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Biomechanical but not timed performance asymmetries persist between limbs 9 months after ACL reconstruction during planned and unplanned change of direction.

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Abstract

Whilst anterior cruciate ligament injury commonly occurs during change of direction (CoD) tasks, there is little research on how athletes execute CoD after anterior cruciate ligament reconstruction (ACLR). The aims of this study were to determine between-limb and between-test differences in performance (time) and joint kinematics and kinetics during planned and unplanned CoD. One hundred and fifty-six male subjects carried out 90° maximal effort, planned and unplanned CoD tests in a 3D motion capture laboratory 9 months after ACLR. Statistical parametric mapping (2 x 2 ANOVA; limb x test) was used to identify differences in CoD time and biomechanical measures between limbs and between tests. There was no interaction effect but a main effect for limb and task. There was no between-limb difference in the time to complete both CoD tests. Between-limb differences were found for internal knee valgus moment, knee internal rotation and flexion angle, knee extension and external rotation moment and ankle external rotation moment with lower values on the ACLR side (effect size 0.72-0.5). Between tests differences were found with less contralateral pelvis rotation, distance from centre of mass to the ankle in frontal plane, posterior ground reaction force and greater hip abduction during the unplanned CoD (effect size 0.75-0.5). Findings demonstrated that kinematic and kinetic differences between limbs are evident during both CoD tests 9 months after surgery, despite no statistical differences in performance time. Biomechanical differences between tests were found in variables, which have previously been associated with ACL injury mechanism during unplanned CoD.

Introduction

Change of direction (CoD) is one of the most common mechanisms of injury (up to 50%) to the anterior cruciate ligament (ACL) of the knee in high demand field sports (Alentorn-Geli, Myer et al. 2009). However, there is a paucity of scientific literature on biomechanical risk factors for primary or secondary ACL injury during CoD. It has been reported that when athletes return to play (RTP) differences exist between limbs in strength and power as well the biomechanical variables during jump and landing tasks relating to deficits on the ACLR side (Myer, Martin et al. 2012, King E. 2017, O'Malley E. 2017). However, no study has yet examined biomechanical differences between limbs during CoD as athletes return after ACLR. An exploratory study is required identify these differences and their magnitude. Such differences between limbs may reflect incomplete rehabilitation of the ACLR limb and may identify factors influencing outcomes relating to return to sport and re-injury.

Movement of the whole body can influence knee loading during CoD in healthy, previously non-injured subjects. Ground reaction force (GRF) magnitude and moment arm (Kristianslund and Krosshaug 2013, Sigward, Cesar et al. 2015), hip abduction angle (Kristianslund and Krosshaug 2013, Sigward, Cesar et al. 2015), hip internal rotation angle (McLean, Huang et al. 2005, Sigward, Cesar et al. 2015), foot rotation/placement (Dempsey, Lloyd et al. 2007, Dempsey, Lloyd et al. 2009, Kristianslund and Krosshaug 2013), trunk rotation/side flexion (Dempsey, Lloyd et al. 2007, Jamison, Pan et al. 2012, Frank, Bell et al. 2013) and position of the centre of mass (COM) relative to stance leg and direction of travel (Donnelly, Lloyd et al. 2012) have all been reported to increase external knee valgus moment, a variable which has been proposed to predict primary ACL injury in female athletes (Hewett, Myer et al. 2005). Furthermore, many of the above-mentioned measures, have been identified as being evident during video analysis of ACL injurious events involving CoD (Boden, Dean et al. 2000, Olsen, Myklebust et al. 2004, Cochrane, Lloyd et al. 2007, Krosshaug, Nakamae et al. 2007). Research analysing agility and CoD tests after ACLR has focused on the timed performance of the tests, in particular between-limb (reconstructed against non-reconstructed) task completion time differences (Myer, Schmitt et al. 2011, Kyritsis, Bahr et al. 2016). Full body biomechanical analysis may highlight differences between limbs that can be targeted during rehabilitation and suggest variables of interest when assessing individuals' subsequent re-injury risk.

The influence of planned and unplanned CoD on biomechanics has not been analysed after ACLR. Recent systematic reviews have indicated that non-injured subjects performing an unplanned CoD demonstrate an increase in variables associated with ACL injury risk, compared to a planned CoD task (Brown, Brughelli et al. 2014, Almonroeder, Garcia et al. 2015). Analysis of differences between the two tests could identify variables that are indicative of increased risk of ACL injury during unplanned CoD after ACLR influencing its inclusion in RTP testing batteries. In addition, differences in biomechanical variables between limbs during CoD tasks may alter depending on whether they are planned or unplanned maneuvers. The presence of common or varying differences between limbs in both tests may influence the decision as to whether an athlete is ready to return to play and indicate if either or both tests are suitable for inclusion in RTP testing.

The first aim of this study was to identify differences in timed performance and biomechanical variables through the kinetic chain between the ACLR and non-ACLR limbs during stance phase of a 90° planned and unplanned CoD. The second aim was to identify differences in kinematic and kinetic variables, between planned and unplanned CoD for each leg. We tested the hypothesis that there would be differences in joint kinematic and kinetic variables between ACLR and non-ACLR limb for each test with deficits on the ACLR side relating to incomplete rehabilitation. In addition, there would be differences between planned and unplanned tests for both limbs, in variables previously associated with ACL injury mechanism, during unplanned testing.

Methods

This cohort study was carried out in the Sports Surgery Clinic, Dublin. Subjects were recruited from the caseload of two orthopaedic surgeons with expertise in knee surgery between January 2014 and December 2016. All subjects were male athletes, aged between 18 and 35 years and were participating in multidirectional field sports (i.e. Gaelic Football, Soccer, Hurling, Rugby). One hundred and fifty-six subjects were recruited into the study with a mean age of 24.8 years (+/- 4.8), height 180cm (+/-8) and mass of 84Kg (+/- 15.2). Subjects were tested on average 8.8 months (+/- 0.7) after surgery and underwent primary ACLR without other knee ligament or meniscal repair. All subjects had the stated intention of returning to full participation in multidirectional sport after surgery. Subjects who had multiple ligament reconstructions, previous ACL surgery, meniscal repair or were not returning to multidirectional sport were excluded from the study. All subjects had their ACL reconstruction performed using a bone patellar tendon bone graft or hamstring graft (semitendinosis/gracilis) harvested from the ipsilateral limb during reconstruction. The study received ethical approval from University of Roehampton, London (LSC 15/122) and Sports Surgery Clinic Hospital Ethics committee (25AFM010) and was registered at clinicaltrials.gov (NCT02771548).

The testing took place in a biomechanics laboratory using an eight-camera motion analysis system (200Hz; Bonita-B10, Vicon, UK), synchronized (Vicon Nexus 1.8.5) with two force platforms (1000Hz BP400600, AMTI, USA) recording 24 reflective markers (1.4cm diameter) and ground reaction force (GRF). Subjects wore their own athletic footwear for use on the astroturf surface with reflective markers secured to the shoe or to the skin using tape, at bony landmarks on the lower limbs, pelvis and trunk according to the Plug-in-Gait marker set(Marshall, Franklyn-Miller et al. 2014). Motion and force data were low-pass filtered using a fourth-order Butterworth filter (cut-off frequency of 15Hz)(Kristianslund, Krosshaug et al. 2012). 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 (Winter 2009.). A custom MATLAB program (MathWorks Inc, Natick, Massachusetts, USA) was used for processing (gap filling and waveform screening) and the calculation of additional kinematic measures: trunk to pelvis and foot progression to pelvis angles in the transverse plane and COM position to the knee and ankle joints (King E. 2017). The stance phase was defined from when the GRF was greater than 20N and normalized to 100% stance. To ensure that similar neuromuscular characteristics of the eccentric and concentric phases of the waveforms were being compared, a dynamic time warping process (Ramsey 2006) was used to align the end of the eccentric phase across the all curves when vertical

COM power reached zero during stance. The mean of each variable for the three trials was used in analysis.

Before data collection, subjects undertook a standardised warm-up including 2-minute jog, 5 bodyweight squats, 2 submaximal and 3 maximal countermovement jumps. A static trial was then captured as reference for the dynamic trials. The analysis described formed part of a larger study with CoD testing preceded by 3 trials of double and single leg drop jump, single leg hop for distance and a hurdle hop, the results of which have been reported previously (King E. 2017). Each subject underwent 2 submaximal trials and 3 maximal trials carrying out a 90° cutting manoeuver on each leg. The start line was 5 metres from the force plates (Fig 1). Speed gates (Smartspeed, Fusion Sport, Chicago, Illinois, USA) were used to time each subject with a trigger gate 2 metres 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. The CoD was timed from the trigger gate to the exit gate for both planned and unplanned tests. Planned CoD was carried out first before introducing the added difficulty associated with the reaction required to complete the unplanned CoD, to ensure the subject could safely execute one before progressing to the next. For both planned and unplanned CoD, subjects were instructed to complete the cut as quickly as possible and to accelerate forward through the exit gates after changing direction rather than decelerate or side shuffle through. For the planned CoD, subjects ran maximally at the force plate cutting left or right while planting their contralateral foot on the force plate (i.e. planting off left foot to cut right). They carried out the test on the non-operated limb first and then on the operated limb. Full foot contact had to be made with the force plate for a valid trial.

Figure 1. Dimensions for planned and unplanned change of direction test

For the unplanned CoD, subjects ran maximally from the start line. When the subject broke the trigger gate 2 meters from the start line (and thus 3 meters from the force plate), the left or right exit gate automatically lit up signaling the subject to cut in that direction. The order of the cutting direction was randomly assigned and continued until the subject had 3 successful trials (maximal effort and organize footwork so as to hit the force plate with the outside leg to change direction i.e. plant off left leg to turn right) from each leg. Subjects could withdraw from testing at any point if they did not feel comfortable carrying out the test or did not want to continue. Similarly, the assessor could stop testing if they felt the subject could not carry out the task properly (i.e. maximal effort) or safely.

To examine between-limb and between-test differences in performance measures for the planned and unplanned CoD, ground contact time, total cutting time and forward COM velocity at initial contact were analysed using a 0d statistical parametric mapping (SPM) 2 x 2 ANOVA (Limb: ACLR, non-ACLR x test: planned, unplanned). To examine between limb and between test differences in the kinematic and kinetic measures, SPM (1d ANOVA) was carried out over 100% stance for the ankle, knee and hip joint angles and moments in three dimensions and the additional segment angles (trunk and foot to pelvis) and COM to ankle and knee distances. To account for variations caused by differing COM velocity at initial contact, kinematic and kinetic variables were regressed against COM velocity at initial contact (in a point-by-point manner and the residuals of the regression were compared between the ACLR and non-ACLR limb and planned and unplanned CoD test (using a 1d SPM paired t-test; Figure 2) over the entire stance phase.(Vanrenterghem, Venables et al. 2012) Analysis was carried out on both sets of waveforms where COM velocity at initial contact was and was not accounted for.

Figure 2. Regression of knee angle in the sagittal plane against approach speed at initial contact.

If differences were found, the beginning and end of the time period over which significant difference occurred, the mean difference throughout that phase and the mean value for each limb for that variable across that phase were reported. To determine magnitude of significant differences, Cohen's D effect size (ES) was calculated in a point-by-point manner (d>0.5-0.79 = medium; d>0.8 = strong) and the average reported across that phase of difference. Biomechanical differences with a Cohen's D smaller than 0.5 were judged non-relevant and hence discarded from analysis (Cohan 1988).

Results

One hundred and forty-seven subjects out of the cohort of 156 had complete data for both CoD tests for analysis. Nine subjects did not have required data for one or other tests (e.g. missed force plate, missing markers, did not complete the assessment). The ANOVA indicated no interaction effect but a main effect for limb and test for all analysis. The findings reported are for the data not adjusted for COM velocity at initial contact, as findings were consistent between analyses.

Performance Analysis

There was no difference in overall completion time and ground contact times for the planned and unplanned CoD between the ACLR and non-ACLR limbs (Table 1). The ACLR limb demonstrated significantly slower COM velocity at initial contact with small effect sizes both planned and unplanned CoD ($p < 0.001$; ES 0.43). Between tests, there were significant differences with a large effect size for completion time ($p < 0.001$; ES 0.73), and small effect size differences for ground contact time ($P < 0.001$; ES 0.35) and COM velocity at initial contact ($p < 0.001$; ES 0.34) with shorter times and faster COM velocity at initial contact during the planned CoD.

Table 1 Performance variables for planned and unplanned change of direction.

Performance Variables for Planned and Unplanned Change of Direction						
Test	**Variable**	**ACLR Mean (+/- STD)**	**95% CI**	**Non-ACLR Mean (+/- STD)**	**95% CI**
Planned	Completion Time (s)	1.44 (0.13)	1.42 to 1.46	1.45 (0.13)	1.43 to 1.48
	Ground Contact Time (s)	0.33 (0.05)	0.33 to 0.34	0.32 (0.05)	0.33 to 0.35
	COM velocity at Initial Contact (m/s)	2.63 (0.32)	2.58 to 2.69	2.72 (0.39)	2.72 to 2.83
Unplanned	Completion Time (s)	1.53 (0.12)	1.51 to 1.56	1.56 (0.14)	1.52 to 1.58
	Ground Contact Time (s)	0.35 (0.05)	0.34 to 0.36	0.36 (0.05)	0.36 to 0.37
	COM velocity at Initial Contact (m/s)	2.54 (0.12)	2.49 to 2.59	2.68 (0.3)	2.63 to 2.73

STD – standard deviation; CI – Confidence Interval; m/s – metres per second; s – seconds ACLR – anterior cruciate ligament reconstruction; Nm – Newton-meters

Biomechanical Analysis

Biomechanical differences between limbs

There were a number of biomechanical differences between limbs throughout stance phase in the planned and unplanned CoD tests (Table 2; Appendix A). The difference with the largest effect size was less internal knee valgus moment on the ACLR limb in the middle of the stance phase (19-85%; ES 0.72). There was less knee flexion angle (19-84%; ES 0.57), ankle external rotation moment (19-83%; ES 0.56), knee external rotation moment (19-82%; ES 0.54), knee extension moment (15-91%; ES 0.50) as well as less knee internal rotation angle throughout all of stance phase (0-100%; ES 0.56) on the ACLR side.

Table 2. Biomechanical difference between limbs during planned and unplanned change of direction.

Biomechanical Differences Between Limbs (Planned and Unplanned Combined)								
Variable	**Direction**	**Start**	**End**	**ACLR (+/- STD)**	**95% CI**	**Non-ACLR (+/- STD)**	**95% CI**	**Effect Size**
Knee Abduction Moment (Nm/Kg)	Valgus	19	85	5.6 (6.7)	4.6 to 6.5	11.9 (9.2)	10.5 to 13.4	0.72
Knee Angle Sagittal (º)	Flexion	19	84	55.3 (8.6)	53.9 to 56.7	60.3 (8.4)	58.6 to 62	0.57
Ankle Moment Transverse (Nm/Kg)	External Rotation	19	83	-0.2 (2.3)	-0.4 to 0.01	1.9 (4.6)	1.6 to 2.4	0.56
Knee Angle Transverse (º)	Internal Rotation	0	100	16.2 (10.8)	15.5 to 16.9	22.6 (11)	21.6 to 23.5	0.56
Knee Moment Transverse (Nm/Kg)	External Rotation	19	82	0.52 (1.9)	0.3 to 0.8	2.4 (4.3)	2 to 2.8	0.54
Knee Moment Sagittal (Nm/Kg)	Extension	15	91	17.1 (8.7)	15.4 to 18.9	21.6 (8.7)	19.6 to 23.7	0.5

STD – standard deviation; CI – Confidence Interval; m/s – metres per second; ACLR – anterior cruciate ligament reconstruction; Nm – Newton-meters; Kg – kilogram; N – Newtons;

Biomechanical differences between tests

There were a number of biomechanical differences between the planned and unplanned CoD for both the ACLR and non-ACLR limbs (Table 3; Appendix A). The largest effect size difference was with the pelvis less rotated towards the direction of travel throughout stance phase during the unplanned CoD (0-100%; ES 0.75). In addition, the COM was closer to the stance limb in relation to the ankle (0-56%; ES 0.58) in the frontal plane through the eccentric phase of stance during the unplanned CoD. There was lower posterior GRF during the unplanned CoD (23-100%; ES 0.52) and greater hip abduction during the unplanned CoD (49-100%; ES 0.50) for both limbs.

Table 3. Biomechanical differences between planned and unplanned change of direction on ACLR limb

Biomechanical Differences Between Tests (ACLR and Non-ACLR Combined)								
Variable	**Direction**	**Start**	**End**	**Planned (+/- STD)**	**95% CI**	**Unplanned (+/- STD)**	**95% CI**	**Effect Size**
Pelvis Angle Transverse (º)	Contralateral Rotation	0	100	38.7 (12.1)	37.7 to 39.6	29.2 (11.1)	28 to 30.3	0.75
COM to Ankle Frontal (mm)	Contralateral	0	56	440 (51)	438 to 442	407 (59)	404 to 409	0.58
Ground Reaction Force (N/Kg)	Posterior	23	100	-5.3 (1.5)	-4.6 to -6	-4.6 (1.3)	-3.9 to -5.2	0.52
Hip Angle Frontal (º)	Abduction	49	100	-19.5 (6.5)	-19.1 to -20	-22.5 (6.5)	-22 to -23	0.5

STD – standard deviation; CI – Confidence Interval; COM – centre of mass; ACLR – anterior cruciate ligament reconstruction; N – Newtons; Kg – kilogram; mm - millimeter

Discussion

This study demonstrated that biomechanical differences throughout the kinetic chain exist between limbs during CoD tasks 9 months after ACLR, despite no difference in CoD performance time. During a maximal effort CoD these asymmetries are consistent between planned and unplanned CoD, reflecting deficits on the ACLR side, regardless of approach speed. Biomechanical differences exist for both limbs between planned and unplanned CoD in variables that have been previously associated with ACL injury mechanism during unplanned cutting.

Differences in Timed Performance

Timed performance during CoD tests has been used previously as a measure of rehabilitation status after ACLR (Myer, Paterno et al. 2006, Kyritsis, Bahr et al. 2016). There was no difference in overall time to CoD between limbs for the planned and unplanned CoD 9 months after ACLR. This is in agreement with previous data that demonstrated bipedal tasks (such as run and cut) do not demonstrate between-limb differences that exist during single tasks (such as single leg hop) (Myer, Schmitt et al. 2011). However, there were differences in the biomechanical variables to achieve the task. The COM had a lower velocity at initial contact on the ACLR limb for both planned and unplanned cutting despite the same overall execution time. The slower velocity at initial contact on the ACLR limb may reflect a poorer ability to deal with the higher demands at initial contact (Vanrenterghem, Venables et al. 2012) or reflect reduced confidence in its ability to execute the CoD compared to the non-ACLR limb. It may occur due to greater deceleration on the non-ACL limb on the penultimate step prior to change of direction in order to offload when stepping off the ACL limb (Havens and Sigward 2015) and may be a useful outcome measure during rehabilitation. These results question the appropriateness of using performance time as a rehabilitation measure due to the ability of the body to compensate to execute the task and the existence of biomechanical asymmetries between limbs in the presence of similar performance times.

Biomechanical Difference between Limbs

The analysis reported no interaction effect but a main effect of limb highlighting the asymmetry in task execution was irrespective of whether it was a planned or unplanned CoD. Differences were found in the sagittal plane with less knee flexion and less knee extension moment on the ACLR side and in the frontal/transverse planes with lower knee valgus moment, ankle external rotation moment and knee internal rotation angle and external rotation moment for both tests on the ACLR side. Many of these differences between limbs have been identified previously in jumping and landing tasks at a similar time after surgery (King E. 2017).

After initial contact, the ACLR limb demonstrated less internal knee valgus moment after 20% of stance phase. This is evident with the other coupled movement differences – less knee internal rotation angle and knee and ankle external rotation moment on the ACLR limb, and of these, internal knee rotation has been demonstrated to increase strain on the ACL (Berns, Hull et al. 1992, Fleming, Renstrom et al. 2001, Hame, Oakes et al. 2002, Meyer and Haut 2008, Shimokochi and Shultz 2008). However, the less internal knee varus moment may suggest the ACLR limb has less "room for error" in resisting external knee valgus moments during CoD and reflect insufficient redevelopment of frontal plane control during rehabilitation. This ongoing difference between limbs may influence the susceptibility to re-injury on return to higher-level activity.

The ACLR limb had less knee flexion throughout most of stance phase for both tests. In addition, the ACLR limb had a lower knee extension moment throughout the same phase of stance. A more extended knee position has been commonly reported in ACL injury mechanism literature (Alentorn-Geli, Myer et al. 2009) and attributed to the greater anterior tibial shear (Markolf, Burchfield et al. 1995, Li, Defrate et al. 2005) and unopposed pull of the quadriceps in this position thus leaving the ACLR limb more at risk of injury (Herzog and Read 1993). Reduced knee extension moment on the ACLR limb has been reported previously in jump testing and has been linked with ongoing quadriceps strength differences (Lewek, Rudolph et al. 2002, Schmitt, Paterno et al. 2012). This reduction in extension capacity during the stance phase of the CoD tests may be reflected in the slower COM velocity at initial contact and may contribute to the ACLR knee maintaining a more extended position through stance. This combination of reduced ability to absorb load on the ACLR limb and the deficits in frontal/transverse plane control may influence re-injury susceptibility on return their chosen sports. The results suggest that these variables are different between limbs for both tests highlighting potential areas to be targeted during rehabilitation. It also suggests that when assessing for biomechanical asymmetries after ACLR to assess rehabilitation status or to identify variables, which may influence return to sport or re-injury outcomes that the planned and unplanned CoD tests provide similar results.

Biomechanical Differences between Planned and Unplanned CoD

Previous research in non-injured athletes has reported that joint and segment mechanics differ when executing a planned and unplanned CoD tests (Brown, Brughelli et al. 2014, Almonroeder, Garcia et al. 2015). This is consistent with the results of this study where we found no interaction effect was found but a main effect of task suggesting that differences between tests were consistent for both tests and were due to the task demand. These differences also persisted when COM velocity at initial contact was considered, suggesting that they are related to CoD task demands. Many of the differences in the unplanned CoD were in variables associated with ACL injury mechanism or risk factors associated with ACL injury. Increased ipsilateral pelvis rotation (i.e. reduced rotation in the direction of intended travel) was found in unplanned CoD for both limbs and has been shown to increase external knee valgus moments during CoD (Dempsey, Lloyd et al. 2009, Jamison, Pan et al. 2012, Frank, Bell et al. 2013) and has been previously demonstrated between tests in healthy subjects (Dempsey, Lloyd et al. 2009, Mornieux, Gehring et al. 2014). The position of the COM relative to the ankle was also different between the tests indicating a systematic change in movement to meet the task demands. In the unplanned CoD, the COM was closer towards the stance leg, a mechanism that is commonly observed during CoD ACL injury (Alentorn-Geli, Myer et al. 2009). Donnelly et al, (Donnelly, Lloyd et al. 2012) demonstrated *in silico* that a more medial position of COM relative to stance leg and in the direction of intended travel reduced external knee valgus loading. In addition, increased hip abduction angle has also been shown to increase external knee valgus moments during CoD and was greater during the unplanned CoD for both limbs in this study (Sigward and Powers 2007, Kristianslund, Faul et al. 2014, Sigward, Cesar et al. 2015). There was higher posterior GRF for both limbs during the planned CoD and may reflect greater ability to decelerate while changing direction during planned CoD which may contribute to the faster CoD times during planned CoD. These results demonstrated that there are biomechanical differences between planned and unplanned CoD testing after ACLR and those variables in unplanned CoD have been previously associated with ACL injury mechanism and risk factors. This should be considered when choosing to include unplanned CoD during rehabilitation and RTP testing after ACLR.

None of the differences between limbs and between tests reported changed when velocity was accounted for in analysis, supporting the validity of maximum effort trials in exposing biomechanical differences between limbs after ACLR during planned and unplanned CoD testing.

Limitations

Multiple comparisons were carried out within each test as we wanted to examine variables across the entire kinetic chain. This increases the risk of Type II error and identifying variables which are not of interest. We did not adjust the p-value threshold as the study is exploratory and preferred to avoid Type II error potentially missing relevant variables. To offset against this, effect sizes were used in conjunction with p-values to report only variables with medium and large effect size difference between limbs for future analysis. Of note all the variables reported had a $p < 0.0001$ which would have met the corrected p-value threshold. The testing in this study was carried out using a 90° angle. Cutting angle has been demonstrated to influence biomechanics with greater angles increasing knee valgus moment thus limiting comparison to other studies using different angles. A 90° CoD task requires greater deceleration and is more of a challenge than 45° cut and is highly prevalent in ACL injury therefore was decided it would be more appropriate for analysis in this cohort (Havens and Sigward 2015). The plug in gait model that was used to generate kinetic and kinematic data was originally developed for clinical analysis of walking and there may be more suitable models for use in highly dynamic tasks such as CoD (Besier, Sturnieks et al. 2003, Vanrenterghem, Gormley et al. 2010, Robinson, Donnelly et al. 2014). The fixed order of testing between tasks and limbs for the planned CoD was to provide a graduated neuromuscular challenge during testing after ACLR but may have facilitated familiarisation effects that could have influenced study findings.

Conclusion

This is the first study to examine kinetics and kinematics during planned and unplanned CoD after ACLR. Biomechanical differences between ACLR and non-ACLR limbs exist at 9 months after surgery despite no difference in CoD performance time, questioning the use of test time alone rather than with respect to mechanics, as a measure of rehabilitation status. Differences between limbs were consistent between planned and unplanned CoD and may have relevance to future injury risk. Differences between tests on both the ACLR and non-ACLR limbs demonstrated variables associated with increased knee loading and ACL injury mechanism during unplanned CoD.

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Conflict of Interest Statement

There is no conflict of interest

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Figure 1. Dimensions for planned and unplanned change of direction test

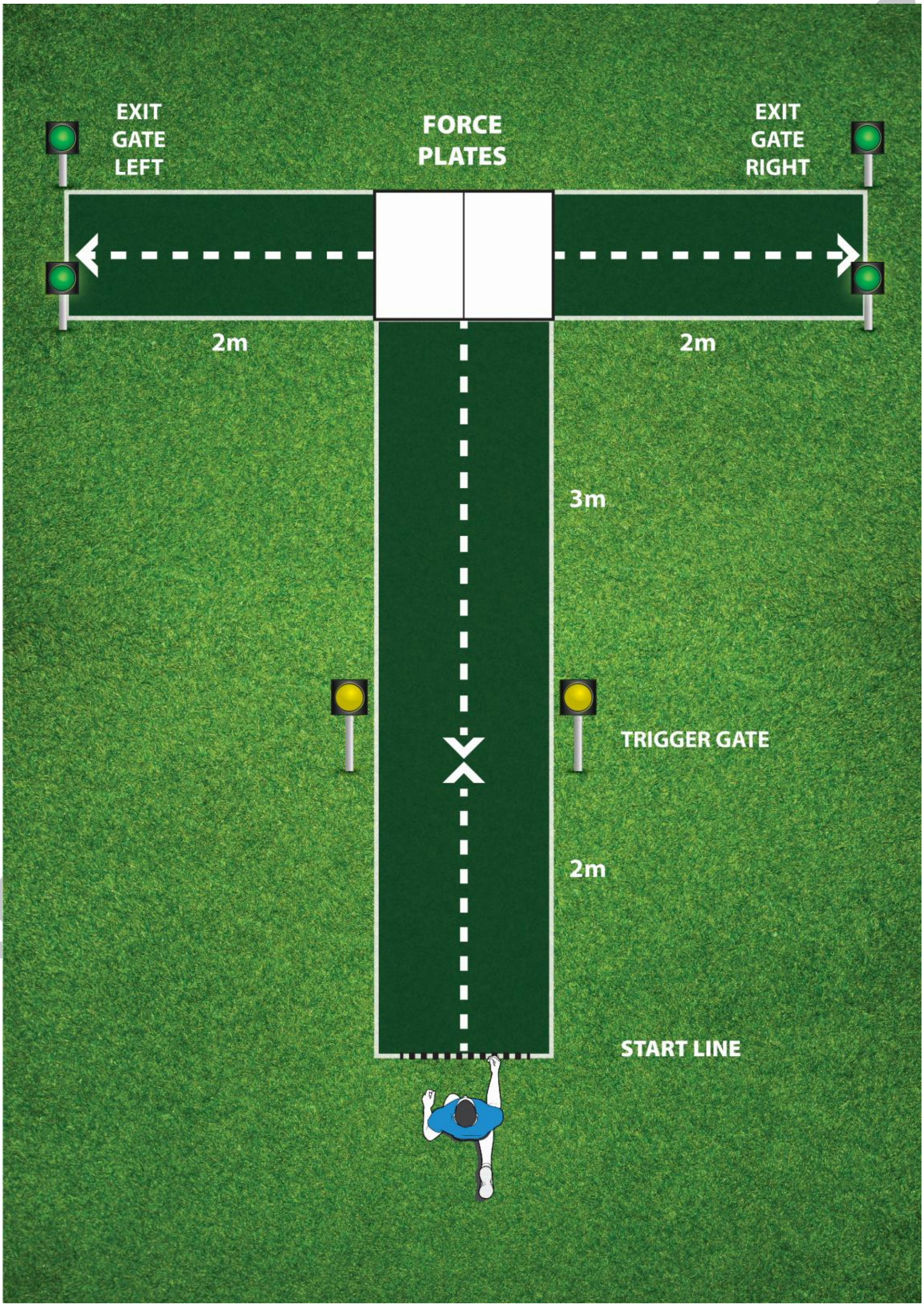
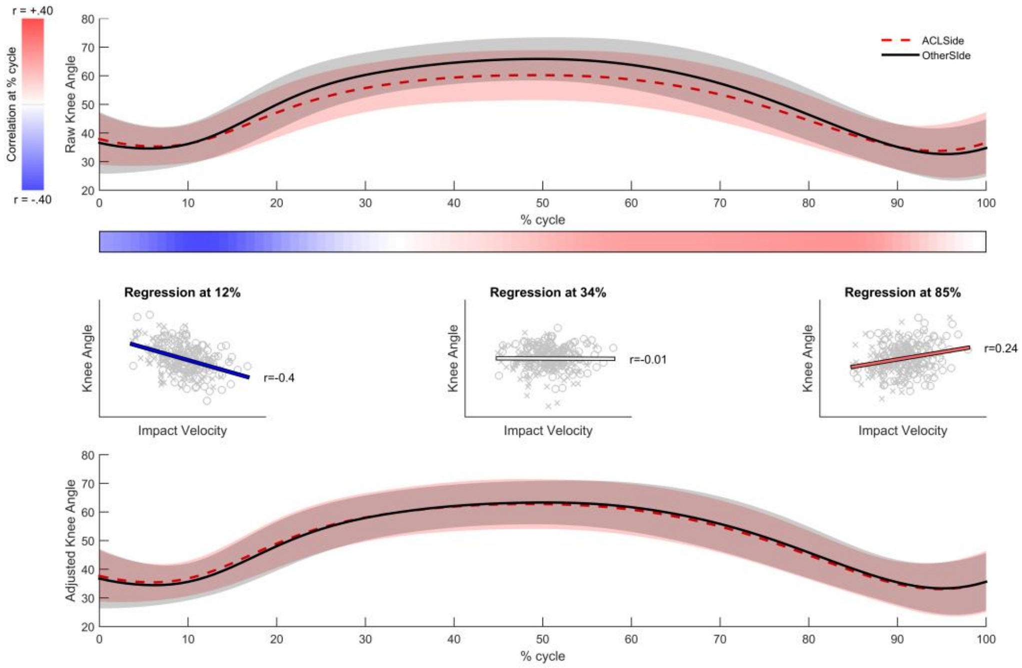


Figure 2. Regression of knee angle in the sagittal plane against approach speed at initial contact. The top graph demonstrates the mean and standard deviation of the ACLR and non ACLR limbs with the colour bar below demonstrating the regression against impact velocity (blue for negative and red for positive). The middle graph plots the regression of knee angle against impact velocity (with the % of stance phase indicated at the top of the graph). A high regression with velocity indicates that the variable is associated with speed while no regression indicates that the variable is not associated with speed. For example, at 12% of stance, the knee flexion angle is moderately and negatively associated with speed, indicating that the knee tends to become more extended as speed increases while at 34% stance, there is no association with speed, finally at 85% stance, the knee angle tends to be weakly positively associated with speed, a more flexed angle tends to occur at higher speeds. The bottom graph demonstrates the revised curves when the residual is subtracted from the mean displaying the adjusted knee angle which highlights no difference in knee angle between limbs when velocity is accounted for.

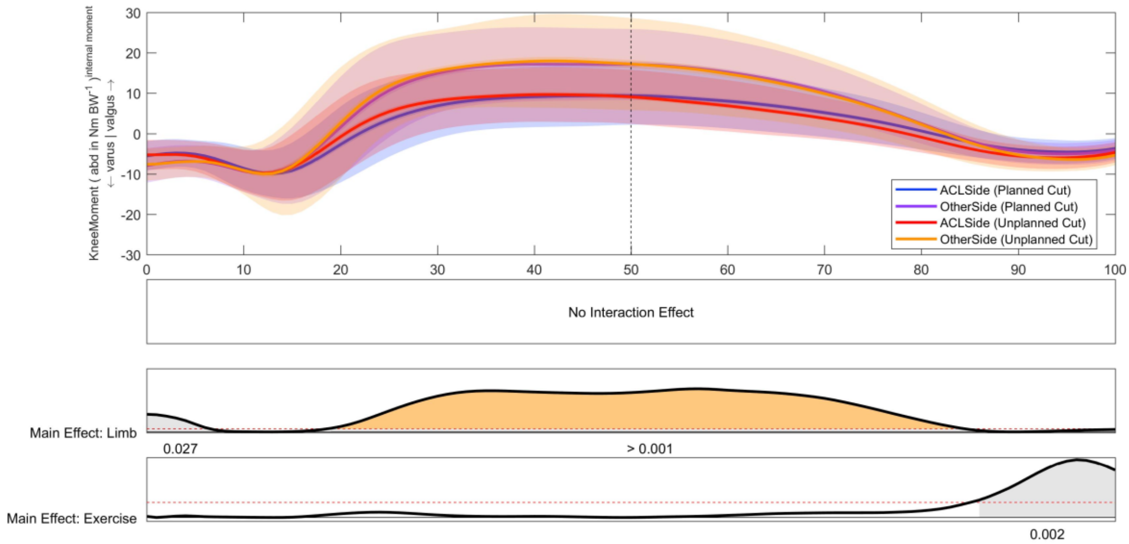


Appendix A - Waveforms of Reported Variables in Results Section

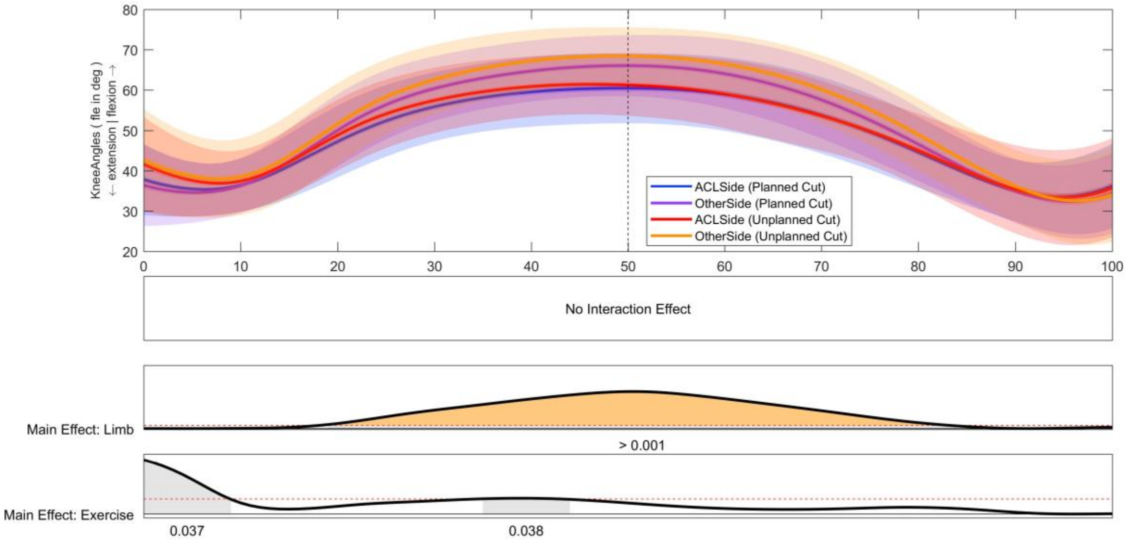
In the middle and bottom panel the number reported under the shaded area is the p - value. The colour of the shaded area reflects the effect size across that phase with grey - small; orange - medium; red - large effect size

Differences between limbs

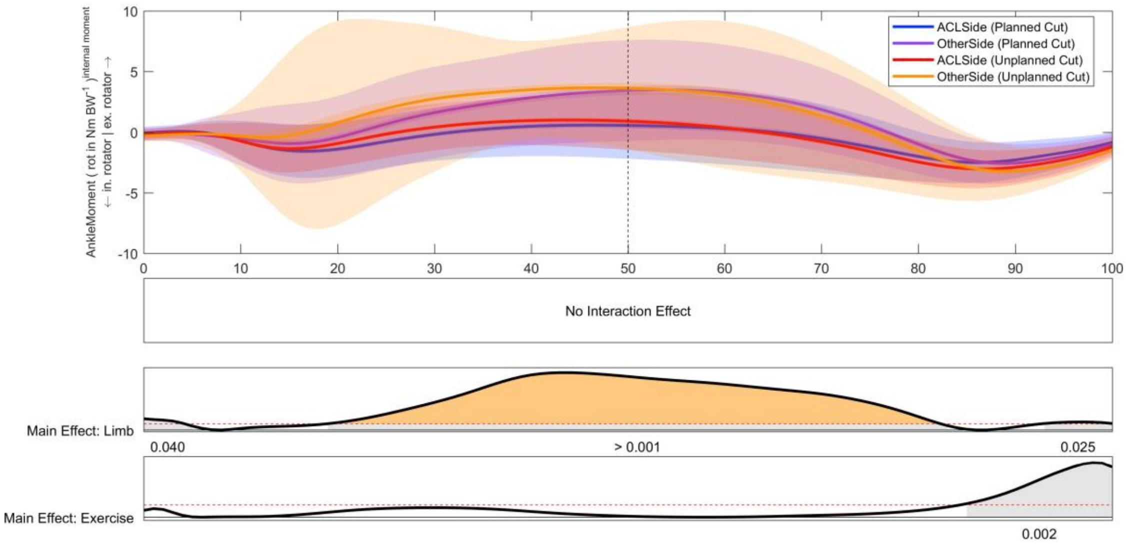
Knee Moment Frontal



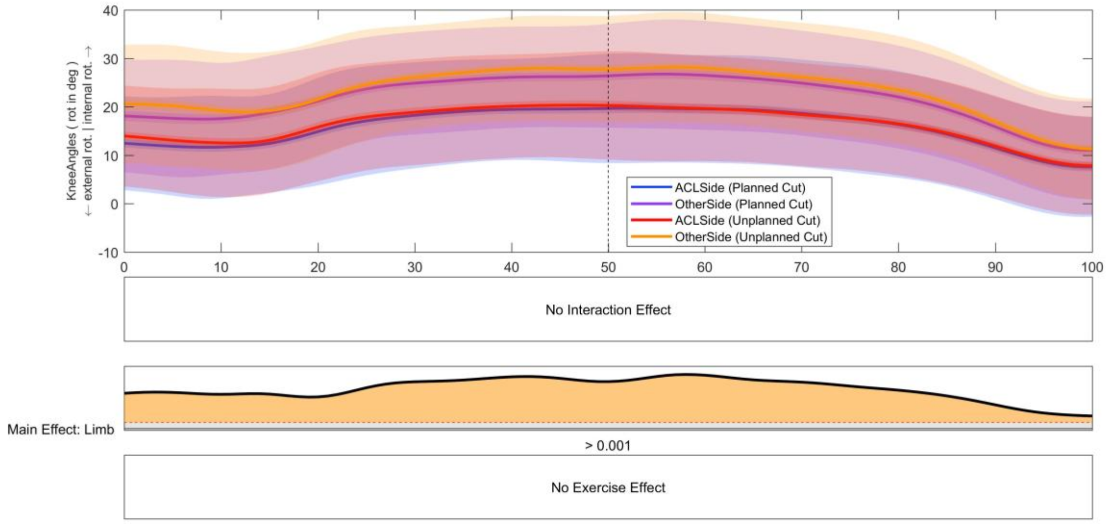
Knee Angle Sagittal



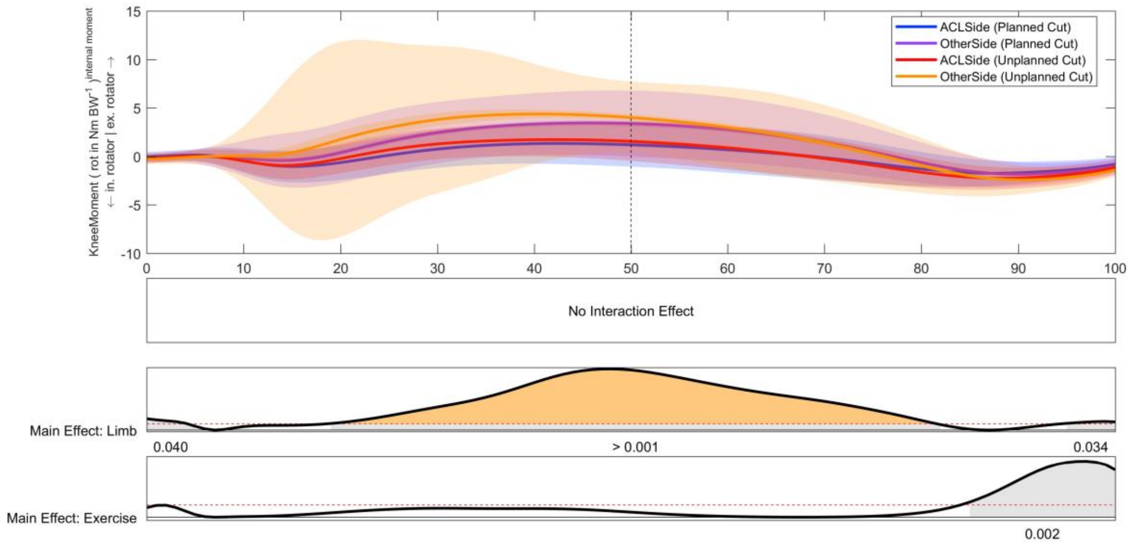
Ankle Moment Transverse



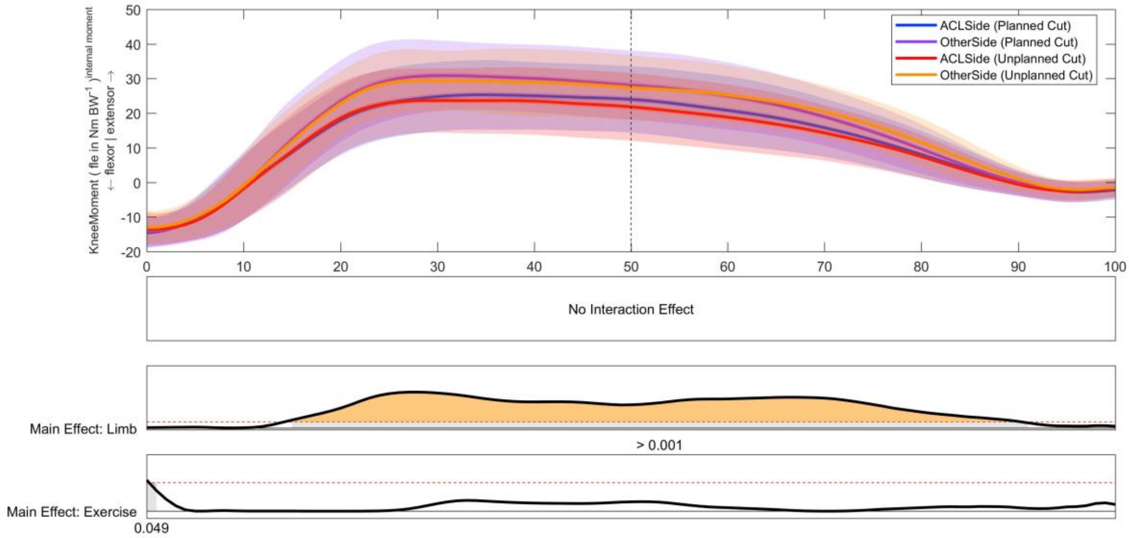
Knee Angle Transverse



Knee Moment Transverse

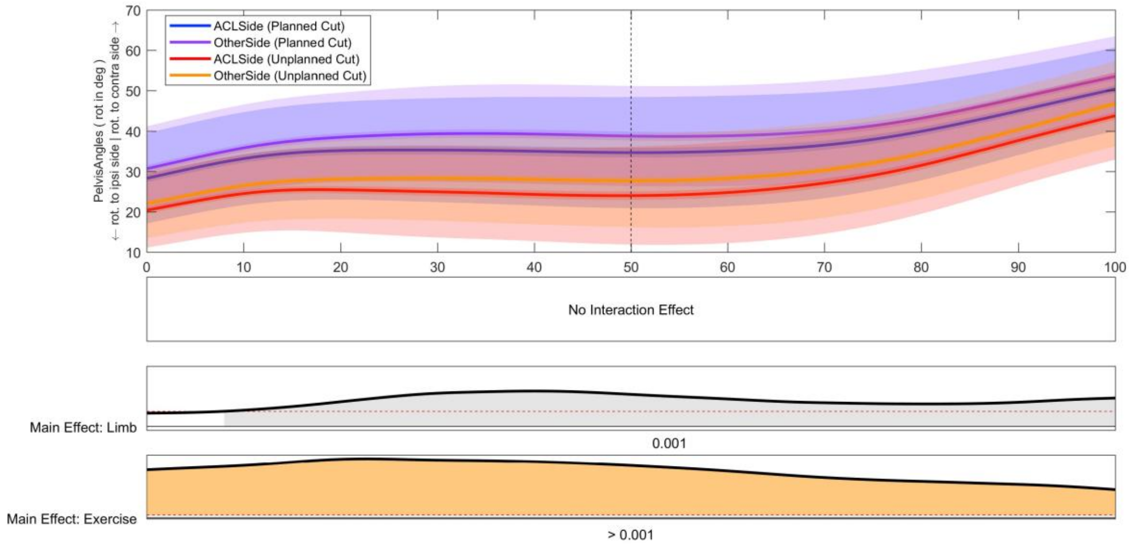


Knee Moment Extension

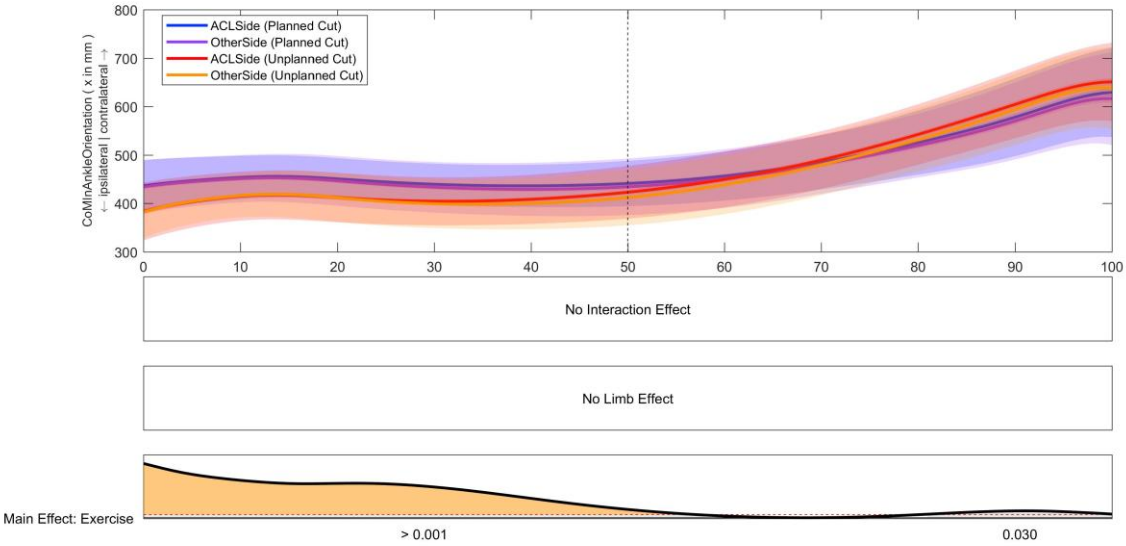


Differences between tests

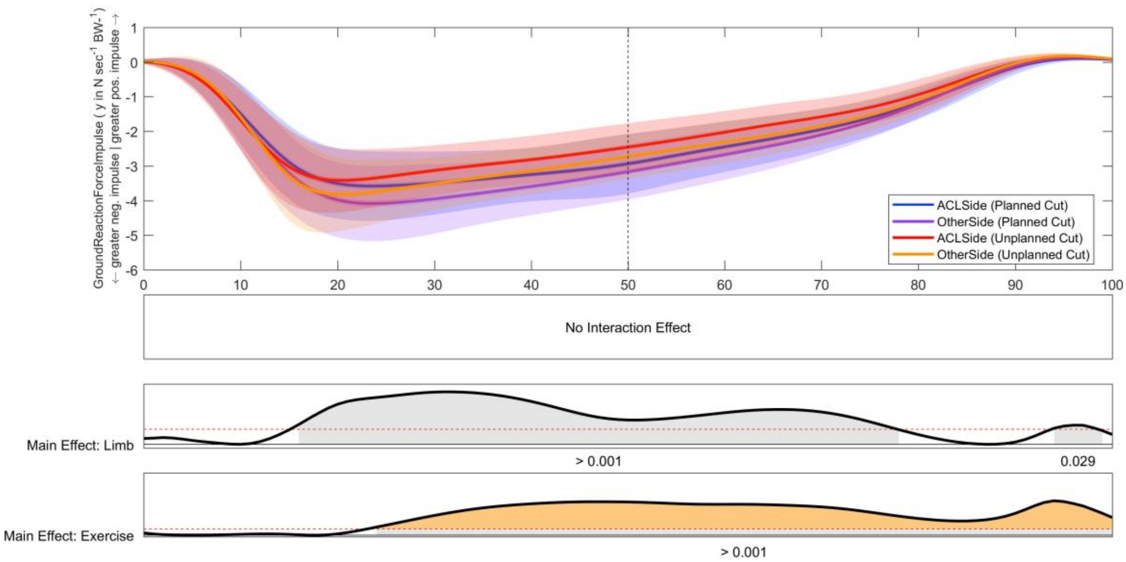
Pelvic Angle Transverse



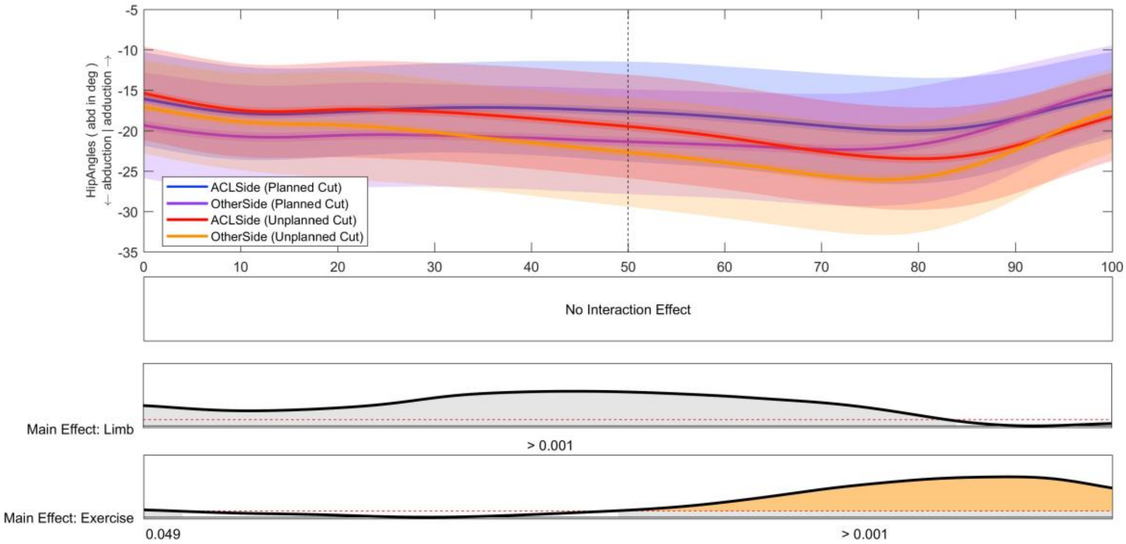
Centre of Mass Distance to Ankle Frontal



Ground Reaction Force (Posterior)



Hip Angle Frontal


HipAngles (abd in deg)
← abduction | adduction →
ACLSide (Planned Cut)
OtherSide (Planned Cut)
ACLSide (Unplanned Cut)
OtherSide (Unplanned Cut)
No Interaction Effect
Main Effect: Limb
> 0.001
Main Effect: Exercise
0.049
> 0.001