# Back to normal symmetry? Biomechanical variables remain more asymmetrical than normal during jump and change of direction testing 9 months after anterior cruciate ligament reconstruction


## Abstract

***Background***

Following anterior cruciate ligament reconstruction (ACLR), athletes have demonstrated performance asymmetries compared to healthy cohorts but little research has investigated if biomechanical asymmetries are also different during jump and change of direction (CoD) tasks between groups.

***Purpose***

To identify if differences in magnitude of asymmetry of biomechanical and performance variables exist between these groups.

***Study Design***

Case-Control Study

***Methods***

Analysis of 156 male subjects nine months after surgery and 62 healthy subjects was conducted. 3D motion capture and analysis was carried out on double leg drop jump (DLDJ), single leg drop jump (SLDJ), single leg hop for distance (SLHD) and planned and unplanned change of direction (CoD). Asymmetry between limbs was calculated for each variable using root mean square difference between limbs. Statistical parametric mapping was used to identify the between group differences in magnitude of asymmetry of performance and biomechanical variables.

***Results***

There were differences in asymmetry of biomechanical variables across all jump and CoD tests with greater asymmetries in the ACLR group. The majority of differences between groups were in the sagittal and frontal planes with more differences found in the jump than CoD tests. The SLDJ demonstrated large differences in performance asymmetry (effect size 0.94) with small differences for both CoD tests (0.4) and none for SLHD.

***Conclusion***

This study demonstrated greater asymmetry of biomechanical variables 9 months after ACL reconstruction compared to healthy subjects across all tests suggesting insufficient rehabilitation of normal symmetry. This highlights the importance of including biomechanical as well as performance variables when assessing rehabilitation status after ACLR.

**Key Terms:** Anterior Cruciate Ligament, Return to Play, Biomechanics, Asymmetry

**What is known on the subject:**

Asymmetry of performance measures during jump and change of direction testing have been used to assess rehabilitation status and readiness to return to play after anterior cruciate ligament reconstruction (ACLR) and differences have been demonstrated between those that have had surgery and healthy cohorts. Differences in biomechanical variables between limbs have been demonstrated after ACLR but the magnitude of this asymmetry has not been compared with healthy cohorts to identify asymmetries that are greater than normal.

**What this study adds to existing knowledge:**

This study demonstrates greater biomechanical asymmetry across jump and change of direction tests 9 months after ACLR compared to healthy subjects. The differences between groups were primarily in variables in the sagittal and frontal planes and were found at different stages of stance. There were greater differences in asymmetry for biomechanical variables than performance variables suggesting that both biomechanical and performance analysis of jump and change of direction testing may be appropriate when assessing rehabilitation status after ACLR.

## Introduction

Anterior cruciate ligament reconstruction (ACLR) is recommended for athletes who have suffered ACL injury and are intending to return to sports involving landing, pivoting and change of direction[28]. Asymmetry between limbs with respect to strength, power and movement patterns develops after ACL injury and subsequent reconstruction[7, 9, 22, 25, 43, 45] and has been reported to persist after athletes have returned to play.[25, 39, 40, 43] Jump, landing and change of direction (CoD) tests are commonly used to assess rehabilitation status and to inform RTP decision making after ACLR.[8, 11, 21, 26] These tests assess the restoration of lower limb power and explosiveness in movements commonly performed in field sports and replicate the most common ACL injury mechanisms.[11, 21, 29, 41] To guide rehabilitation and optimise RTP outcomes, asymmetry in performance (jump height, jump length, change of direction [CoD] times) of healthy subjects (usually within 10% between-limb difference) has been used previously as a benchmark for completed rehabilitation.[1, 3, 21, 26, 37, 43] The achievement of a normal level of performance asymmetry (i.e. <10%) across a battery of tests has been associated with a reduced risk of subsequent injury after ACLR.[11, 21] However assessing asymmetry of performance measures alone is limited as the movement strategy used to achieve the result is not analysed and to date no comparison of biomechanical asymmetry between ACLR and healthy subjects exists in the literature.

Biomechanical differences between limbs have been demonstrated throughout the kinetic chain during jump, gait, running and CoD tests after ACLR.[10, 12, 15-17, 30] These differences are particularly evident in the sagittal (knee extension angle and moment) and frontal planes (knee valgus moment) of the knee joint.[10, 12, 15, 30] Previous research has demonstrated between limb differences in biomechanical variables during jump testing (double leg drop jump [DLDJ], single leg drop jump [SLDJ] and single leg hop for distance [SLHD]) as well as CoD testing (planned and unplanned 90° cuts) nine months after ACLR.[10, 16, 17, 31] However it is not known if this level of asymmetry reflects incomplete rehabilitation and if the magnitude of asymmetry is different compared to healthy subjects. Examining differences in asymmetry between groups in both jump and CoD tests may provide a more complete analysis of return to normal function after ACLR and identify biomechanical as well as performance measures to be targeted during rehabilitation that may influence outcomes after RTP.

The aim of this study was to identify differences in asymmetry of biomechanical and performance variables during jump and CoD testing between athletes who were 9 months after ACLR and a matched healthy cohort. Our hypothesis was that there would be greater asymmetry across the kinetic chain for all the tests in the ACLR group in the sagittal and frontal planes.

**Methodology**

One hundred and fifty six eligible subjects were recruited to form the ACLR group in this case-control study. They were recruited after initial diagnosis and prior to surgery from January 2014 until October 2015. Subjects were part of a longer term research project with physical testing at 6 and 9 months post operatively and via e-mail at annual follow up afterwards. A matched healthy cohort (NORM) of 62 male subjects were recruited from multidirectional field sports teams locally from December 2014 to August 2016. This study received ethical approval and was a registered clinical trial (NCT02771548).

Inclusion criteria for the ACLR group included male, multidirectional field sports athletes with the intention of returning to same level of sporting participation post-surgery. Subjects were to be aged between 18-35, undergoing primary ACL reconstruction and tested approximately 9 months after surgery (8-10 months inclusive). Subjects who had multiple concurrent ligament reconstructions, previous ACL surgery, meniscal repair, full thickness chondral injury or did not intend returning to the same level of multidirectional sport were excluded from the study. All subjects in ACLR group had a bone patellar tendon bone graft or hamstring graft (semi-tendinosis and gracilis) from the ipsilateral side during surgery. After surgery, all subjects underwent an accelerated rehabilitation protocol with weight bearing as tolerated on crutches for two weeks followed by a progressive strengthening and neuromuscular control programme. The program progressed to include power and plyometric drills as competency progressed before advancing to linear running and CoD drills as competency and knee symptoms allowed. Due to the geographic spread of subjects, rehabilitation was supervised by their local physiotherapist and they were reviewed with their orthopaedic surgeon at 2 weeks, 3 months and 6-9 months post surgery. The NORM cohort excluded anyone who did not play multidirectional field sport, those with previous ACL injury, previous knee injury that required surgery and those who had any lower limb injury in the previous 12 weeks. Both groups were matched for age, sex, height and mass. Informed written consent was received from all subjects prior to participation. All testing took place in a 3D biomechanics laboratory. Subjects undertook a standardised warm-up: a 2 minute jog, 5 bodyweight squats, 2 submaximal and 3 maximal double leg countermovement jumps. The testing protocol included the DLDJ from 30cm, SLDJ from 20cm, SLHD and 90° planned and unplanned CoD. All the tests have been described previously[16, 17] and were carried out in sequence to allow increasing dynamic challenge throughout the testing process. Each subject underwent two sub-maximal practice trials of each movement before test trials were captured. A 30 second recovery was taken between trials. Three valid attempts (maximal effort and full foot contact on force plate) were recorded for each limb. Each of the tests were explained to the subjects in advance and they could decline being tested on any test in the sequence if they did not want, or were not able, to carry out the test. The assessor could stop testing at any point if they felt the subject could not carry out the test properly or without injury. The non-ACLR limb and the dominant limb (the limb with which the subject stated they could kick a ball furthest) were assessed first for each of the tests for the ACLR and NORM groups respectively. The mean results for the 3 valid repetitions was used for all variables.

Kinetic and kinematic data were collected using an eight-camera motion analysis system (Bonita-B10, Vicon, UK) filming at 200Hz, synchronized with two force platforms (BP400600, AMTI, USA) sampling at a frequency of 1000Hz, recording motion data from 24 reflective markers (14mm diameter) and ground reaction forces (Vicon Nexus 1.8.5), which were low-pass filtered using a fourth-order Butterworth filter (cut-off frequency of 15Hz)[19]. Subjects wore their own athletic footwear while reflective markers were secured using tape, at bony landmarks on the lower limbs, pelvis and trunk as per the Plug-in-Gait marker set[23]. Standard inverse dynamics analysis was used to calculate kinetic variables (reported as internal moments) at the ankle, knee and hip. All kinetic variables were normalized to body mass. Time to perform the 90° CoD was recorded using speed gates (Smartspeed, Fusion Sport, Chicago, Illinois, USA) with a trigger from the start line and exit gate 2 meters to the left and right of the force plates to indicate the end of the maneuver. A custom MATLAB program (MathWorks Inc, Natick, Massachusetts, USA) was used for processing and calculating the trunk to pelvis and foot to pelvis angles in the transverse plane[16] as well as jump height (calculated by impulse-momentum) and jump length (distance from heel marker at start to landing spot).The program also calculated the distance from the COM to the ankle and knee joint in all 3 planes using the direction of the joint and the global system as the reference.[16] Kinetic and kinematic analysis was carried out for the stance phase of each of the jumps and CoD tests (defined by the ground reaction force [GRF] > 20N) apart from the SLHD where the test finished on the force plate so analysis was carried out to the end of the eccentric phase of landing (from GRF > 20N until COM power equalled zero). Curves were normalized to 101 frames and landmark registered[38] to when centre of mass power reached zero in the Z axis on landing for all tests apart from the SLHD which was normalised to maximum peak power during eccentric phase. This process aligned the onset of the eccentric phase to 50% of the movement cycle across subjects to ensure an appropriate comparison of neuromuscular characteristics between limbs and subjects during continuous waveform analysis. Subjects random tests were excluded where valid trials were not available for analysis due to missing or invalid kinetic (full foot contact not made on the force plate) or kinematic (missing marker) data after processing. Differences in age, weight and height between groups were calculated using an independent t-test (SPSS, Version 21.0, IBM Corp, Armonk, New249  York, U.S.A.). The magnitude of asymmetry between limbs was calculated using the root mean square difference between the dominant and non-dominant limb for the NORM group and the ACLR limb and the non-ACLR limb for the ACLR group for the performance and at every percentage of stance for the biomechanical variables[4]. Difference in asymmetry of performance (jump height and length and time to perform CoD) between the NORM and ACLR groups was examined using

Statistical Parametric Mapping (SPM; 0d, non-parametric unpaired t test). To determine magnitude of significant differences, Cohen's D effect size was calculated (d>0.2-0.5 = small; d>0.5-0.79 = medium; d>0.8 = strong) [6]. For the biomechanical variables the magnitude of asymmetry for each group was plotted in a point by point manner throughout stance and difference in asymmetry between ACLR and NORM groups was examined using SPM (1d non-parametric unpaired t test)[32]. The mean effect size was reported across identified phases with significant differences, with phases with Cohen's D smaller than 0.5 excluded. Data processing and statistical parametric mapping were performed using MATLAB (R2015a, MathWorks Inc., USA). The time points between which there was a significant difference in asymmetry between both groups, the mean effect size and mean magnitude of asymmetry for both groups across that phase were reported.

**Results**

There was no significant difference between the 62 subjects in the NORM group and the 156 subjects in the ACLR group with respect to age (24.7 years +/- 3.9 vs 24.8 years +/- 4.2; p = 0.87), height (183cm +/- 6.2 vs 180cm +/- 11.8; p = 0.06) and weight (82.9Kg +/- 9 vs 84.5Kg +/- 15.6; p = 0.43). The ACLR group was tested 9.4 months (+/- 0.7) after surgery. There were valid trials suitable for analysis for 58 NORM and 145 ACLR for DLDJ, 57 NORM and 145 ACLR for SLDJ, 57 NORM and 137 ACLR for SLHD, 54 NORM and 137 ACLR for the planned and 48 NORM and 134 ACLR for the unplanned CoD. Graphs presented in the results are for the variable with the largest effect size difference for each test with graphs for all the reported variables included in Appendix A. Results in each of the tables are ordered with variables with largest effect size first.

***Double Leg Drop Jump***

There was a significant difference in asymmetry between the ACLR and NORM groups for a number of kinetic and kinematic variables with greater asymmetry in the ACLR group for each variable (Table 1; Appendix A). For the GRF, there was greater asymmetry (% of stance; effect size[ES]) in vertical (35-100%; 0.71; Figure 1), medial (95-100%; 0.62) and posterior directions (67 – 85% and 90-100%; 0.6 and 0.62) in the ACLR group compared to the NORM group. At the ankle, there was greater asymmetry in eversion moment (94-100%; 0.62), plantarflexion moment (70-99%; 0.59) and external rotation moment (16-80%; 0.51). At the hip there were greater differences in the extension moment in early stance (16-26%; 0.6) and flexion angle in later stance (94-100%; 0.57). At the knee, there was greater asymmetry of knee valgus moment in the ACLR group through most of middle of stance (15-78%; 0.5).

Table 1. Difference in asymmetry between NORM and ACLR groups during double leg drop jump

**Differences in Asymmetry betweeen NORM and ACLR groups - Double Leg Drop Jump**

| Variable | Direction | Start | End | Mean NORM (+/- STD) | 95% CI | Mean ACLR (+/- STD) | 95% CI | Effect Size |
|---|---|---|---|---|---|---|---|---|
| Ground Reaction Force (N/Kg) | Vertical | 35 | 100 | 1.3 (1.3) | 1.2 to 1.5 | 2.6 (0.9) | 2.4 to 2.9 | 0.71 |
| Ground Reaction Force (N/Kg) | Medial | 95 | 100 | 0.04 (0.03) | 0.01 to 0.06 | 0.07 (0.03) | 0.05 to 0.07 | 0.62 |
| Ankle Moment Frontal (Nm/Kg) | Eversion | 94 | 100 | 0.07 (0.05) | 0.03 to 0.1 | 0.15 (0.12) | 0.13 to 0.18 | 0.62 |
| Ground Reaction Force (N/Kg) | Posterior | 90 | 100 | 0.07 (0.05) | 0.05 to 0.1 | 0.12 (0.05) | 0.11 to 0.14 | 0.6 |
| | | 67 | 85 | 0.28 (0.21) | 0.27 to 0.3 | 0.47 (0.1) | 0.42 to 0.52 | 0.57 |
| Hip Moment Sagittal (Nm/Kg) | Extension | 16 | 26 | 4.3 (2.1) | 4.1 to 4.6 | 7.8 (2.3) | 7 to 8.6 | 0.6 |
| Ankle Moment Sagittal (Nm/Kg) | Plantarflexion | 70 | 99 | 1.7 (1.1) | 1.4 to 2 | 3.1 (1.3) | 2.8 to 3.4 | 0.59 |
| Hip Angle Sagittal (º) | Flexion | 94 | 100 | 2.2 (1.9) | 2.1 to 2.3 | 3.5 (0.3) | 3.2 to 3.9 | 0.57 |
| Ankle Moment Transverse (Nm/Kg) | External Rotation | 16 | 80 | 2.3 (2) | 2.2 to 2.5 | 3.7 (1.2) | 3.3 to 4.2 | 0.51 |
| Knee Moment Frontal (Nm/Kg) | Valgus | 15 | 78 | 6.1 (5.3) | 5.8 to 6.5 | 9.2 (2.2) | 8.2 to 10.2 | 0.5 |

STD – standard deviation, NORM – normal , ACLR – anterior cruciate ligament reconstruction, CI – confidence interval, Kg – kilogram, N – newton, Nm – newton-metre, start/end –beginning/end % stance phase when the difference was greatest between limbs.

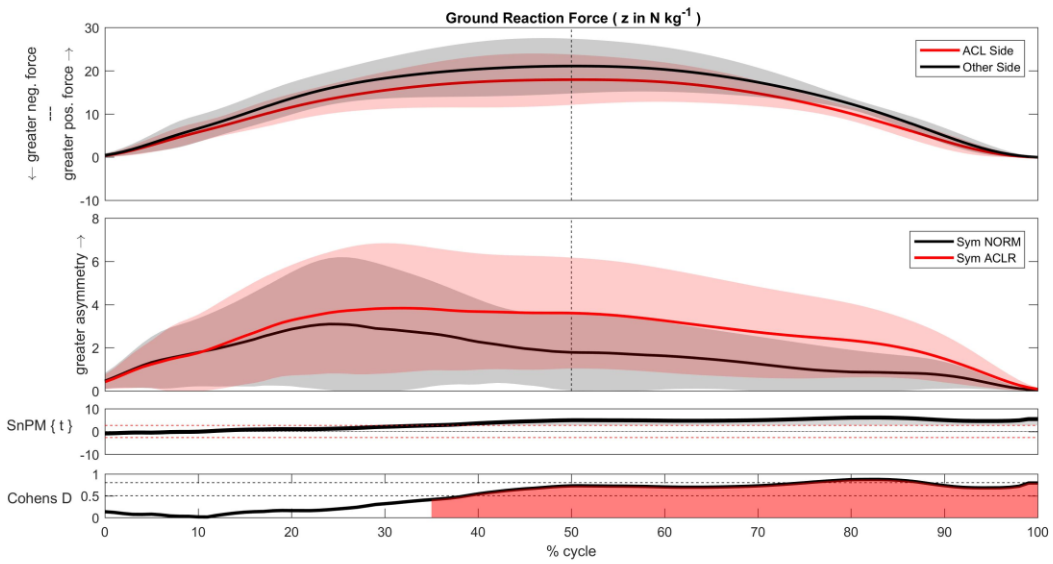


Figure 1. Difference in magnitude asymmetry of vertical GRF between NORM and ACLR groups during double leg drop jump. The top panel illustrates the mean and SD clouds for the ACLR (red) and non-ACLR limbs (black) in the ACLR group as a reference for the movement. The second panel illustrates the mean absolute asymmetry and SD clouds for the ACLR (red) and NORM (black) groups. The third panel illustrates the SPM{t} – the t-statistic as a function of time describing the difference between the two groups. The dotted red line and shaded portion of the SPM curve indicates $p<0.05$ and that a significant difference exists between the groups. The bottom panel illustrates the effect size as a function of time describing the magnitude of the effect. The dotted black line and shaded portion of the bottom panel indicates and average Cohen's d>0.5 with red indicating a strong effect size throughout that phase. The between-limb asymmetry was significantly different with a large effect size from 35-100% of stance, in the latter part of the eccentric phase until take-off. The ACLR group was more asymmetrical than the NORM group.

***Single Leg Drop Jump***

There was a significant difference in jump height asymmetry between the NORM and ACLR groups with greater asymmetry in the ACLR group (ES 0.94; Figure 2). The ACLR group had an average asymmetry of 3.2cm (+/- 1.8) between limbs while the NORM group had an asymmetry of 1.4cm (+/-1.3) between limbs. Where differences in asymmetry were found in the biomechanical variables, the ACLR group was more asymmetrical than the NORM group in all cases (Table 2). Medium effect size differences were evident in posterior (95-100%; 0.69), lateral (91-100%; 0.69) and vertical (42-88%; 0.67) GRF. Greater asymmetry was also found in knee flexion angle (17-78% and 92-100%; 0.61 and 0.71), posterior position of COM relative to knee(17-82%; 0.68) as well as knee extension moment (32-71%; 0.52) through the middle of stance phase in the ACLR group. In addition, hip flexion angle (91-100%; 0.61) at the end of stance phase and ankle external rotation moment (23-84%; 0.53) and plantarflexion angle (22-74%; 0.5) in the middle of stance phase were different between the two groups.

Table 2. Difference in asymmetry between NORM and ACLR groups during single leg drop jump

**Differences in Asymmetry betweeen NORM and ACLR groups - Single Leg Drop Jump**

| Variable | Direction | Start | End | Mean NORM (+/- STD) | 95% CI | Mean ACLR (+/- STD) | 95% CI | Effect Size |
|---|---|---|---|---|---|---|---|---|
| Knee Angle Sagittal (º) | Flexion | 17 | 78 | 3.6 (1.1) | 3.6 to 3.7 | 6.8 (0.9) | 5.9 to 7.6 | 0.61 |
| | | 92 | 100 | 2.77 (1) | 2.6 to 3 | 5.8 (1.1) | 5.1 to 6.4 | 0.71 |
| Ground Reaction Force (N/Kg) | Posterior | 95 | 100 | 0.06 (0.05) | 0.02 to 0.1 | 0.12 (0.05) | 0.11 to 0.14 | 0.69 |
| Ground Reaction Force (N/Kg) | Lateral | 91 | 100 | 0.09 (0.05) | 0.04 to 0.11 | 0.14 (0.05) | 0.13 to 0.16 | 0.69 |
| COM to Knee Sagittal (mm) | Posterior | 17 | 82 | 15.4 (6) | 15.1 to 15.8 | 30.3 (3.9) | 26.8 to 33.8 | 0.68 |
| Ground Reaction Force (N/Kg) | Vertical | 42 | 88 | 1.5 (0.8) | 1.3 to 1.6 | 2.7 (0.9) | 2.5 to 3 | 0.67 |
| Hip Angle Sagittal (º) | Flexion | 91 | 100 | 3.7 (0.8) | 3.6 to 3.7 | 6.2 (0.8) | 5.5 to 6.9 | 0.61 |
| Ankle Moment Transverse (Nm/Kg) | External Rotation | 23 | 84 | 2.6 (1) | 2.4 to 2.7 | 4.3 (1.1) | 3.8 to 4.8 | 0.53 |
| Knee Moment Sagittal (Nm/Kg) | Extension | 32 | 71 | 6.2 (2) | 6.0 to 6.3 | 9.7 (1.7) | 8.7 to 10.8 | 0.52 |
| Ankle Angle Sagittal (º) | Dorsiflexion | 22 | 74 | 3.5 (1.1) | 3.4 to 3.5 | 5.4 (0.7) | 4.8 to 6 | 0.5 |

COM – centre of mass, STD – standard deviation, NORM – normal , ACLR – anterior cruciate ligament reconstruction, CI – confidence interval, n/a – not applicable, sec – second, mm – millimetre Kg – kilogram, N – newton, Nm – newton-metre, start/end –beginning/end % stance phase when the difference was greatest between limbs.

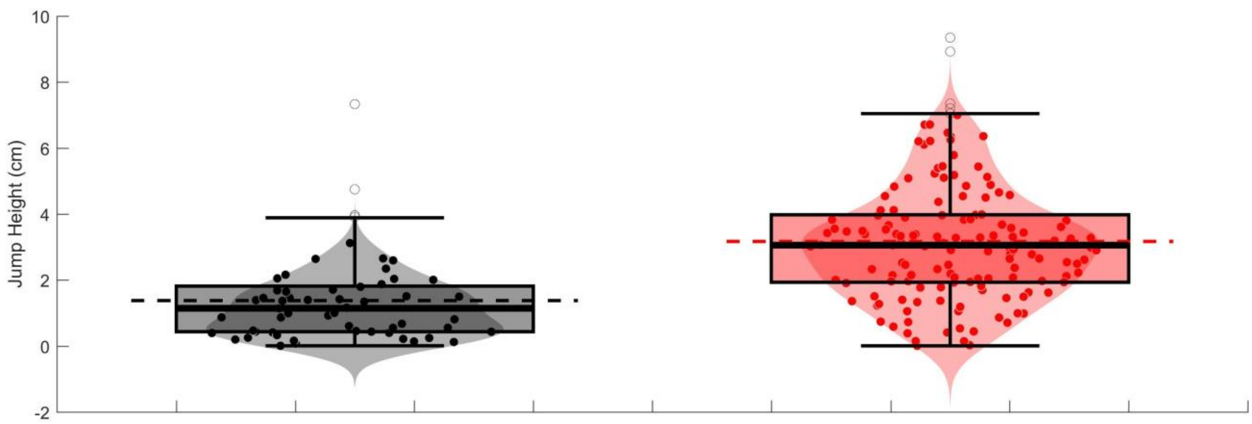


Figure 2 Difference in asymmetry of jump height between NORM (black) and ACLR (red) groups during single leg drop jump. This illustration is the combination of a violin plot and boxplot to aid the best representation of the data. The shaded area reports the kernel distribution of the data, while the dots represent the each subjects magnitude recorded. Overlaid is a boxplot with the box representing the 25th to 75th percentile. The whiskers describe the upper and lower limit of the data that is either the (IQR*1.5) + 75th percentile and (IQR*1.5) – the 25th percentile or the maximal and minimal value if these extremes are within then range of the IQR*1.5 +/- 75th and 25th percentile. The median of the data is represented by the solid line and the mean is represented by the dotted line. There was a large effect size difference in jump asymmetry between groups (ES 0.94) with greater asymmetry in the ACLR group.

***Single Leg Hop for Distance***

There was no significant difference in asymmetry of jump length between the two groups (p = 0.1; ES 0.23). There was greater asymmetry in the NORM group for ankle eversion moment during early stance (7-19%; 0.72; Table 3; Figure 3). All other reported variables demonstrated greater asymmetry in the ACLR group, mostly in the sagittal plane. There was a medium effect size difference between groups in posterior position of COM to knee (22-100%; 0.7), knee flexion angle (16-100%, 0.51), hip extension moment (35-43%, 56-69% and 87-100%; all 0.5) as well as ankle dorsiflexion angle (12-27% and 67-100%; both 0.5) through most of the eccentric phase of landing. There was also greater asymmetry in knee valgus moment (66-92%; 0.52) in the frontal plane in the ACLR group.

Table 3. Difference in asymmetry between NORM and ACLR groups during single leg hop for distance

**Differences in Asymmetry betweeen NORM and ACLR groups - Single Leg Hop for Distance**

| Variable | Direction | Start | End | Mean Normal (+/- STD) | 95% CI | Mean ACLR (+/- STD) | 95% CI | Effect Size |
|---|---|---|---|---|---|---|---|---|
| Ankle Moment Frontal (Nm/Kg) | Eversion | 7 | 19 | 1.15 (0.65) | 0.73 to 1.57 | 0.71 (0.5) | 0.62 to 0.81 | -0.72 |
| COM to Knee Sagittal (mm) | Posterior | 22 | 100 | 1.37 (1.31) | 20.4 to 20.9 | 3.2 (1.9) | 2.86 to 3.47 | 0.7 |
| Knee Moment Frontal (Nm/Kg) | Valgus | 66 | 92 | 6.4 (1) | 6.19 to 6.68 | 9.8 (0.7) | 8.7 to 10.9 | 0.52 |
| Knee Angle Sagittal (º) | Flexion | 16 | 100 | 4.3 (1.6) | 4.1 to 4.4 | 7.1 (1.7) | 6.2 to 8 | 0.51 |
| | | 35 | 43 | 6.7 (3.7) | 6.4 to 6.7 | 11 (2.4) | 9.7 to 12.4 | 0.51 |
| Hip Moment Sagittal (Nm/Kg) | Extension | 56 | 69 | 5.7 (2.3) | 5.4 to 6 | 9.6 (1.9) | 8.2 to 10.9 | 0.5 |
| | | 87 | 100 | 4.6 (1.3) | 4.5 to 4.7 | 7.35 (1.9) | 6.5 to 8.2 | 0.5 |
| Ankle Angle Sagittal (º) | Dorsiflexion | 12 | 27 | 3.7 (1.6) | 3.2 to 4.1 | 6 (3.1) | 5.3 to 6.7 | 0.5 |
| | Dorsiflexion | 67 | 100 | 3.9 (0.5) | 3.9 to 4 | 5.9 (0.5) | 5.2 to 6.6 | 0.5 |

COM – centre of mass, STD – standard deviation, NORM – normal , ACLR – anterior cruciate ligament reconstruction, CI – confidence interval, mm – millimetre, Kg – kilogram, Nm – newton-metre. * P-value for Jump length p = 0.1, start/end –beginning/end % stance phase when the difference was greatest between limbs.

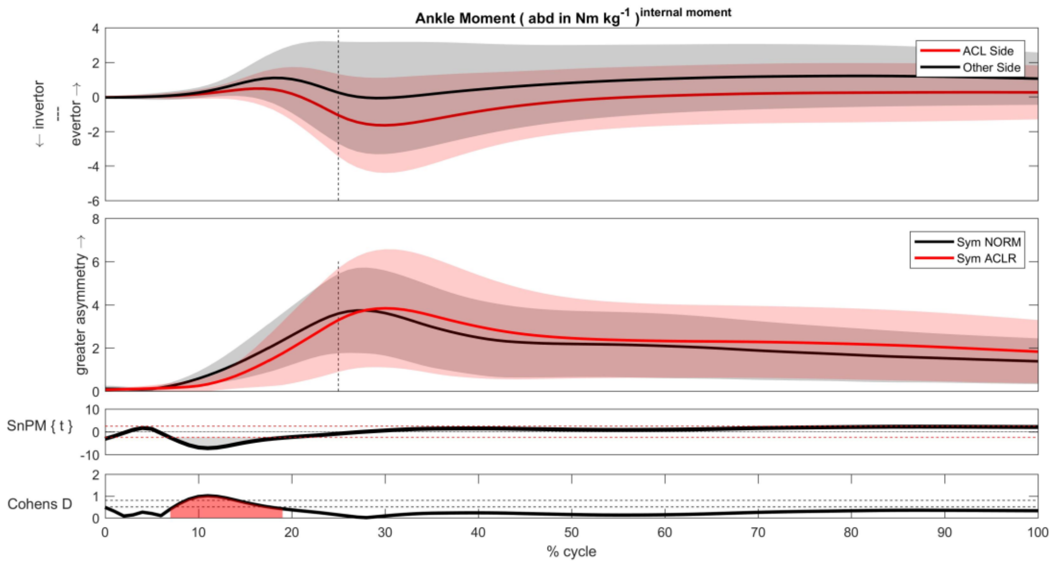


Figure 3. Difference in asymmetry of ankle eversion moment between NORM and ACLR groups during single leg hop for distance. The top panel illustrates the mean and SD clouds for the ACLR (red) and non-ACLR limbs (black) in the ACLR group as a reference for the movement. The second panel illustrates the mean absolute asymmetry and SD clouds for the ACLR (red) and NORM (black) groups. The third panel illustrates the SPM{t} – the t-statistic as a function of time describing the difference between the two groups. The dotted red line and shaded portion of the SPM curve indicates p<0.05 and that a significant difference exists between the groups. The bottom panel illustrates the effect size as a function of time describing the magnitude of the effect. The dotted black line and shaded portion of the bottom panel indicates and average Cohen's d>0.5 with red indicating a strong effect size throughout that phase. The between limb asymmetry was greater in the NORM group between 7-19% with a medium effect size (0.72).

### *90° Planned CoD*

In the planned CoD there was a significant difference in asymmetry of CoD times (p=0.004) between groups with greater asymmetry in the ACLR group (0.08 sec +/- 0.07) compared to the NORM group (0.05 sec +/- 0.04) however the magnitude of the difference had a small effect size (0.4). There was greater asymmetry in the ACLR group in all the GRF variables early in stance or at toe off (Table 4). This included vertical GRF (0-9% and 59-72%; 0.69 and

0.5; Figure 4), medial GRF (93-100%; 0.69) and posterior GRF (0-5% and 91-100%; 0.56 & 0.57). The ACLR group also demonstrated greater asymmetry for hip abduction moment after initial contact (0-5%; 0.55).

Table 4. Difference in asymmetry between NORM and ACLR groups during 90° planned cut

**Differences in Asymmetry betweeen NORM and ACLR groups - 90º Planned Cut**

| Variable | Direction | Start | End | Mean NORM (+/- STD) | 95% CI | Mean ACLR (+/- STD) | 95% CI | Effect Size |
|---|---|---|---|---|---|---|---|---|
| Ground Reaction Force (N/Kg) | Vertical | 0 | 9 | 0.91 (0.8) | 0.34 to 0.15 | 1.91 (1) | 1.64 to 2.18 | 0.69 |
| | | 59 | 72 | 1.22 (1.05) | 1.2 to 1.25 | 1.96 (0.36) | 1.7 to 2.2 | 0.5 |
| Ground Reaction Force (N/Kg) | Medial | 93 | 100 | 0.15 (0.13) | 0.05 to 0.2 | 0.29 (0.12) | 0.26 to 0.33 | 0.69 |
| Ground Reaction Force (N/Kg) | Posterior | 0 | 5 | 0.1 (0.09) | 0.05 to 0.36 | 0.19 (0.09) | 0.34 to 0.46 | 0.56 |
| | | 91 | 100 | 0.11 (0.09) | 0.06 to 0.14 | 0.18 (0.09) | 0.16 to 0.21 | 0.57 |
| Hip Moment Frontal (Nm/Kg) | Abduction | 0 | 5 | 3.89 (3.2) | 3.73 to 4.04 | 6.34 (1.42) | 5.64 to 7.05 | 0.55 |

STD – standard deviation, NORM – normal , ACLR – anterior cruciate ligament reconstruction, CI – confidence interval, N - newton, Kg – kilogram, start/end –beginning/end % stance phase when the difference was greatest between limbs.

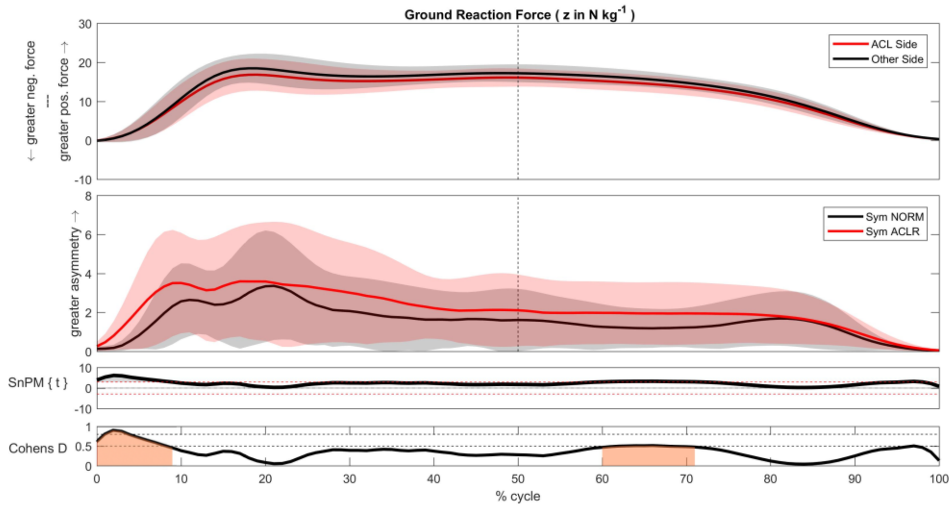


Figure 4. Difference in asymmetry in vertical ground reaction force between NORM and ACLR groups during 90° planned cut. The top panel illustrates the mean and SD clouds for the ACLR (red) and non-ACLR limbs (black) in the ACLR group as a reference for the movement. The second panel illustrates the mean absolute asymmetry and SD clouds for the NORM (black) and ACLR groups (red). The third panel illustrates the SPM{t} – the t-statistic as a function of time describing the difference between the two groups. The dotted red line and shaded portion of the SPM curve indicates p<0.05 and that a significant difference exists between the groups. The bottom panel illustrates the effect size as a function of time describing the magnitude of the effect. The dotted black line and shaded portion of the bottom panel indicates an average Cohen's d>0.5 with orange indicating a medium effect size in the two phases which met this threshold. There was greater asymmetry in vertical GRF in the ACLR group from 0-9% and 59-72%.

### *90° Unplanned CoD*

In the unplanned CoD there was a significant difference in asymmetry of CoD times (p=0.008) between groups with greater asymmetry in the ACLR group (0.09 sec +/- 0.08) compared to the NORM group (0.06 sec +/- 0.07) however the magnitude of the difference had a small effect size (0.4). There was greater asymmetry in the ACLR group for vertical GRF (0-5%; 0.69), medial GRF (94-100%; 0.62) and knee flexion angle (22-66%; 0.51).

However there was greater asymmetry in the NORM group for trunk on pelvis flexion angle (0-83%; -0.5).

Table 5. Difference in asymmetry between NORM and ACLR groups during 90° unplanned cut

**Differences in Asymmetry betweeen NORM and ACLR groups - 90º Unplanned Cut**

| Variable | Direction | Start | End | Mean NORM (+/- STD) | 95% CI | Mean ACLR (+/- STD) | 95% CI | Effect Size |
|---|---|---|---|---|---|---|---|---|
| Ground Reaction Force (N/Kg) | Vertical | 0 | 5 | 0.5 (0.41) | 0.08 to 0.91 | 1.08 (0.61) | 0.93 to 1.23 | 0.69 |
| Ground Reaction Force (N/Kg) | Medial | 94 | 100 | 0.16 (0.14) | 0.07 to 0.25 | 0.31 (0.15) | 0.27 to 0.34 | 0.62 |
| Knee Angle Sagittal (º) | Flexion | 29 | 66 | 5.6 (4) | 5.5 to 5.9 | 9.1 (2.3) | 8 to 10.1 | 0.51 |
| Thorax to Pelvis Angle Sagittal (º) | Flexion | 0 | 83 | 11.9 (12.3) | 11.6 to 12.2 | 7.4 (1.7) | 6.3 to 8.5 | -0.5 |

STD – standard deviation, NORM – normal , ACLR – anterior cruciate ligament reconstruction, CI – confidence interval, N - newton, Kg – kilogram, start/end –beginning/end % stance phase when the difference was greatest between limbs.

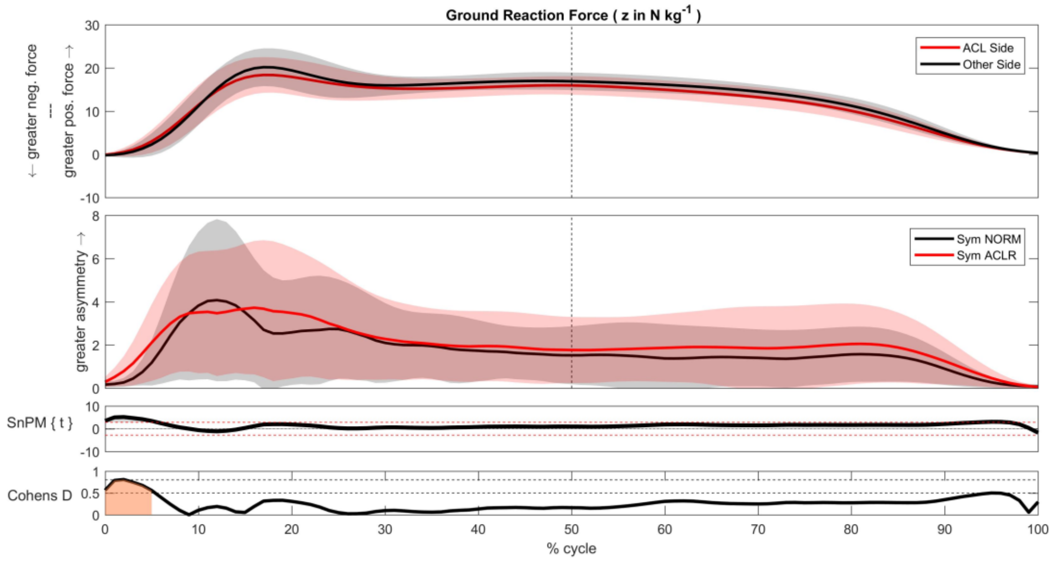


Figure 5. Difference in asymmetry during vertical ground reaction force between NORM and ACLR groups during 90° unplanned cut. The top panel illustrates the mean and SD clouds for the ACLR (red) and non-ACLR limbs (black) in the ACLR group as a reference for the movement. The second panel illustrates the mean absolute asymmetry and SD clouds for the NORM (black) and ACLR groups (red). The third panel illustrates the SPM{t} – the t-statistic as a function of time describing the difference between the two groups. The dotted red line and shaded portion of the SPM curve indicates p<0.05 and that a significant difference exists between the groups. The bottom panel illustrates the effect size as a function of time describing the magnitude of the effect. The dotted black line and shaded portion of the bottom panel indicates and average Cohen's d>0.5 with orange indicating a medium effect size throughout that phase. There was a difference in vertical ground reaction force between 0-5% with greater asymmetry in the ACLR group.

## Discussion

The aim of this study was to determine if there was a difference in the magnitude of asymmetry between a group of subjects 9 months after ACLR and a matched healthy control group. This was examined in biomechanical and performance variables during jump and CoD tests to identify variables to be targeted during rehabilitation that may influence outcomes after RTP. The results demonstrated that the largest difference in performance asymmetry was in the SLDJ, only small effect size differences were found for both CoD tests and no difference was found between groups in the SLHD. Differences in magnitude of asymmetry were evident in biomechanical variables across all of the tests. More variables indicated greater asymmetry in the jump tests than in the CoD tests. Differences in asymmetry primarily occurred in the sagittal and frontal planes and all but two variables indicated greater asymmetry in the ACLR group. These results suggest insufficient restoration of normal biomechanical symmetry 9 months after ACLR and that biomechanical asymmetry is an important consideration during jump and CoD testing to assess rehabilitation status after ACLR.

The use of asymmetry as a measure of rehabilitation status has been questioned as ACLR has been shown to affect the biomechanics of both the ACLR and non-ACLR limb.[7, 9] One of the challenges of the study was using an appropriate measure to calculate asymmetry. Calculations of asymmetry after ACLR typically see the ACLR limb value divided by the non-ACLR limb value.[11, 21] However this calculation has methodological challenges in healthy subjects where there is no obvious injured limb and therefore choosing a denominator, (i.e. right vs left, dominant vs non-dominant, preferred kicking leg vs preferred jumping leg) will produce different results and therefore change the results of the comparative analysis.[44] The use of root mean squared difference to calculate the overall magnitude of asymmetry is one method of dealing with this issue by removing the need to select as specific denominator and providing a magnitude of asymmetry which enables consistent comparison between groups/across studies.[4] Although the limb-direction of the asymmetry is not identifiable with this method, previous research on this cohort indicates which direction the asymmetry lies after ACLR.[16, 17]

Biomechanical asymmetries were reported across all the jump tests with most of the differences between groups found in the sagittal plane. Differences in variables between groups were over prolonged periods of stance (e.g. knee moments in the jump tests) or at the end of stance (e.g. medial GRF) rather than at specific discrete points in the stance phase (i.e. initial contact, peak knee flexion). The identification of these variables at different phases of stance highlights the importance of examining the entire waveform rather than a discrete points in this cohort. In the DLDJ and SLDJ, the ACLR group demonstrated greater asymmetry of GRF in all three planes than the NORM group with differences in vertical GRF through a large part of stance phase and with medial and posterior GRF during push off (Table 1, 2 and Figure 1). Previous research has demonstrated reduced GRF on the ACLR side compared to the non-ACLR side 9 months post-surgery.[14, 24, 39] The increased asymmetry may reflect offloading of the ACLR limb beyond that which is normally present due to insufficient rehabilitation. This has been suggested as a risk factor for primary ACL injury and also injury to the contralateral limb post ACLR.[34-36] It has been previously demonstrated that deficits in the ACLR limb, in particular in the quadriceps muscle group, can lead to differences in vertical GRF and hip and knee moments in the sagittal plane between limbs.[9, 40] These greater asymmetries in sagittal plane variables are evident in the DLDJ in hip extension moments during the eccentric phase and hip flexion angles and ankle plantarflexion moments at end of stance phase during push off. Similarly there was greater asymmetry in the SLDJ between groups in the sagittal plane in knee flexion angle, knee extension moment and ankle plantar flexion moment through stance phase and hip extension angle at the end of the stance phase. Greater asymmetry in the posterior distance of the COM to the knee in the ACLR group was found for both the SLDJ and SLHD with the SLHD also demonstrating greater asymmetry in knee flexion angle, hip extension moment and ankle dorsiflexion angle during the eccentric phase in the ACLR group. The difference in COM position to the knee between limbs after ACLR for jump tests has been demonstrated previously and suggested to reflect compensation for quadriceps strength and extensor capacity in the ACLR limb.[16] Given the consistent presence of sagittal plane differences between groups for all of the jump tests greater focus should be placed on this during rehabilitation.

Between-group differences in asymmetry were also evident in the frontal and transverse planes. The DLDJ demonstrated greater asymmetry in internal knee valgus moment and ankle external rotation moment through the middle of the stance phase in the ACLR group compared to NORM. The SLHD also demonstrated greater asymmetry in knee valgus moment in the ACLR group during the eccentric phase of landing although there was greater asymmetry in the NORM group for ankle eversion moment. Differences in knee valgus moment between limbs after ACLR has been demonstrated previously[30] and external knee valgus moment has been suggested to be a predictor of primary & secondary ACL injury and commonly present in ACL injury mechanism.[2, 13, 36] The combination of greater asymmetries in the ACLR group and the variables where those asymmetries are evident suggest insufficient rehabilitation to normal movement at 9 months post-surgery and the potential for increased injury risk to both ACLR or non-ACLR limb.

Fewer differences in asymmetry were found for the two CoD tests than for the jump tests despite previous research demonstrating between-limb differences during CoD 9 months after ACLR.[5] This may be due to greater asymmetry in the NORM group during CoD tests than jump tests as CoD tests are less constrained by their nature resulting in any differences with the ACLR group having smaller effect sizes. Both CoD tests demonstrated larger asymmetry in medial GRF at the end of stance and vertical GRF at the beginning of stance for the ACLR group compared to NORM. Greater asymmetry of vertical GRF, especially at initial contact when ACL injury most commonly occurs[20], may increase the injury risk for either the ACLR or non-ACLR limb.[14] The asymmetry medial GRF later stance may have contributed to the differences in timed CoD performance between groups for both CoD tests and reflect deficits in push off after ACLR. The planned CoD demonstrated greater asymmetry in hip abduction moment at initial contact in the ACLR group and the unplanned CoD demonstrated greater asymmetry in knee flexion angle, both of which have been associated with increased knee loading and ACL injury mechanism.[2] The thorax on pelvis flexion angle was the only variable that demonstrated greater asymmetry in the NORM group during unplanned CoD. The greater difference between NORM and ACLR asymmetries in the jump tests compared the CoD tests suggests jump testing may be more effective in identifying differences in biomechanical asymmetry compared to normal during the rehabilitation after ACLR.

The ability to regain symmetry of performance after injury is often used as an assessment for readiness to return to play after ACLR.[11, 21] Failure to reach appropriate levels of asymmetry has been demonstrated to lead to an increased risk of injury on return to sport.[11, 21, 33] In this study the largest difference in performance asymmetry between ACLR and NORM was in the SLDJ, with no difference in asymmetry of the SLHD jump length and small effect size differences in asymmetry time for both CoD tests. The SLDJ has not been included in previous studies examining outcomes after ACLR whereas there is widespread use in clinical practice and ACL literature of the SLHD[11, 18, 21, 29, 37, 42] and further research is required to assess the ability of SLDJ to predict successful outcome after rehabilitation. The ability to compensate for deficits between limbs during CoD has been demonstrated previously[27] therefore examining CoD times alone may not sufficiently assess the rehabilitation status of an athlete after ACLR. The presence of medium and large differences in biomechanical asymmetry despite small or no differences in performance asymmetry between the two groups suggests both biomechanical and performance variables should be included when assessing restoration of normal function after ACLR. This can be achieved in clinical practice through the use of 2D video analysis or force plates analysis which has increasing availability and affordability.

This study compared asymmetry in male athletes after ACLR with a matched healthy cohort. The findings may be different for other ACL groups such as females, non-multidirectional field athletes or young adolescent athletes which reduces the generalisability of the results to these cohorts. Given the potential differences in movement strategies and levels of asymmetry in these cohorts it was felt that a more controlled analysis would be to focus on a single gender cohort. The relevance or importance of the differences in asymmetry identified between the two groups on outcomes after ACLR is unknown. Although some of the differences between groups had small to large effect sizes, the magnitude of the differences for some variables was very small (i.e. difference in mean asymmetry of CoD time for both tests was 0.03 seconds) and the meaningfulness of these small differences will have to be explored further. In addition a number of different joints and variables demonstrated differences but their relevance to outcomes is unknown. Future studies should investigate the influence of biomechanical asymmetries after ACLR on return to play and re-injury outcomes as well as identifying what normal asymmetry is in healthy subjects and its relationship with ACL injury risk.

**Conclusion**

This study demonstrated differences in asymmetry of biomechanical and performance variables in ACLR subjects 9 months after surgery compared to matched healthy subjects. The ACLR group were more asymmetrical with asymmetry more prevalent in the jump than CoD testing and related primarily to deficits in the sagittal and frontal planes suggesting incomplete restoration of normal movement 9 months after ACLR. SLDJ performance demonstrated the largest effect size difference between groups with only small effect size difference in CoD tests and none in SLHD. This was despite medium and large effect size differences in asymmetry of biomechanical variables across all tests. This study suggests that the analysis of differences in magnitude of biomechanical asymmetry is an important consideration when assessing rehabilitation back to normal function after ACLR and should be considered in future analysis of factors influencing outcome such as RTP and re-injury.

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