The Relationship Between Lateral Trunk Control During Landing and Lower Extremity Muscle Strength in Young Athletes After ACL Reconstruction

Undergraduate Research Thesis

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By

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The Relationship Between Lateral Trunk Control During Landing and Lower Extremity Muscle Strength in Young Athletes After ACL Reconstruction

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Background: An anterior cruciate ligament (ACL) tear is a devastating injury that is typically treated with ACL reconstruction (ACLR). Previous work shows that young athletes continue to demonstrate asymmetrical lower extremity biomechanics during landing tasks even after rehabilitation and return-to-sport (RTS), and these asymmetries are related to muscle strength deficits and increase the risk of re-injury. However, less is known about lateral trunk control during single-leg landing (SLL).

Hypothesis: The purpose of this study was to test the hypothesis that lateral trunk instability during SLL would be greater in those with ACLR compared to healthy controls and would be associated with quadriceps femoris (QF) and hip abduction (HA) muscle strength deficits.

Methods: 131 individuals (72% female, mean age: 17.2 y) cleared for RTS following unilateral, primary ACLR and 56 healthy controls (73% female, mean age: 17.2 y) participated. Biomechanical data were collected using 3D motion analysis during a SLL task to calculate frontal plane trunk excursion (FPTE; measure of lateral trunk control). FPTE limb symmetry indices were calculated for the ACLR and Control groups [(involved/uninvolved) x100%]. QF and HA strength were measured using an isokinetic dynamometer, and LSI were then calculated. FPTE and FPTE LSI were compared between the ACLR and Control groups using independent t-tests. Within the ACLR group, linear regression was used to examine the relationship of both FPTE and FPTE LSI to QF (involved peak torque; QI) and HA strength (involved peak torque; LSI). Finally, QI was used to divide the ACLR participants into high-quadriceps (HQ) (QI>90%; n = 68) and low-quadriceps (LQ) (QI<85%; n = 53) subgroups, which, in addition to the control group, were compared for differences in FPTE and FPTE LSI using a one-way analysis of variance and post-hoc tests (α=0.05 for all analyses).

Results: Compared to the control group, the ACLR group demonstrated increased FPTE (ACLR: 15.61±4.47°; Control: 12.91±3.61°; p<0.001) and FPTE LSI (ACLR: 143.22±46.57%; Control: 105.74±32.97%; p<0.001). Lower involved limb QF (QI; peak torque) and HA strength (peak torque) predicted greater FPTE during SLL (R²: 11.3%, p<0.001; R²: 12.7%, p<0.001; R²: 4.6%, p=0.015; respectively). Lower involved limb QI and peak torque also predicted greater FPTE LSI during landing (R²: 6.3%, p=0.004; R²:4.9%, p=0.011; respectively). The HQ strength group exhibited significantly increased FPTE compared with both the HQ group (p=0.036) and the control group (p<0.001) (Control: 12.91±3.61°; HQ: 14.66±4.48°; LQ: 16.60±4.31°). The LQ demonstrated greater FPTE LSI than the HQ (p=0.027) and control (p<0.001) groups, and the HQ group also demonstrated greater FPTE LSI compared to the controls (p<0.001) (Control: 105.74±32.97%; HQ: 135.38±47.18%; LQ: 155.84±44.13%).
Conclusion: Compared with controls, individuals who had undergone ACLR demonstrated asymmetrical lateral trunk control during a SLL task at the time of RTS. Both QF and HA strength deficits were related to these asymmetries, with QF strength deficits showing a stronger relationship. Additionally, individuals in the LQ group exhibited greater trunk instability than those in both the HQ and control groups.

INTRODUCTION

A tear to the anterior cruciate ligament (ACL) is a crippling injury that has a long-lasting impact on knee joint health and often leads to ACL reconstruction (ACLR) surgery.1 Young individuals are a group that are at a high risk of sustaining an ACL injury, with between 80,000 to 250,000 ACL injuries occurring each year in individuals between 10 and 25 years old.2 Nearly 100,000 ACLR’s take place each year in the US,2,3 and the goal of this surgical intervention is to regain functional stability of the knee and return to pre-injury level of function.4–7 However, significant proportions of the young population are unable to return to pre-injury levels of activity after ACLR.8–10 A meta-analysis by Ardern et al of 69 studies found that 81% of individuals reported returning to sports after ACLR, with only 65% reporting returning to pre-injury level of sports.11 In addition to suboptimal return-to-sport (RTS) rates after ACLR, rates of re-injury remain high following RTS.12,13 The prevalence of these poor outcomes emphasize the importance of continuing to evaluate musculoskeletal impairments in young athletes following ACLR.

Individuals who have undergone ACLR demonstrate a variety of movement asymmetries during limb-loading tasks when compared to healthy controls. Previous studies have shown that abnormal lower limb biomechanics persist up until two years following ACLR.14–19 Furthermore, a number of biomechanical movement asymmetries have also been identified as risk factors for sustaining a 2nd ACL injury.20 In addition to alterations in lower limb biomechanics, individuals after ACLR also demonstrate altered trunk control in the sagittal plane, demonstrating increased trunk flexion when landing on the ACL-reconstructed limb.15,21 While previous studies have found that decreased lateral trunk control can be predictive of initial knee injuries, including ACL injuries,22,23 the prevalence of decreased lateral trunk control after sustaining an ACL injury and undergoing ACLR has not been examined.

Quadriceps femoris (QF) muscle strength symmetry is commonly used as an important clinical benchmark for determining if an athlete is ready for RTS, as individuals at the time of RTS with larger QF strength deficits exhibit lower knee-related function and greater lower limb biomechanical asymmetry during dynamic jumping and landing tasks.15,16,21,24–26 Even though QF strength symmetry has been identified as an important determinant of successful recovery post-ACLR,7,9 patients are commonly cleared for RTS with deficits that are larger than clinical recommendations (>10% of the uninvolved limb).27,28 While decreased QF strength has been associated with altered lower limb and sagittal plane trunk biomechanics after ACLR,15,16,24 the relationship between muscle strength and lateral trunk control after ACLR has not been examined. Additionally, weaknesses in the hip abductor (HA) muscles have been determined to be a potential predictor of primary ACL injury, due to these weakness related to dynamic valgus
of the knee. However, the relationship between HA muscle strength deficits after ACLR and lateral trunk control has not been previously examined.

Young athletes represent a sub-cohort of individuals after ACLR that often attempt to return to a high level of sports participation. Therefore, it is imperative to develop standardized, objective criteria to aid in clinical decision making to both minimize the risk of future injury and improve the return to activity performance of this cohort. As a first step in achieving this goal, it is critical to observe the relationship between biomechanical alterations of the trunk during a dynamic, sport-related landing task and strength impairments after ACLR. Therefore, the purpose of this study was to examine the presence of lateral trunk instability in young individuals during a single-leg landing (SLL) task at the time of RTS after ACLR, and then determine its relation to muscle strength deficits. The primary hypothesis tested was that individuals who had undergone ACLR would demonstrate greater lateral trunk control asymmetries during a SLL task when compared to healthy controls. The secondary hypothesis tested was that greater lateral trunk instability would be related to deficits in both QF and HA strength.

METHODS

Participants

A total of 187 individuals, ranging in age from 10-25, were recruited from the community, local orthopedic practices, and local physical therapy clinics to take part in this study. Participants were approved for this study by the Institutional Review Board after providing written, informed consent (provided by legal guardians when necessary). The data collected from these participants were part of a larger, prospective study of outcomes following ACLR at Cincinnati Children’s Hospital Medical Center. 131 individuals, who had undergone primary, unilateral ACLR, were recruited for the ACLR group (Table 1). To be included in this study, participants must have completed rehabilitation, gained clearance for return to high-level activity by both their surgeon and rehabilitation specialist, and intended to return to cutting and pivoting sports regularly (≥50 hours/year). Data collection took place within four weeks of participants being cleared for RTS. Potential participants were excluded from the study if they (1) suffered any other ligament damage on the involved limb (except grade I MCL sprain), (2) reported a history of low back pain or lower limb injury (cared for by physician) within the last year, or (3) required a modified pediatric ACLR procedure. All graft types (patellar tendon autograft, allograft, and hamstrings tendon autograft) were included, and meniscus repair or meniscectomy were not considered as exclusion factors. 56 healthy individuals were recruited as the control group (Table 1). Participants must have reported regular participation (≥50 hours/year) in cutting and pivoting sports in order to be included in the control group.

Motion Analysis

Testing Procedure. Three-dimensional motion analysis was used to calculate trunk kinematic data during a SLL task. A 10-camera motion analysis system (240 Hz cameras; Motion Analysis Corp.) was used to track 37 retroreflective markers attached to specific locations and anatomical landmarks on the upper and lower extremities and trunk of each participant. These markers were utilized to determine joint centers and segment position, as well as track segment motion during
SLL trials. During the SLL task, participants stood on one limb on top of a 31-cm box, and then were instructed to drop off of the box and land on a force plate (1200 Hz; AMTI) on that same limb. Participants were required to perform three acceptable trials on each limb.

Data Analysis. Specific trunk kinematic variables were calculated using Visual 3D (Version 4.0, C-motion, Inc.) and custom-written MATLAB (Version 7, The Mathworks Inc.) software during the landing phase of a SLL task. The landing phase was defined as the point of initial contact to the lowest point of the body’s center of mass.\textsuperscript{15,16} Lateral trunk instability was defined as frontal plane trunk excursion (FPTE), and was the sole kinematic variable of interest. FPTE was calculated as the sum of the peak lateral trunk position to the right and to the left during the landing phase of the single-leg landing task. The mean of the FPTE values for the involved/nonpreferred limb and uninvolved/preferred limb for the three SLL trials were used to calculate limb symmetry indices (LSI) (Formula 1). The ACL reconstructed limb was defined as the involved limb for the ACLR individuals. The preferred limb of the control participants was defined as the limb that first contacted the force platform most often during three previously performed drop-vertical jump tests.

\textit{Formula 1: LSI} = \left( \frac{\text{involved or nonpreferred limb value}}{\text{uninvolved or preferred limb value}} \right) \times 100\%

\textbf{QF and HA Strength Assessment}

\textit{Quadriiceps femoris strength assessment.} QF strength was measured using an isokinetic dynamometer (Biodex Medical Systems) during a maximum voluntary isometric contraction. This methodology is commonplace for quantifying isometric QF torque following ACL injury or ACLR, and provides reliable measurements which are used to identify strength asymmetries between limbs.\textsuperscript{15,24,25,31} Strength testing was performed by use of methods previously described.\textsuperscript{16} The peak torque obtained for each limb for the three trials was normalized to body mass (Nm/kg). From the peak torque, quadriceps indices (QI) were calculated:

\[ QI = \left( \frac{\text{involved QF peak torque}}{\text{uninvolved QF peak torque}} \right) \times 100\% \]

The calculated QI values were then used to divide the ACLR group into a high-quadriceps (HQ; QI≥90%) and low-quadriceps (LQ; QI≤85%) subgroups. These cutoff symmetry values were based on previous similar work,\textsuperscript{15,16,24,26} commonly recommended QF strength values for RTS,\textsuperscript{32} and research demonstrating that side-to-side differences in peak QF output of greater than 10% reflect differences in muscle performance beyond measurement error.\textsuperscript{28}

\textit{Hip abduction strength assessment.} HA strength was measured using an isokinetic dynamometer (Biodex Medical Systems), with the participant standing with the testing hip in line with the dynamometer axis. Isokinetic HA strength testing was performed by use of methods previously described.\textsuperscript{33} The peak torque obtained for each limb for five trials was normalized to body mass (Nm/kg), and then used to calculate HA LSI values:

\[ HA \ LSI = \left( \frac{\text{involved HA peak torque}}{\text{uninvolved HA peak torque}} \right) \times 100\% \]
Statistical Analyses

IBM SPSS (version 21) software was used to perform statistical analyses, with statistical significance established \( a \ priori (\alpha \leq .05) \) for all analyses. To test the hypothesis that lateral trunk instability would be greater in the ACLR group compared to the control group during a single-leg landing task, an independent t-test was performed for both FPTE and FPTE LSI. The independent variable was the group assignment (ACLR vs. Control), and measures of lateral trunk instability (FPTE, FPTE LSI) were the dependent variables. Linear regressions were used to test the second hypothesis that increased lateral trunk instability would be related to strength deficits. Separate regressions were performed for FPTE and FPTE LSI, using QF peak torque, QI, HA peak torque, and HA LSI as the independent variables (established \( a \ priori \)). Finally, a one-way ANOVA was used to detect the differences in lateral trunk instability between QF strength groups during SLL. Group assignment (HQ, LQ, control) was the independent variable, and measures of lateral trunk instability (FPTE, FPTE LSI) were used as the independent variables. Post hoc testing was performed using pairwise t-tests if significant between-group differences were found.

RESULTS

Group Comparison

Table 1 demonstrates demographic data for the ACLR group and the control group. The ACLR group demonstrated increased total involved FPTE when compared with the control group (ACLR involved limb: 15.61±4.47°; control non-preferred limb: 12.91±3.61°; \( p<0.001 \)). FPTE LSI was also greater in the ACLR group than in the control group (ACLR involved limb: 143.22±46.57%; control non-preferred limb: 105.74±32.97%; \( p<0.001 \)).

Linear Regression

In only the ACLR subjects (n=131), lower QI was a predictor of greater FPTE (\( R^2: 11.3\%, \ p<0.001 \)) (Figure 1) and FPTE LSI (\( R^2: 6.3\%, \ p=0.004 \)) (Figure 2). Likewise, lower involved limb QF peak torque was a predictor of greater FPTE (\( R^2: 12.7\%, \ p<0.001 \)) (Figure 3) and FPTE LSI (\( R^2: 4.9\%, \ p=0.011 \)) (Figure 4). While lower involved limb HA peak torque was a predictor of greater FPTE (\( R^2: 4.6\%, \ p=0.015 \)) (Figure 5), it was not a significant predictor of greater FPTE LSI (\( R^2: 0.4\%, \ p=0.464 \)) (Figure 6). HA LSI was neither a significant predictor of FPTE (\( R^2: 4.6\%, \ p=0.015 \)) (Figure 7) nor of FPTE LSI (\( R^2: 0.0\%, \ p=0.952 \)) (Figure 8).

Strength Group Comparison

One-way ANOVA revealed differences in both FPTE (\( p<0.001 \)) and FPTE LSI (\( p<0.001 \)) between the groups. Pairwise t-tests revealed that the LQ group (16.60±4.31°) exhibited greater total FPTE than both the HQ (14.66±4.48°; \( p=0.036 \)) and control (12.91±3.61°; \( p<0.001 \)) groups. The FPTE values for the HQ and control groups were not determined to be significant (\( p=0.063 \)) (Figure 9). Pairwise comparisons also revealed that the LQ group (155.84±44.13%) displayed greater FPTE LSI when compared to both the HQ (135.38±47.18%; \( p=0.027 \)) and control (105.74±32.97%; \( p<0.001 \)). Additionally, the HQ group displayed significantly greater FPTE LSI than the control group (\( p<0.001 \)) (Figure 10).
DISCUSSION

The purpose of this study was to examine the presence of lateral trunk instability in young individuals at the time of return to sports after ACLR, and determine its relationship to deficits in QF and HA strength deficits. The results support our first hypothesis that individuals in the ACLR group would demonstrate greater lateral trunk instability during landing than those individuals in the healthy control group. Specifically, the ACLR group demonstrated greater total FPTE when landing on the involved limb as well as greater FPTE limb asymmetry compared with those in the control group. The results also supported our second hypothesis that lateral trunk instability would be related to QF and HA muscle strength deficits. Involved limb QF peak torque and QF strength symmetry (as measured by QI) were both stronger predictors of lateral trunk instability than any of the HA strength measures. HA peak torque was found to be a predictor of FPTE, but was the only HA strength measure that could explain variation in FPTE. Further analysis of the effects of QF strength on lateral trunk control demonstrated that individuals who had greater QF strength deficits (LQ group) were found to have greater trunk motion asymmetry in the frontal plane compared with both the HQ and control groups. Interestingly, the HQ group also demonstrated significantly greater lateral trunk instability when compared specifically with the control group.

Suboptimal RTS rates identified in this cohort, and re-injury rates as high as 29.5% in young athletic individuals following ACLR, necessitate further examination of biomechanical variables to improve ACLR outcomes. Increased peak trunk flexion during a single-leg landing task after ACLR has been identified in a number of previous studies, but to our knowledge trunk movement in the frontal plane during SLL following ACLR has not been examined. FPTE was chosen as a variable of interest because of preliminary results from our laboratory, and the fact that previous studies have shown that decreased lateral trunk control is a risk factor for sustaining an initial knee injury. A prospective study of 277 collegiate athletes by Zazulak et al found that the strongest predictor of knee, ligament, and ACL injuries was lateral trunk displacement (P=0.009). Likewise, lateral trunk movement and knee abduction loading patterns may be related, and a modality for sustaining noncontact ACL injuries. In the current study, lateral trunk instability was observed after ACLR in individuals who had been cleared for RTS. ACLR participants exhibited on average 2.7° more FPTE than controls, and 37.48% greater asymmetry of FPTE between limbs. Although these values were determined to be statistically significant between the two groups, the clinical significance of this difference on risk of a second ACL injury is unknown.

QF strength deficits were chosen to attempt to explain lateral trunk instability as a result of previous studies that have identified relationships between QF strength deficits and altered movement mechanics after ACLR. Unlike in previous studies, QF strength was used in this study to explain variation in movement mechanics in the frontal plane, as opposed to the sagittal plane. Interestingly, QF strength measures were predictors of lateral trunk instability, despite the QF muscles typically considered as operating in the sagittal plane. One potential explanation of this result might be that knee joint stiffness during SLL in those with QF strength deficits might necessitate lateral trunk compensation. The moderate R² values attained indicate...
that other factors influence FPTE beyond just muscle strength. When the ACLR group was subdivided into HQ and LQ groups, and compared with controls for between-group differences, the relationship between QF strength symmetry and movement mechanics was further clarified. As seen in previous studies,\textsuperscript{15,16,24,26} the LQ group (QI \( \leq 85\% \)) exhibited more asymmetric movement than the HQ and control groups. These results illustrate the clinical importance of attaining symmetric QF strength at the time of RTS to ensure normalized lower limb and trunk movement patterns during SLL. While previous studies have identified hip abductor strength deficits as a potential risk factor of knee injury,\textsuperscript{20,29,30} hip abductor strength deficits were weak predictors of trunk movement asymmetry in the current study.

**Limitations and Future Work**

The young, athletic background of this cohort may limit the ability to generalize the results of this study to the entire population of individuals after ACLR. Likewise, all graft types were considered within the ACLR group. As previously mentioned, the modest R\(^2\) values for the linear regression results indicate that other variables account for the variation in lateral trunk control, and other variables were not considered in the current analyses. Fear of 2\(^{nd}\) ACL injury is one of the most commonly reported reasons for not returning to sports,\textsuperscript{36} and may alter trunk mechanics during SLL. Additionally, the strength measures used in this study were chosen based on previous literature and potential ability to predict trunk movement asymmetries in the frontal plane, even though other measures of ankle, knee, and hip strength have previously been reported after ACLR.\textsuperscript{29} This study was not designed to determine a specific strength cutoff, but indeed the results exhibit that strength deficits (QI/HA LSI\( \leq 85\% \)) are related to increased trunk movement in the frontal plane. Further analysis is needed to investigate the persistence of FPTE over time, as well as the ability of FPTE to predict 2\(^{nd}\) ACL Injury.

**CONCLUSION**

Young athletes at the time of RTS after ACLR exhibited increased FPTE during a SLL task when compared with healthy controls. This decreased lateral trunk control was associated with muscle strength deficits, particularly QF strength deficits. Specifically, individuals with lesser QF strength asymmetry demonstrated greater frontal plane trunk excursion. Further investigation is needed to determine if improvement in FPTE may increase RTS rates, as well as decrease the risk of future additional ACL injury.
References:


### Table 1. Participant characteristics

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### Figure 1. Scatterplot only in ACLR group (n=131) of involved FPTE vs. quadriceps strength symmetry

![Scatterplot of INV FPTE vs. Quadriceps Strength Symmetry](image)
**Figure 2.** Scatterplot only in ACLR group (n=131) of FPTE symmetry vs. quadriceps strength symmetry

**Figure 3.** Scatterplot only in ACLR group (n=131) of involved FPTE vs. involved peak quadriceps torque

**Figure 4.** Scatterplot only in ACLR group (n=131) of FPTE symmetry vs. involved peak quadriceps torque
Figure 5. Scatterplot only in ACLR group (n=131) of involved FPTE vs. involved peak hip abduction torque

![Scatterplot of INV FPTE vs. Involved Peak HA Torque](image1)

Figure 6. Scatterplot only in ACLR group (n=131) of FPTE symmetry vs. involved peak hip abduction torque

![Scatterplot of FPTE Symmetry vs. Involved Peak HA Torque](image2)

Figure 7. Scatterplot only in ACLR group (n=131) of involved FPTE vs. hip abduction strength symmetry

![Scatterplot of INV FPTE vs. HA Strength Symmetry](image3)
Figure 8. Scatterplot only in ACLR group (n=131) of FPTE symmetry vs. hip abduction strength symmetry

Figure 9. Boxplot of involved FPTE between control group (n=56), high-quadriceps group (n=68), and low-quadriceps group (n=53)

Figure 10. Boxplot of FPTE symmetry between control group (n=56), high-quadriceps group (n=68), and low-quadriceps group (n=53)