Whole-body change of direction task execution asymmetries after anterior cruciate ligament reconstruction

Katherine A J Daniels[1,2,3], Eleanor Drake[1,4], Enda King[1,5] and Siobhán Strike[5]

[1] Sports Medicine Research Department, Sports Surgery Clinic, Northwood Avenue, Santry, Dublin, Ireland

[2] Queen's School of Engineering, University of Bristol, University Walk, Bristol, UK

[3] Department of Sport and Exercise Science, Manchester Metropolitan University, Manchester, UK

[4] Department for Health, University of Bath, Claverton Down, Bath, UK

[5] Department of Life Sciences, Roehampton University, Holybourne Avenue, London, UK

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Correspondence address:

Katherine A J Daniels

Department of Sport and Exercise Sciences

Manchester Metropolitan University

All Saints' Building

Oxford Road

Manchester M1 5GF

UK

Email: k.daniels@mmu.ac.uk

Abstract

Cutting manoeuvres can be executed at a range of angles and speeds, and these whole-body task descriptors are closely associated with lower-limb mechanical loading. Asymmetries in angle and speed when changing direction off the operated and non-operated limbs after anterior cruciate ligament reconstruction (ACLR) may therefore influence the interpretation of inter-limb differences in joint-level biomechanical parameters. We hypothesised that athletes would reduce centre of mass (COM) heading angle deflection and body rotation during the change of direction stance phase when cutting from the operated limb, and would compensate for this by orienting their COM trajectory more towards the new intended direction of travel prior to touchdown. 144 male athletes 8-10 months post-ACLR performed a maximum-effort sidestep cutting manoeuvre while kinematic, kinetic and ground reaction force data were recorded. COM heading angle deflection during stance phase was reduced for cuts performed from the operated limb and was negatively correlated with heading angle at touchdown. Between-limb differences in body orientation and horizontal velocity at touchdown were also observed. These systematic asymmetries in cut execution may require consideration when interpreting joint-level inter-limb asymmetries after ACLR, and are suggestive of the use of anticipatory control to co-optimise task achievement and mechanical loading.

Keywords: biomechanics, cut, ACL, manoeuvre.

Introduction

In order to change direction while running it is necessary to rotate the body and deflect the trajectory of the centre of mass towards the new direction of travel. Cutting manoeuvres, in which this change of direction takes place rapidly and over only a small number of steps, are ubiquitous in many field sports [1] and the task most-commonly associated with non-contact anterior cruciate ligament (ACL) rupture [2–4]. ACL rupture is a common sporting knee injury, often requiring reconstruction surgery (ACLR) and extensive rehabilitation [5,6]. In the period from six to twelve months after surgery, during which most athletes return to sport [7], asymmetries in kinematic and kinetic variables related to deficits on the operated limb have been noted during cutting manoeuvres [8,9] as well as other jumping and landing tasks [10–14]. Objective assessment of these asymmetries may present a useful approach for monitoring later-stage rehabilitation after ACLR and in assessing readiness to return to sport [9,15].

Cutting manoeuvres can be performed at a variety of angles and speeds, and these whole-body task descriptors are major determinants of knee joint loading during the movement [16–19]. At more-acute angles, larger changes to the direction in which the centre of mass (COM) is travelling (COM heading angle) and the direction in which the body is facing (body orientation angle) are necessitated. Greater deceleration in the original direction of travel is thus required, and braking impulses, peak ground reaction forces and external knee extension and abduction moments increase [18,20–24]. At higher running speeds, ground contact time is reduced so less time is available for the required COM deflection and body rotation, and braking forces also increase alongside knee frontal and sagittal plane moments [18,23,25]. Athletes appear to trade off velocity and angle when maximum-effort manoeuvres are attempted [26,27], reducing the executed change of direction angle if higher velocities are enforced [18] and *vice versa* [20,22]. In these studies the observed modifications to both approach speed and direction of travel occurred before the instant of touchdown so it is evident that this modulation arises, at least in part, from anticipatory control prior to foot contact.

If approach speeds and change of direction angles differ when cutting from the operated and non-operated legs, between-limb asymmetries in joint mechanics after ACLR would be expected to reflect this non-equivalence in the completed task rather than being solely indicative of different movement patterns within an identical task. In order to interpret joint-level differences in change of direction mechanics after ACLR it is thus necessary to understand how these basic whole-body determinants of mechanical demand differ between limbs. Lower approach velocities for cuts performed from the operated limb have previously been reported nine months after surgery [8]. However, it is not known whether inter-limb differences are also found in the magnitude of COM heading angle deflection and body orientation rotation during the cut step. Such differences - which may reflect reduced ability to tolerate the demands of the task, an altered post-injury motor strategy and/or reduced confidence in the operated limb - would indicate the presence of asymmetries in the whole-body manoeuvre and suggest that any identified joint-level differences between the operated and the non-operated leg should be interpreted in this context.

The aim of this study was to investigate asymmetries in whole-body change of direction task execution 8-10 months after ACLR, which is around the time of return to sport [28,29]. We hypothesised that post-ACLR athletes would reduce COM heading angle deflection and body rotation during the stance phase of the change of direction step when cutting from the operated limb, concomitant with reduced lower limb loading. As we imposed boundary constraints on the overall change in angle required to complete the task by requiring participants to run through fixed entry and exit gates, we expected to find that these reduced deflections and rotations during stance phase would be associated with compensatory body rotation and COM deflection towards the new intended direction of travel prior to touchdown. We thus hypothesised that body rotation and COM deflection angle in the intended new direction of travel at touchdown would be greater on the operated side, and that negative correlations between angle at touchdown and change in angle during stance phase would be present.

Methods

One hundred and forty-four male multidirectional field sport athletes (mean±SD age 25±4 years, height 179±7 cm, body mass 83±14 kg) participated in the study. All had undergone primary ACLR surgery using a bone-patellar tendon-bone (n=110) or hamstrings tendon (semitendinosus and gracilis; n=34) autograft from the ipsilateral limb 8-10 months prior to testing and had reported pre-surgery that they intended to return to multidirectional sport. Those who had concurrent meniscal repair, concurrent multiple ligament reconstructions, previous ACL reconstructions or did not intend to return to multidirectional sport were excluded. The study received ethical approval from the Sports Surgery Clinic Hospital Ethics Committee and informed written consent was obtained from all participants.

Retroreflective markers of 14 mm diameter were positioned on the lower limbs, pelvis and trunk of the participant in accordance with a modified Plug-In Gait (Vicon Motion Systems Ltd, UK) marker set [30]. This included markers placed on the left and right anterior superior and posterior inferior iliac spines to define the pelvis segment orientation, and markers placed on the 7th cervical vertebra, 10th thoracic vertebra, xiphoid process of the sternum and suprasternal notch to define the thorax segment orientation. Additional markers were placed on the iliac crests to facilitate interpolation of the pelvis marker trajectories using rigid-body assumptions if the target markers were temporarily obscured from camera view. Participants completed a standardised warm-up comprising a two-minute jog, five body-weight squats and five counter-movement jumps. They then performed an assessment battery of double-leg and single-leg drop jumps, mediolateral hurdle hops and single leg hops for distance prior to testing of cutting manoeuvres. The cutting manoeuvre testing comprised three practice trials followed by three maximum-effort trials in each direction. Trials in which the participant cut from their non-operated limb were performed first: Pilot testing in healthy controls indicated that there was no systematic learning effect on any of the examined variables introduced by standardising limb testing order, nor any effect of limb dominance. For each trial, the participant ran straight through an entry gate positioned 2 m from the centre of a force platform and performed a side-step cut turn, planting the limb on the contralateral side to the intended direction of travel (i.e. planting the left foot on the force platform to cut to the right, rotating the body towards the new direction of travel). They then continued running straight through a second 1.5 m wide exit gate positioned 2 m from the force platform at 90° to the angle of the start gate. Participants had a 3 m run-up approach to the first gate and were instructed to complete the task as quickly as possible.

A 10-camera optical motion capture system (200Hz; Bonita B10, Vicon Motion Systems Ltd, UK) synchronised with two force platforms (1000 Hz, AMTI, USA) recorded ground reaction forces (GRFs) and marker positions during each trial. Data were filtered using a fourth order zero-lag Butterworth filter with corner frequency 15 Hz (Kristianslund et al., 2012) then processed using the Vicon Plug-in Gait model to calculate segment kinematics, knee external joint moments and the position of the centre of body mass (COM). In this model the pelvis and thorax angles are defined as YXZ Cardan angles calculated from the rotation transformation of the global laboratory coordinate system (Y aligned with the initial target approach direction, Z vertical, X orthogonal to Y and Z) onto the segment orientation. Stance phase of the cut step, from touchdown to toe-off, was identified using GRF > 10 N.

COM heading angle in the horizontal plane, thorax rotation angle and pelvis rotation angle at the start and end of the cut stance phase were extracted (Figure 1). The mean of the three trials in each direction was used for analysis. Paired Student's t-tests were used to test for differences between the operated and non-operated limbs at touchdown and for differences in the magnitude of change in the variables from touchdown to toe-off. Between-limb differences in COM heading angle at toe-off were also analysed, as this 'exit angle' is relevant to whether or not the task can be successfully completed by passing through the exit gate. Finally, horizontal velocity of the COM at the instant of touchdown was analysed for completeness, although inter-limb asymmetries in this variable have previously been published in an overlapping cohort [8]. Cohen's d standardised effect size (ES) was reported for all group comparisons and interpreted as trivial ($d<0.2$), small ($0.2 \leq d<0.5$), medium ($0.5 \leq d<0.8$) and large ($d \geq 0.8$) [31]. Pearson's correlation coefficients were interpreted as small ($0.1 \leq r<0.3$), moderate ($0.3 \leq r<0.5$) or moderate ($r \geq 0.5$) [31]. Significance was accepted at $\alpha=.05$.

The final angle of heading or body segment orientation at toe-off is the sum of the angle at touchdown and the change in angle during stance. Pearson's correlation was used to analyse whether these two variables were negatively correlated, i.e. whether participants with the largest heading or orientation angle in the direction of travel at the instant of touchdown were also those with the smallest changes in the relevant angle during stance. Cuts from the operated and non-operated limbs were analysed separately.

In order to verify previously-published differences in lower-limb loading between the operated and non-operated limb for this task [8], peak resultant GRF and peak knee moment in each plane (sagittal, frontal and transverse) were extracted as metrics of lower limb loading. These variables were divided by body mass and the mean of the three trials in each direction calculated prior to further analysis. Paired Student's t-tests were used to test for differences between the operated and non-operated limbs.

Results

COM heading angle was more oriented towards the new intended direction of travel at touchdown when cutting from the operated limb (p<.001, ES 0.50), and less deflection took place during the cut stance phase (p<.001, ES 0.46). COM heading angle at toe-off was greater for the non-operated than for the operated limb but with a trivial effect size (p=.006, ES 0.19). The pelvis (p=.001, ES 0.27) and thorax (p<.001, 0.40) were less oriented towards the new direction of travel at touchdown when cutting from the operated limb, but no differences were identified in the rotation of either segment during stance phase (pelvis p=.22, ES 0.09; thorax p=.67, ES 0.03). Horizontal velocity at touchdown was lower when cutting from the operated limb (p<.001, ES 0.38; Table 1).

When cutting from both the operated and the non-operated limbs, angle at touchdown and change in angle during stance phase were negatively correlated for COM heading angle (operated limb r=-.60, p<.001; non-operated limb r=-.58, p<.001; Figure 2) and for pelvis orientation angle (operated limb r=.39, p<.001; non-operated limb r=-.50, p<.001). Participants who had already deflected their COM or oriented their pelvis more towards their new direction of travel by the instant of touchdown were those who deflected or rotated less during stance phase. No correlation was identified for thorax orientation angle.

Peak resultant GRF (p<.001, ES 0.25) and peak knee moments in all three planes (sagittal p<.001, ES 0.72; frontal p<.001, ES 1.16; transverse p<.001, ES 0.75) were greater when cutting from the non-operated limb than from the operated limb (Table 2).

Discussion

Centre of mass heading angle deflection and body rotation characterise cutting manoeuvres and are key determinants of lower-limb joint loading. Both differed in post-

ACLR athletes when cutting from the operated versus the non-operated limb, demonstrating small systematic asymmetries in basic whole-body task execution. Corresponding differences, indicative of reduced loading on the operated limb, were identified in knee joint moments and GRF.

Differences in COM heading angle were evident at initial contact: heading angle was oriented more in the direction of the turn when cutting from the operated than from the non-operated limb. Despite the reduced heading angle deflection during stance on the operated limb, there was therefore a mean inter-limb difference of less than 1.5° between COM heading angles at the end of stance phase (trivial effect; ES 0.19). In combination with the negative correlation observed between heading angle at touchdown and deflection angle during stance for both limbs (Figure 2), this suggests that the final heading angle at toe-off was a controlled target parameter for the manoeuvre, and that participants manipulated approach direction and deflection angle to ensure their desired exit angle was achieved. Athletes may thus be using anticipatory control to modulate lower-limb joint loading, altering their approach direction as well as their speed to reduce the demand of the task whilst still ensuring that they exit the cut at the desired angle to pass through the final gate. Average pre-contact deviations of up to eight degrees from the intended approach direction have previously observed in healthy athletes when performing cutting tasks at faster speeds [18], which may similarly demonstrate adaptation of the approach phase to modify the execution of the manoeuvre in a way that co-optimises task achievement and mechanical loading. Whether the participants' primary target for regulation was approach speed or deflection angle cannot be established from our data because of the covariance of the two parameters [18], but is an interesting focus for future controlled experimental studies. Changing direction on the sports field is often in response to an unanticipated stimulus such as movement of an opponent or the ball, so this level of regulation is unlikely to be possible in a game situation and some combination of reduced task achievement and increased mechanical loading might thus be expected in comparison to pre-planned manoeuvres. Indeed, laboratory studies have consistently found unplanned reactive cutting manoeuvres to have a higher rate of task failure and greater stance limb joint mechanical loading than pre-planned manoeuvres [32–35].

Changing direction, particularly at higher speeds and through larger angles, takes place over more than one step [36]. The change in COM heading angle during stance when cutting from either limb was much larger than the change in body (pelvis and thorax) rotation angle (Table 1), and over a third of the total 90° pelvis rotation required for the complete manoeuvre had already been completed by the time the stance foot landed on the ground. This is in contrast to the behaviour exhibited when changing direction in walk, in which the COM is deflected first and then the body rotated [37]. The body rotation requirement for cutting hence appears to be more evenly distributed over multiple steps than COM deflection, and may present less of a localised demand on the operated limb during the main cut stance step. The relative contribution of body rotation to lower-limb loading is unclear: cutting tasks (COM deflection plus body rotation) have been reported to be associated with higher external knee abduction, flexion [38] and rotation [39] moments than sidestep tasks (COM deflection only), but deflection angles were not explicitly compared or controlled in these studies so the differences may have resulted solely or partly from between-task disparities in COM deflection. The temporal sequence of rotation and deflection within stance phase may also affect knee loading, but no systematic differences in the orientation of the thorax relative to the pelvis across stance phase were found in previous investigations of inter-limb differences after ACLR [8,9] so such differences do not appear to be evident in this population. While COM heading angle at touchdown was oriented more towards the new direction of travel when cutting from the operated than from the non-operated limb, the opposite was true for pelvis and thorax orientation at touchdown. This is congruent with the previously-reported associations between reduced body rotation in the direction of travel at touchdown and lower speeds or smaller cutting angles [30,40].

Covert modifications to task execution to reduce the mechanical demands on the operated limb after ACLR have been observed in a variety of other movements. When instructed to perform an identical task on the operated and non-operated limbs, post-ACLR athletes have been found to modify drop technique to reduce vertical velocity at landing on the operated side [41,42], use the push-off from the non-operated limb to accelerate the body upwards and to reduce landing velocity in a step-up task [42], and to reduce running speed in the approach to a cut step to be performed from the operated limb [8]. These anticipatory modifications are presumably in response to awareness of reduced neuromuscular capacity and/or confidence in the affected limb. Understanding the extent to which task modifications influence the outcome measures of interest is key to the interpretation of inter-limb differences in joint-level biomechanical variables, i.e. discerning whether the athlete is performing the same task with a different movement pattern for each limb or whether the task itself has been altered in a way that changes the mechanical demands on the body. As well as the effect of injury, such considerations are also relevant in the context of understanding the influence of training and rehabilitation interventions [43–45], anticipation [35,46] and gender [19,47] on joint-level cutting biomechanics.

Only male multi-directional field sports athletes were included in this study, so the findings should not be assumed to generalise to other cohorts. Gender and skill level have previously been reported to affect change of direction mechanics [47–49] so different strategies may be used by female athletes or by those unfamiliar with this type of manoeuvre. Graft type is also known to influence knee strength and jump loading asymmetries at this post-surgical timepoint [11,50] so results may differ in alternative cohorts with disparate graft selections. The absolute accuracy of the reported orientations is limited by soft tissue artefact and the use of generic scaled segment inertial parameters to calculate the position of the body COM, but our conclusions regarding inter-limb asymmetries are expected to be robust to this type of error due to the within-subject nature of the study design.

All the effects we identified for touchdown and stance phase inter-limb asymmetries had small to medium standardised effect sizes (ES 0.27-0.50) and represented mean asymmetries of 2.6-4.2°, similar to many of the joint-level inter-limb angle differences previously reported [8]. To provide context, the difference in thorax orientation angle at touchdown between cuts from the ACLR and from the non-ACLR limbs (3.7 ± 5.1°) was similar to the difference between this metric when comparing cutting in a pre-planned direction to cutting in a direction indicated by a light stimulus two steps prior to the cut (mean 4.0°) [51]. Whether asymmetries of these magnitudes are sufficient to influence the interpretation of limb mechanics during cutting manoeuvres is unknown: Further work is thus needed to determine the clinical relevance of the established task execution differences and identify contexts in which they may or may not need to be considered when interpreting joint-level biomechanical variables after ACLR.

Our findings suggest that small systematic asymmetries in whole-body task execution are present when sidestep cutting manoeuvres are performed from the operated versus from the non-operated limb 8-10 months post-ACLR. These differences are likely indicative of the use of anticipatory control strategies to co-optimise task achievement and mechanical loading, and may require consideration when interpreting joint-level inter-limb asymmetries in athletes returning to sport after ACL reconstruction.

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References

1. Taylor JB, Wright AA, Dischiavi SL, Townsend MA, Marmon AR. Activity Demands During Multi-Directional Team Sports: A Systematic Review. *Sport Med*. 2017;47(12):2533-2551. doi:10.1007/s40279-017-0772-5
2. Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surgery, Sport Traumatol Arthrosc*. 2009;17(7):705-729. doi:10.1007/s00167-009-0813-1
3. Boden BP, Dean CS, Feagin JA, Garrett WE. Mechanisms of anterior cruciate ligament injury. *Orthopedics*. 2000;23(6):573-578. doi:10.3928/0147-7447-20000601-15
4. Griffin LY, Agel J, Albohm MJ, et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg*. 2000;8(3):141-150. doi:10.5435/00124635-200005000-00001
5. Beynnon BD, Johnson RJ, Abate JA, Fleming BC, Nichols CE. Treatment of anterior cruciate ligament injuries, part I. *Am J Sports Med*. 2005;33(10):1579-1602. doi:10.1177/0363546505279913
6. Beynnon BD, Johnson RJ, Abate JA, Fleming BC, Nichols CE. Treatment of anterior cruciate ligament injuries, Part 2. *Am J Sports Med*. 2005;33(11):1751-1767. doi:10.1177/0363546505279922
7. Myklebust G, Bahr R. Return to play guidelines after anterior cruciate ligament surgery. *Br J Sports Med*. 2005;39:127-131.
8. King E, Richter C, Franklyn-Miller A, et al. Biomechanical but not timed performance asymmetries persist between limbs 9 months after ACL reconstruction during planned and unplanned change of direction. *J Biomech*. 2018;81:93-103. doi:10.1016/j.jbiomech.2018.09.021
9. King E, Richter C, Franklyn-Miller A, Wadey R, Moran R, Strike S. 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. *Am J Sports Med*. 2019;47(5):1175-1185. doi:10.1177/0363546519830656
10. Orishimo KF, Kremenic IJ, Mullaney MJ, McHugh MP, Nicholas SJ. Adaptations in single-leg hop biomechanics following anterior cruciate ligament reconstruction. *Knee Surgery, Sport Traumatol Arthrosc*. 2010;18(11):1587-1593. doi:10.1007/s00167-010-1185-2
11. Miles JJ, King E, Falvey ÉC, Daniels KAJ. Patellar and hamstring autografts are associated with different jump task loading asymmetries after ACL reconstruction. *Scand J Med Sci Sports*. 2019;0:1-11. doi:10.1111/sms.13441
12. King E, Richter C, Franklyn-Miller A, et al. Whole-body biomechanical differences between limbs exist 9 months after ACL reconstruction across jump/landing tasks. *Scand J Med Sci Sports*. 2018:1-12. doi:10.1111/sms.13259
13. Gokeler A, Hof AL, Arnold MP, Dijkstra PU, Postema K, Otten E. Abnormal landing

strategies after ACL reconstruction. *Scand J Med Sci Sport*. 2010;20(1):12-19. doi:10.1111/j.1600-0838.2008.00873.x
14. Smeets A, Verheul J, Vanrenterghem J, et al. *Single-Joint and Whole-Body Movement Changes in ACL Athletes Returning to Sport*.; 2020. doi:10.1249/mss.0000000000002308
15. Paterno M V., Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med*. 2010;38(10):1968-1978. doi:10.1177/0363546510376053
16. McBurnie AJ, Dos'Santos T, Jones PA. Biomechanical Associates of Performance and Knee Joint Loads During A 70–90° Cutting Maneuver in Subelite Soccer Players. *J Strength Cond Res*. 2019:1-9. doi:10.1519/jsc.0000000000003252
17. David S, Mundt M, Komnik I, Potthast W. Understanding cutting maneuvers – The mechanical consequence of preparatory strategies and foot strike pattern. *Hum Mov Sci*. 2018;62(November 2017):202-210. doi:10.1016/j.humov.2018.10.005
18. Vanrenterghem J, Venables E, Pataky T, Robinson MA. The effect of running speed on knee mechanical loading in females during side cutting. *J Biomech*. 2012;45(14):2444-2449. doi:10.1016/j.jbiomech.2012.06.029
19. Sigward SM, Cesar GM, Havens KL. Predictors of Frontal Plane Knee Moments During Side-Step Cutting to 45 and 110 Degrees in Men and Women: Implications for Anterior Cruciate Ligament Injury. *Clin J Sport Med*. 2015;25(6):529-534.
20. Havens KL, Sigward SM. Whole body mechanics differ among running and cutting maneuvers in skilled athletes. *Gait Posture*. 2015;42(3):240-245. doi:10.1016/j.gaitpost.2014.07.022
21. Schot P, Dart J, Schuh M. Biomechanical analysis of two change-of-direction maneuvers while running. *J Orthop Sports Phys Ther*. 1995;22(6):254-258.
22. Schreurs MJ, Benjaminse A, Lemmink KAPM. Sharper angle, higher risk? The effect of cutting angle on knee mechanics in invasion sport athletes. *J Biomech*. 2017;63:144-150. doi:10.1016/j.jbiomech.2017.08.019
23. Kristianslund E, Faul O, Bahr R, Myklebust G, Krosshaug T. Sidestep cutting technique and knee abduction loading: Implications for ACL prevention exercises. *Br J Sports Med*. 2014;48(9):779-783. doi:10.1136/bjsports-2012-091370
24. Havens KL, Sigward SM. Joint and segmental mechanics differ among running and cutting maneuvers in skilled athletes. *Gait Posture*. 2015;41(1):33-38. doi:10.1016/j.gaitpost.2014.07.022
25. Dai B, Garrett WE, Gross MT, Padua DA, Queen RM, Yu B. The effect of performance demands on lower extremity biomechanics during landing and cutting tasks. *J Sport Heal Sci*. 2019;8(3):228-234. doi:10.1016/j.jshs.2016.11.004
26. Dos'Santos T, Thomas C, Comfort P, Jones PA. The effect of angle and velocity on change of direction biomechanics: An angle-velocity trade-off. *Sport Med*. 2018;48(10):2241-2259. doi:10.1007/s40279-018-0968-3
27. Besier TF, Lloyd DG, Cochrane JL, Ackland TR. External loading of the knee joint during running and cutting maneuvers. *Med Sci Sports Exerc*. 2001;33(7):1168-1175. doi:10.1097/00005768-200301000-00019
28. Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: The Delaware-Oslo ACL cohort study. *Br J Sports Med*. 2016;50(13):804-808. doi:10.1136/bjsports-2016-096031
29. Morris RC, Hulstyn MJ, Fleming BC, Owens BD, Fadale PD. Return to play following anterior cruciate ligament reconstruction. *Clin Sports Med*. 2016;35(4):655-668.

doi:10.1016/j.csm.2016.05.009

30. Marshall BM, Franklyn-Miller AD, King E, et al. Biomechanical factors associated with time to complete a change of direction cutting maneuver. *J Strength Cond Res*. 2014;28(10):2845-2851. doi:10.1519/JSC.0000000000000463
31. Cohen J. A Power Primer. *Psychol Bull*. 1992;112(1):155-159. doi:10.1037/0033-2909.112.1.155
32. Almonroeder TG, Garcia E, Kurt M. The Effects of Anticipation on the Mechanics of the Knee During Single-Leg Cutting Tasks: A Systematic Review. *Int J Sports Phys Ther*. 2015;10(7):918-928.
33. Brown SR, Brughelli M, Hume PA. Knee Mechanics During Planned and Unplanned Sidestepping: A Systematic Review and Meta-Analysis. *Sport Med*. 2014;44(11):1573-1588. doi:10.1007/s40279-014-0225-3
34. Lee MJC, Lloyd DG, Lay BS, Bourke PD, Alderson JA. Different visual stimuli affect body reorientation strategies during sidestepping. *Scand J Med Sci Sport*. 2017;27(5):492-500. doi:10.1111/sms.12668
35. Lee MJC, Lloyd DG, Lay BS, Bourke PD, Alderson JA. Effects of different visual stimuli on postures and knee moments during sidestepping. *Med Sci Sports Exerc*. 2013;45(9):1740-1748. doi:10.1249/MSS.0b013e318290c28a
36. Andrews JR, McLeod WD, Ward T, Howard K. The cutting mechanism. *Am J Sports Med*. 1977;5(3):111-121. doi:10.1177/036354657700500303
37. Patla AE, Adkin A, Ballard T. Online steering: coordination and control of body center of mass, head and body reorientation. *Exp Brain Res*. 1999;129(4):0629-0634. doi:10.1007/s002210050932
38. Tanikawa H, Matsumoto H, Komiyama I, Kiriyama Y, Toyama Y, Nagura T. Comparison of knee mechanics among risky athletic motions for noncontact anterior cruciate ligament injury. *J Appl Biomech*. 2013;29(6):749-755. doi:10.1123/jab.29.6.749
39. Mok KM, Bahr R, Krosshaug T. Reliability of lower limb biomechanics in two sport-specific sidestep cutting tasks. *Sport Biomech*. 2018;17(2):157-167. doi:10.1080/14763141.2016.1260766
40. Dos'Santos T, McBurnie A, Thomas C, Comfort P, Jones PA. Biomechanical determinants of the modified and traditional 505 change of direction speed test. *J Strength Cond Res*. 2019;0(0):1-12. doi:10.1519/JSC.0000000000003439
41. Richter C, King E, Strike S, Franklyn-Miller A. Objective classification and scoring of movement deficiencies in patients with anterior cruciate ligament reconstruction. *PLoS One*. 2019;14(7):e0206024.
42. Baumgart C, Schubert M, Hoppe MW, Gokeler A, Freiwald J. Do ground reaction forces during unilateral and bilateral movements exhibit compensation strategies following ACL reconstruction? *Knee Surgery, Sport Traumatol Arthrosc*. 2017;25(5):1385-1394. doi:10.1007/s00167-015-3623-7
43. Dos'Santos T, Thomas C, Comfort P, Jones PA. The Effect of Training Interventions on Change of Direction Biomechanics Associated with Increased Anterior Cruciate Ligament Loading: A Scoping Review. *Sport Med*. 2019;49(12):1837-1859. doi:10.1007/s40279-019-01171-0
44. King E, Franklyn-Miller A, Richter C, et al. Clinical and biomechanical outcomes of rehabilitation targeting intersegmental control in athletic groin pain: prospective cohort of 205 patients. *Br J Sports Med*. 2018;52:1054-1062. doi:10.1136/bjsports-2016-097089
45. Yang C, Yao W, Garrett WE, et al. Effects of an Intervention Program on Lower Extremity Biomechanics in Stop-Jump and Side-Cutting Tasks. *Am J Sports Med*.

2018;46(12):3014-3022. doi:10.1177/0363546518793393
46. Kim JH, Lee K, Kong SJ, An KO. Effect of Anticipation on Lower Extremity Biomechanics During Side- and Cross- Cutting Maneuvers in Young Soccer Players. *Am J Sports Med*. 2014;42(8):1985-1992. doi:10.1177/0363546514531578
47. Pollard CD, Davis IMC, Hamill J. Influence of gender on hip and knee mechanics during a randomly cued cutting maneuver. *Clin Biomech*. 2004;19(10):1022-1031. doi:10.1016/j.clinbiomech.2004.07.007
48. Green BSB, Blake C, Caulfield BM. A comparison of cutting technique performance in rugby union players. *J Strength Cond Res*. 2011;0(0):1-13.
49. Sigward SM, Pollard CD, Havens K, Powers CM. The influence of sex and maturation on knee mechanics during sidestep cutting. *Med Sci Sports Exerc*. 2012;44(8):1497-1503. doi:10.1249/MSS.0b013e31824e8813
50. Xergia SA, McClelland JA, Kvist J, Vasiliadis HS, Georgoulis AD. The influence of graft choice on isokinetic muscle strength 4-24 months after anterior cruciate ligament reconstruction. *Knee Surgery, Sport Traumatol Arthrosc*. 2011;19(5):768-780. doi:10.1007/s00167-010-1357-0
51. Mornieux G, Gehring D, Fürst P, Gollhofer A. Anticipatory postural adjustments during cutting manoeuvres in football and their consequences for knee injury risk. *J Sports Sci*. 2014;32(13):1255-1262. doi:10.1080/02640414.2013.876508

Figures

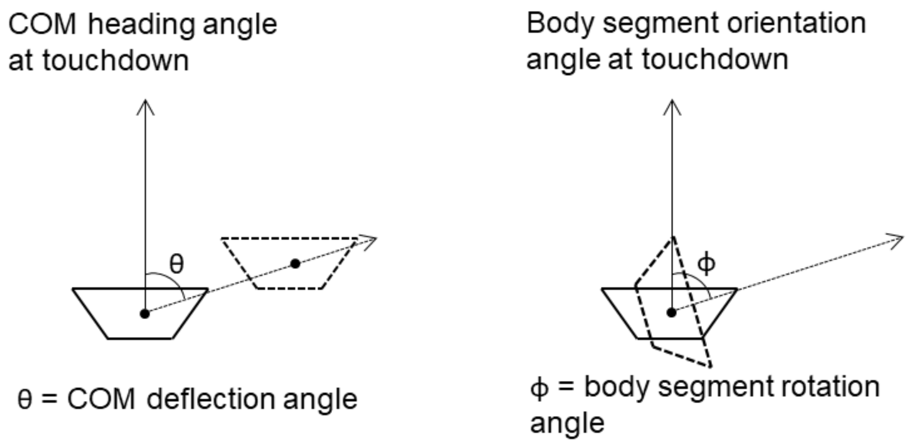

Figure 1 Variables defining COM heading and deflection angles (left) and pelvis and thorax body segment orientation and rotation angles (right) during the change of direction stance phase.

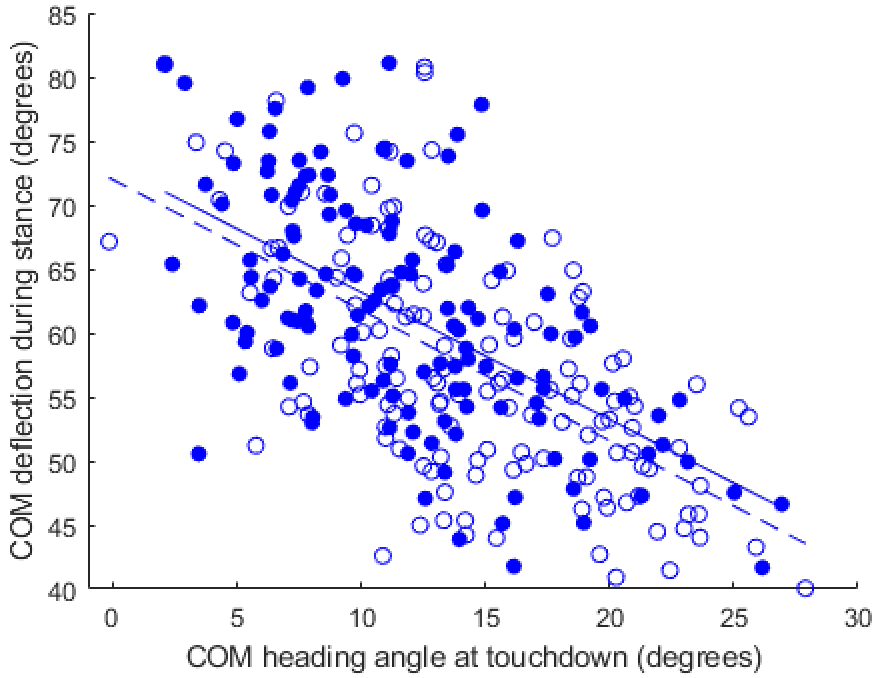

Figure 2 Relationship between COM heading angle at touchdown and COM heading angle deflection during the cut stance phase. Blue open circles and broken least-squares line represent cutting manoeuvres from the operated limb (r=-0.60, p<0.001); blue filled circles and unbroken least-squares line represent cutting manoeuvres from the non-operated limb (r=-0.58, p<0.001).

Tables

Table 1 Change of direction stance phase centre of mass heading angle, horizontal velocity and body segment orientation.

Variable	Operated		Non-operated		95% CI	*p*	ES
	Mean	SD	Mean	SD			
COM heading angle at touchdown (°)	14.4	5.5	11.8	5.3	-3.6--1.9	<.001*	0.50
COM heading angle stance phase deflection (°)	57.3	9.2	61.4	8.9	3.0-5.6	<.001*	0.46
COM heading angle at toe-off (°)	71.7	7.4	73.2	7.3	0.5-2.6	.006*	0.19
Pelvis orientation angle at touchdown (°)	29.2	10.8	32.1	10.6	1.1-4.5	.001*	0.27
Pelvis orientation angle stance phase rotation (°)	19.8	7.7	20.6	8.9	-0.5-2.3	.219	0.09
Thorax orientation angle at touchdown (°)	14.8	9.5	18.5	9.3	2.0-5.4	<.001*	0.40
Thorax orientation angle stance phase rotation (°)	31.6	11.2	32.0	12.2	-1.4-2.1	.686	0.03
COM horizontal velocity at touchdown (m/s)	2.6	0.3	2.8	0.3	0.1-0.2	<.001*	0.38

Note. A positive touchdown or toe-off angle represents a COM trajectory/body segment oriented towards the new intended direction of travel; a positive stance phase deflection or rotation represents a turn towards the new intended direction of travel during stance phase. CI = confidence interval; ES = Cohen's d standardised effect size. *P* values are followed by an asterisk if the null hypothesis for the inter-limb comparison was rejected.

Table 2 Change of direction stance phase peak ground reaction force and knee moments

Variable	Operated		Non-operated		95% CI	*p*	ES
	Mean	SD	Mean	SD			
Peak resultant GRF ($N.kg^{-1}$)	16.3	3.3	17.1	3.4	0.4-1.4	<.001*	0.25
Peak knee flexion moment ($N.m.kg^{-1}$)	2.4	0.6	2.9	0.7	0.3-0.6	<.001*	0.72
Peak knee abduction moment ($N.m.kg^{-1}$)	1.0	0.5	1.6	0.7	0.6-0.8	<.001*	1.16
Peak knee internal rotation moment ($N.m.kg^{-1}$)	0.2	0.1	0.3	0.2	0.1-0.2	<.001*	0.75

Note. GRF = ground reaction force; CI = confidence interval; ES = Cohen's d standardised effect size. *P* values are followed by an asterisk if the null hypothesis for the inter-limb comparison was rejected.