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Longitudinal Analysis of Inter-Limb Coordination Before and After Anterior Cruciate Ligament Injury: The JUMP-ACL Study

Benjamin M. Goerger[1] · **Stephen W. Marshall**[2] · **Anthony I. Beutler**[3] · **J. Troy Blackburn**[1] · **John H. Wilckens**[4] · **Darin A. Padua**[1]

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Abstract

Purpose Inter-limb coordination may provide insight into why patients with anterior cruciate ligament reconstructive surgery (ACLR) have an increased risk for future injury and osteoarthritis. The purpose of this study was to compare inter-limb coordination prior-to anterior cruciate ligament (ACL) injury and following ACLR.

Methods Unilateral lower extremity biomechanics during a double-leg jump landing were collected prior-to ACL injury (baseline) and after ACLR, rehabilitation, and return to physical activity (follow-up). Sixty-nine participants were included in this analysis: 31 participants suffered an ACL injury since baseline: 12 injured the leg tested at baseline [ACLR-injured leg (ACLR-INJ), $n=12$] and 19 injured the leg that was not tested at baseline [ACLR-uninjured leg (ACLR-UNINJ) $n=19$]; 38 participants served as matched controls. Inter-limb coordination—calculated as the mean coupling angle—between the hip and knee were measured in the respective leg of each defined group and compared amongst groups at baseline and follow-up.

Results We observed no significant change in sagittal or frontal plane inter-limb coordination amongst groups or across time ($P>0.05$). A significant decrease in inter-limb coordination in the transverse plane from baseline and follow-up was observed but limited to the ACLR-INJ group ($P=0.016$).

Conclusion The primary finding of this study is that inter-limb coordination between the hip and knee in the sagittal and frontal plane is unchanged by ACL injury and ACLR. This may help explain previous observations of changes in kinematics at both the hip and knee in this population. Our observation of alterations in the transverse plane should be interpreted with caution, but may provide additional evidence for potential mechanisms that lead to the development of osteoarthritis in ACLR patients.

Keywords Anterior cruciate ligament · Anterior cruciate ligament reconstruction · Knee · Injury · Inter-limb coordination

Introduction

Despite significant advances in treatment and rehabilitation of anterior cruciate ligament (ACL) injuries, poor outcomes have been identified following reconstructive surgery (ACLR) as evidenced by decreased physical activity [2, 22] and heightened risk for a secondary ACL injury [7, 13–15] and osteoarthritis [12, 25] compared to those with no history of ACL injury. Focusing on how to improve movement and joint loading patterns through rehabilitation may be key, as recent evidence indicates that these are predictive of subsequent ACL injury [16] and that the risk for re-injury is similar between the previously injured and uninjured legs [28].

We have previously observed that biomechanical differences post-ACLR are caused by ACL injury and ACLR, and not residual movement patterns that existed prior to ACL injury [8]. These alterations occur in both the injured and uninjured leg [8] and are consistent with previously observed prospective risk factors for secondary ACL injury [16]. These prior analyses provide useful information to help direct rehabilitation, but have been limited to analyzing and

✉ Benjamin M. Goerger
bgoerger@email.unc.edu

[1] Department of Exercise and Sport Science, The University of North Carolina at Chapel Hill, Chapel Hill, NC, USA

[2] Department of Epidemiology, The University of North Carolina at Chapel Hill, Chapel Hill, NC, USA

[3] Musculoskeletal Clinical Program, Intermountain Healthcare, Provo, UT, USA

[4] Department of Orthopaedic Surgery, Johns Hopkins University, Baltimore, MD, USA

reporting biomechanical variables independently, which may not provide a full evaluation of lower extremity joint motion.

Inter-limb coordination describes the relative amount of motion between two joints across planes of motion, and has previously been used to describe unique movement patterns following ACL injury [10, 24]. Describing if and how inter-limb coordination changes between the knee and hip joint as a result of ACL injury and ACLR could provide new insights into the motor control strategies employed by these patients post-injury; potentially improving rehabilitation strategies and return-to-play decisions. The importance of assessing inter-limb coordination could be further verified by analyzing changes prior-to and following ACL injury and ACLR in a cohort of patients that have demonstrated changes in hip and knee kinematics [8]. Therefore, the purpose of this study was to compare inter-limb coordination prior-to ACL injury and following ACLR in a cohort of patients that have been previously observed to have altered hip and knee kinematics. We hypothesized that inter-limb coordination between the hip and knee would change as a result of ACL injury and ACLR. We expected to see changes that reflected greater relative movement of the hip relative to the knee, and expected to observe these changes in both the injured and uninjured leg. We expected to observe no changes in inter-limb coordination of the matched control group.

Methods

Participants

Participants and procedures for this study has been previously described [8] and will be summarized here. This study employed a repeated measures, case—cohort research design. Participants were recruited from the Joint Undertaking to Monitor and Prevent ACL Injury (JUMP-ACL) Study, a multi-year prospective study conducted at the United States service academies—United States Air Force Academy, United States Naval Academy, United States Military Academy. Initial biomechanical testing (baseline) for the JUMP-ACL Study was conducted during the summer of their enrollment year at the academies. Participants were prospectively monitored during their careers at the service academy for ACL injury. Participants identified for enrollment in this study (follow-up), were limited to those with complete baseline—prior to initial ACL injury—biomechanical data and who had no history of ACL injury prior to enrollment in the JUMP-ACL Study.

Cases were identified as having suffered an ACL injury during their enrollment in the JUMP-ACL Study, and still enrolled in the JUMP-ACL Study and their respective academy at follow-up. Unilateral biomechanics were captured at baseline, and not all ACL injuries for the cases occurred on the tested leg: 12 injured the tested leg and 19 injured the untested leg. Therefore cases ($n = 31$) were further subdivided into two separate groups; ACLR-injured leg (ACLR-INJ; $n = 12$) for those who injured the tested leg and ACLR-uninjured leg (ACLR-UNINJ; $n = 19$) for those who injured the untested leg. Twenty-nine of the cases had no history of ACL injury at baseline. Two cases were retained in the ACLR-INJ group with previous ACL injury because their uninjured leg was tested at baseline and the same leg was subsequently injured, representing data that qualified them for the ACLR-INJ group. For each case, three possible controls were identified for follow-up, matched based on sex, cohort year and service academy. We identified and recruited three control participants per case in hopes of achieving at least a 2:1 ratio in our control to case group numbers. Thirty-eight of the potential participants identified to serve as the control group volunteered and completed testing at follow-up; a 2:1 ratio relative to the ACLR-UNINJ group and a 3.17:1 ratio relative to the ACLR-INJ group.

Procedures

All procedures were conducted after institutional review board (IRB) approval for each institution. Informed consent was obtained prior to data collection for all participants with prescribed procedures to avoid coercion. Each participant performed a double leg jump-landing at baseline and follow-up (Fig. 1). Participants were required to stand atop a 30 cm high box located a distance from the edge of a force plate equal to half their body height, jump forward from the box, landing with the foot of their instrumented leg completely on the force plate, and upon landing immediately make a maximal effort vertical jump. At least three successful trials were recorded for each participant.

Biomechanical data were collected using an electromagnetic tracking system (Ascension Technologies Inc., Burlington, VT, USA) integrated with a non-conductive force

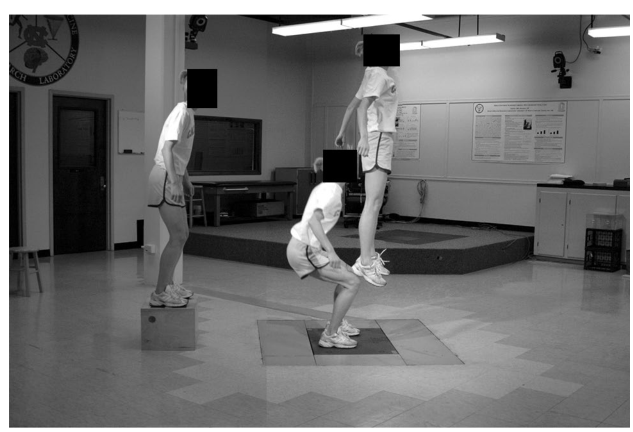


Fig. 1 Double leg jump landing

plate (Bertec Co., Columbus, OH, USA) and controlled using the MotionMonitor Software (Innovative Sports Training, Inc., Chicago, IL, USA). Prior to completion of the double leg jump-landing, all participants were instrumented so that electromagnetic sensors were affixed to the shank and thigh of the test leg, and pelvis. The positions of the medial and lateral malleoli, medial and lateral femoral epicondyles, and the anterior superior iliac spines relative to the segment sensors were recorded using a moveable sensor. The ankle and knee joint centers were estimated as the midpoints between the malleoli and femoral epicondyles, respectively. The hip joint center was estimated based on the location of the anterior superior iliac spines according to the Bell method [3]. A segment-link model of the shank, thigh and pelvis was developed based on these points, with the shank segment defined by the ankle and knee joint centers and the shank sensor, the thigh segment defined by the knee and hip joint centers and the thigh sensor, and the pelvis by the anterior superior iliac spines and the pelvis sensor. Local right-handed axis systems were embedded in each segment to describe position and orientation. Knee and hip joint angles were defined as the shank position relative to the thigh and thigh position relative to the pelvis, respectively. Joint angles at each were calculated using an Euler sequence with first rotation defining flexion/extension, second rotation defining valgus/varus or adduction/abduction, and third rotation defining internal/external rotation.

Kinematic and kinetic data were sampled at frequencies of 144 Hz and 1444 Hz, respectively. All kinematic data were filtered using a 4th order low pass Butterworth filter (14.5 Hz), and exported using the MotionMonitor software (Innovative Sports Training, Inc., Chicago, IL, USA).

For the purposes of this study we were interested in describing change in the inter-limb coordination of hip and knee motion prior to and following ACL injury and ACLR during a double leg jump-landing task. The time period of landing was defined as initial ground contact—vertical ground reaction force first exceeded 10 N—to maximum knee flexion. Time series data for hip and knee angles in all three planes were extracted for each trial during the landing phase and normalized to 101 data points and used to form angle-angle plots of the joint interactions of interest.

Angle-angle plots were generated to describe the relative motion between the hip and knee joints in the sagittal, frontal, and transverse planes. Plots were generated with hip kinematics on the horizontal axis and knee kinematics on the vertical axis. Inter-limb coordination was quantified as the mean coupling angle between the hip and knee based on techniques previously used by Heiderscheit et al. [9]. Using these conventions, an average coupling angle value of 45° represents equal relative motion between the two joints, a value greater than 45° represents greater relative motion of the knee, and a value less than 45° represents greater relative motion of the hip. This procedure was completed for each subsequent data point of the angle–angle plot and the mean of the values across the landing were calculated and averaged across the three trials. All calculations were performed using a customized MATLAB program (Mathworks, Inc., Natick, MA, USA).

Three, 3 × 2 [Group (ACLR-INJ, ACLR-UNIJ, Control) × Time (baseline, follow-up)] mixed model analyses of covariance (sex) were performed to determine the effect of ACL injury and ACLR on inter-limb coordination. Post hoc analyses consisted of Tukey's HSD and were implemented for any significant interaction effects. A priori alpha levels of 0.05 were set for all analyses (IBM SPSS v19, SPSS, Inc., an IBM Company, Chicago, IL, USA).

Results

Demographics and anthropometrics for each group at baseline and follow-up are summarized in Table 1. The number of years between baseline and follow-up were 2.94 (SD 0.54) for the ACLR-INJ group, 3.42 (SD 0.49) for the ACLR-UNINJ group, and 2.94 (SD 0.49) for the Control group. The number of years from baseline to ACL injury were 1.01 (SD 0.43) for the ACLR-INJ group and 1.46 (SD 0.73) for the ACLR-UNINJ group. The number of days from ACL injury to ACLR surgery were 33.70 (SD 20.29) for the ACLR-INJ group, and 40.39 (SD 24.92) for the ACLR-UNINJ group. The number of years from ACLR surgery to follow-up were 1.83 (SD 0.57) years for the ACLR-INJ group, and 1.89 (SD 0.67) for the ACLR-UNINJ group.

We observed a significant Time × Group interaction for inter-limb coordination of the hip and knee in the transverse plane (Hip and Knee Transverse Plane: $F(2,65) = 4.398$, $P = 0.016$). There were no differences among groups at

Table 1 Group demographics and anthropometrics at baseline and follow-up (mean ± SD)

	Baseline			Follow-Up		
	ACLR-INJ	ACLR-UNINJ	Control	ACLR-INJ	ACLR-UNINJ	Control
Age (years)	18.64 ± 0.50	18.52 ± 0.58	18.47 ± 0.46	21.42 ± 0.79	21.47 ± 0.77	20.95 ± 0.73
Height (cm)	174.10 ± 7.31	170.06 ± 9.26	172.05 ± 8.65	174.29 ± 7.56	170.05 ± 9.13	172.16 ± 8.71
Mass (kg)	72.64 ± 9.48	68.99 ± 10.93	69.16 ± 11.47	76.25 ± 9.95	72.87 ± 12.78	72.35 ± 12.37

baseline. The ACLR-INJ group, however, had a significant decrease in the mean coupling angle from baseline [54.85° (SD 6.96°)] to follow-up [47.97° (SD 6.64°)]. Specifically, this change represents less knee rotation of the injured leg after ACL injury ACLR. This was significantly less than the Control group at follow-up, but no different than the ACLR-UNINJ group.

We observed no other significant interactions: Hip and Knee Sagittal Plane [$F(2,65) = 0.850$, $P = 0.432$], Hip and Knee Frontal Plane [$F(2,65) = 0.247$, $P = 0.782$]. Descriptive statistics for each variable of interest are provided in Table 2.

Discussion

This is the first report—to our knowledge—that has captured measures of inter-limb coordination prior to and following ACL injury and ACLR. Our primary finding was that changes in inter-limb coordination between the hip and knee caused by ACL injury and ACLR were isolated to the transverse plane of the injured leg, causing constrained knee rotation. We also observed that sagittal and frontal plane inter-limb coordination was unaltered by ACL injury and ACLR; providing initial evidence as to why ACL injury and ACLR causes changes in kinematics of both the knee and hip [8].

The direction of change we observed in the mean coupling angle indicates a decrease in the amount of knee rotation relative to hip rotation, or more equal relative motion between the hip and knee. We observed these changes in transverse plane inter-limb coordination for the ACLR-INJ group despite previously observing no changes in peak kinematic values for hip or knee rotation for this group [8]. Therefore, inter-limb coordination was able to detect changes associated with increased risk for the development of osteoarthritis. This information would be lost if kinematics of the hip and knee were assessed independently as we were previously unable to observe changes in hip or knee rotation when these peak kinematic values were analyzed in isolation [8].

This observation is a tentative first observation but may be important, as alterations in knee rotation observed following ACL injury and ACLR have been proposed to influence loading of articular cartilage and the risk for the development of osteoarthritis [1]. Mean coupling angle provides a general measure of the relative inter-limb coordination across the entire landing phase of the double leg jump landing. We have included angle-angle plots for the ACL-INJ group at baseline (Fig. 2) and follow-up (Fig. 3) to supplement these measures and better characterize the shift in inter-limb coordination. At baseline, it appears that a majority of the initial transvers plane motion during landing was produced by the knee for this group. This increase in knee rotation is present for the plot at follow-up as well, but the rise is not as steep—indicating greater accompanying hip rotation. This may represent a loss of independence of knee rotation as a result of ACL injury and ACLR.

We are unable at this point to determine if our observations are the result of alterations in motor control and neuromuscular factors or the result of surgical procedures which would help direct future interventions. Differences in the magnitude of knee rotation—rotation of the tibia relative to the femur—among those with prior ACL injury and ACLR have been previously reported though [5, 6, 18–20, 23, 26, 27]. These differences have included observations of decreased internal rotation [6, 26, 27] or greater external rotation offset [23] and increased tibial internal rotation [5, 18, 19]. Cadaveric studies have also demonstrated that tibial rotation may not be restored following ACLR [29] and is particularly sensitive to femoral tunnel placement, with more oblique tunnel placements allowing for more similar rotational patterns of an intact knee [11, 21]. Future work should address the cause of this observed change in transverse plane inter-limb coordination between the hip and knee.

Table 2 Average coupling angle (º) for each group at baseline and follow-up [mean (SD), (95% confidence intervals)]

	ACLR-INJ		ACLR-UNINJ		Control	
	Baseline	Follow-Up	Baseline	Follow-Up	Baseline	Follow-Up
Hip and knee Sagittal plane	53.99 ± 6.79, (50.08, 57.91)	55.32 ± 8.96, (50.16, 60.49)	54.76 ± 6.75, (51.67, 57.85)	51.64 ± 8.90, (47.56, 55.71)	53.76 ± 6.75, (51.57, 55.95)	52.48 ± 8.90, (49.60, 55.36)
Hip and knee frontal Plane	44.31 ± 7.34, (40.07, 48.54)	44.52 ± 7.48, (40.21, 48.83)	43.42 ± 7.30, (40.07, 46.76)	41.29 ± 7.43, (37.89, 44.70)	43.23 ± 7.29, (40.86, 45.59)	42.26 ± 7.42, (39.86, 44.67)
Hip and knee Transverse plane	54.85 ± 6.96*, (50.84, 58.86)	47.97 ± 6.64*, (44.15, 51.80)	54.98 ± 6.91, (51.81, 58.14)	53.46 ± 6.60, (50.44, 56.48)	52.76 ± 6.91, (50.52, 55.00)	54.78 ± 6.59, (52.64, 56.92)

Values for descriptive statistics are based on sex entered as a covariate in the statistical model at a value of 0.52;

* indicates a significant difference between Hip and knee transverse plane inter-limb coordination for the ALCR-INJ group ($P < 0.05$)

Fig. 2 Ensemble angle-angle plot of hip transverse plane–Knee transverse plane for the ACLR-INJ group at baseline

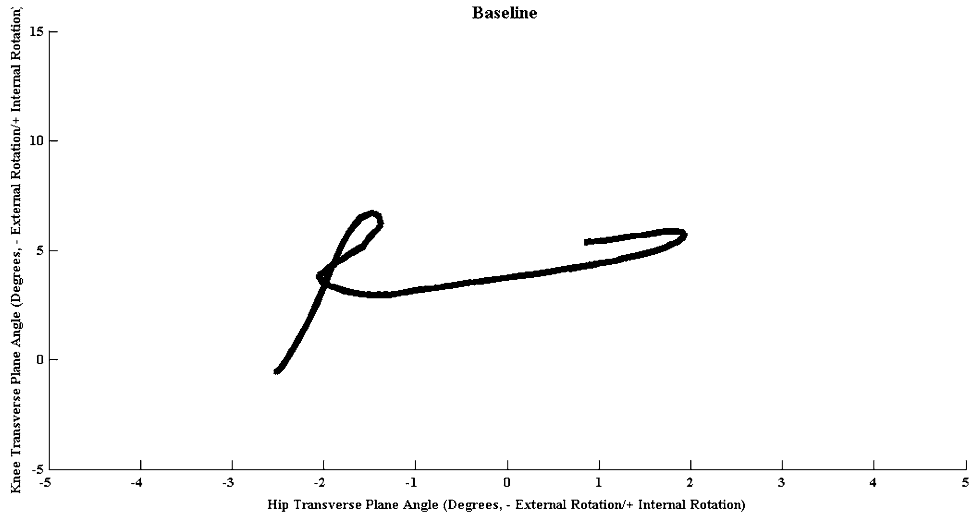
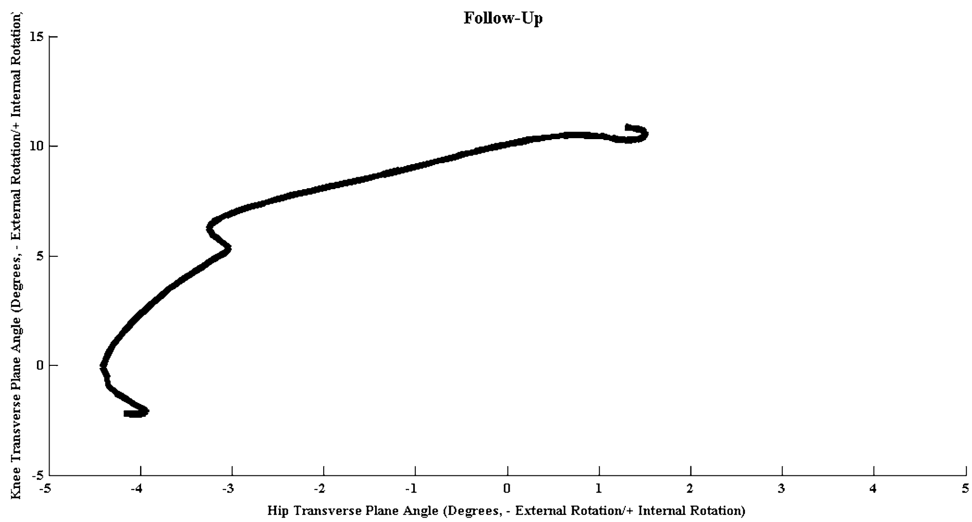


Fig. 3 Ensemble angle-angle plot of hip transverse plane–knee transverse plane for the ACLR-INJ group at follow-up



Despite observations of altered inter-limb coordination in the transverse plane, we did not observe changes in inter-limb coordination in the sagittal or frontal plane as a result of ACL injury and ACLR. This is of particular importance because we know from our previous observations that ACL injury and ACLR caused alterations in the frontal plane kinematics for this cohort and changes occurred in both the hip and knee of the injured and uninjured leg [8]. We previously observed ACL injury and ACLR caused increases in hip adduction and knee valgus for both the ACLR-INJ and ACLR-UNINJ groups [8]. These combined observations indicate that despite an injury that was isolated to the knee, inter-limb coordination between the hip and knee was preserved resulting in alterations in kinematics at both joints. This indicates that endeavors to identify and correct movement patterns that may increase a patient's risk for injury post-ACLR must consider more than just correcting movement at the knee and focus on more than just one kinematic variable. Because inter-limb coordination is persevered and the amount of relative motion between joints is unchanged, then we can expect to see changes in the magnitude of motion at multiple joints. That is, if ACL injury and ACLR causes an increase in knee valgus then we can expect to observe a subsequent increase in hip adduction as well. Likewise, if we observe a decrease in knee flexion then there may also be a subsequent decrease in hip flexion.

Because only three trials were collected at baseline for the initial JUMP-ACL Study, we had a limited number of trials to assess inter-limb coordination. Previous observations of altered inter-limb coordination following ACL injury and ACLR have been reported [4, 10, 24] but these studies employed more sensitive techniques that require multiple trials of continuous movement. Differences in variability of inter-limb coordination between the thigh and shank in the transverse plane were previously observed between healthy males and females by Pollard et al. [17] during a side-step cutting task. This analysis though used a greater number of trials and assessed the variability of inter-limb coordination.

We feel that the novelty of our study—assessing inter-limb coordination prior to and following ACL injury—still provides valuable information.

Our study is not without limitations that must be acknowledged to enhance interpretation of our findings. The first being that we did not control for mechanism of injury, graft selection, or concomitant joint injury when identifying ACL injured participants for inclusion in this study. Because of the unique opportunity to compare inter-limb coordination measures prior-to and following ACL injury and the limited available population for repeat testing, we utilized an open inclusion criteria for our ACL injured groups. While a methodological limitation, this approach also increased the heterogeneity of our sample and also increased the external validity of our findings to a broader population of those with ACL injury and ACLR.

Our findings indicate that ACL injury and ACLR cause a constraint in rotation between the hip and knee, caused by a reduction in knee rotation of the injured leg. This observation provides tentative evidence to help explain possible mechanisms that lead to osteoarthritis post-ACLR, and highlights the importance that assessment of inter-limb coordination has in assessing these patients. In addition, ACL injury and ACLR change kinematics at both the knee and hip and this may be explained in part by the preservation of inter-limb coordination between the two joints, as it was unchanged in the sagittal and frontal plane. This information may help drive new endeavors to improve movement and reduce the risk for re-injury post-ACLR.

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Data Availability Not applicable.

Code Availability Not applicable.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Ethics Approval Institutional Review Board (IRB) approval was granted for all procedures.

Consent to Participate Written informed consent was received from all participants following IRB guidelines and approvals.

Consent for Publication Written informed consent was received from all participants following IRB guidelines and approvals.

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