention programs. These interventions included strengthening, flexibility, jump-landing training, and education on technique. These researchers investigated populations of female athletes participating in sports, such as soccer, volleyball, basketball, and European handball, which were similar to the population examined in our study. Comparing female soccer athletes who performed neuromuscular training with untrained female soccer athletes and untrained male soccer athletes, Hewett et al[45] reported a greater likelihood of untrained athletes than trained female athletes sustaining knee injuries but no differences between the trained female and untrained male athletes. Thus, the interventions not only reduced the number of ACL injuries for female athletes but lowered them to the rate in male athletes. These prospective studies are important for recognizing how neuromuscular training can help prevent serious knee injuries in athletes involved in landing, cutting, and pivoting activities.

Although the female athletes in our study were cleared medically for full participation in their chosen sports, the dynamic-stability measure suggested that they might have possessed a deficit during this and similar tasks. It seems likely that the type of neuromuscular training used in the prospective studies listed[45–49] would help decrease TTS and allow athletes to stabilize faster through proper landing technique and improved neuromuscular control; therefore, future investigation into the effect of this training on TTS is necessary to determine its place as a useful outcome variable and its relationship to ACL injury risk. Based on our finding that female athletes with ACLR knees showed differences in TTS after surgery and rehabilitation compared with healthy matched participants, it might be useful to collect TTS data in people with ACLR knees before and after participation in a neuromuscular training program to determine if changes exist in dynamic stability after the training.

Differences in Jump-Landing Patterns

In their prospective study involving knee-joint angles and moments of female athletes, Hewett et al[14] found differences with jump landing. Of the 205 athletes tested, 9 later ruptured their ACLs. The investigators found that increased knee valgus motion and valgus moments were predictors of ACL injury. In addition, the injured group displayed lower knee flexion at peak contact and a 20% increase in vertical GRFs. The differences in lower extremity biomechanics confirmed that altered control of landing might exist for some athletes before an ACL injury. Our findings and those of many others[39,40,50] have demonstrated that, if not addressed, these alterations might persist after operative repair and return to competition, even when a substantial amount of time has passed since surgery.

Clinical Applications

Some readers might question the clinical significance of our study because fractions of seconds might not appear to be clinically important. However, when considering the rate at which the neuromuscular system functions and subsequently might be disrupted, these milliseconds of difference actually might affect jump-landing stabilization and prevention of injury. In a recent study of mechanisms of ACL injury in basketball players using video analysis, the time of injury was estimated to range from 17 to 50 milliseconds after initial ground contact.[51] In our study, participants with ACLR knees took a mean of 110 milliseconds longer to stabilize than control participants. This implies a much longer time to stabilize than the time to injury, which might affect a person's ability to avoid injury.

We recognize that TTS is not feasible in most clinical settings, but the implications of our results can be integrated into clinical practice. Because stabilization deficits were observed in those participating in collegiate athletics at an average of 2.5 years after ACL reconstruction, clinicians might need to focus rehabilitation efforts on stabilization after landing. These results support the need for intervention programs focused on jump-landing stabilization, not only for prevention of initial ACL injury but also for those recovering from ACL reconstruction surgery.

Limitations

We placed no restrictions on type of ACL reconstruction procedure and, consequently, had a mixed distribution of patellar tendon and hamstrings grafts. We had no control over the extent or type of the rehabilitation protocols completed by each participant. However, we believed that these differences in operative technique and rehabilitation of the athletes would provide a better representation of the general athletic population.

Our sample size was low because we recruited participants from the Division I athletes with reconstructed ACLs who were playing collegiate athletics at the institution where the research was conducted. Future investigators are encouraged to examine these same relationships with larger sample sizes because the effect sizes from our study suggested an important clinical finding.

CONCLUSIONS

Using TTS to study jump landing in female participants demonstrated that those with ACLR knees took longer to stabilize than participants with healthy knees when comparing RVTTS, implying that deficits existed in the dynamic postural control of ACLR knees compared with healthy knees in control participants. This indicated that dynamic postural-control deficits and difficulties in controlling GRFs during landing might be present in those with ACLR knees, even among Division I female athletes at an average of 2.5 years after ACL reconstruction. Clinicians can use this information to focus rehabilitation efforts on dynamic stabilization after jump landing in female athletes recovering from ACL reconstruction. Further research is needed to determine if this measurement can be used to predict future injuries and if dynamic postural training can decrease TTS in these patients.

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