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Are inter-limb differences in change of direction velocity and angle associated with inter-limb differences in kinematics and kinetics following anterior cruciate ligament reconstruction?

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ABSTRACT

Background: Quantifying inter-limb differences in kinematics and kinetics during change of direction is proposed as a means of monitoring rehabilitation following anterior cruciate ligament reconstruction (ACLR). Velocity and centre of mass (CoM) deflection angle are fundamental task descriptors that influence kinematics and kinetics during change of direction. Inter-limb differences in approach velocity and CoM deflection angle have been identified following ACLR and may contribute to the presence of inter-limb differences in kinematics and kinetics during change of direction.

Research question: The aim of this study was to quantify the proportion of variance in kinematic and kinetic inter-limb differences attributable to inter-limb differences in approach velocity and centre of mass deflection angle during a change of direction task.

Methods: A cohort of 192 patients (male, 23.8 ± 3.6 years, 6.3 ± 0.4 months post primary ACLR) completed a pre-planned 90° change of direction task on both their operated and non-operated limb. Inter-limb differences in approach velocity and CoM deflection angle were calculated alongside lower-extremity kinematic and kinetic variables. The relationship between inter-limb differences in task-level variables and inter-limb differences in kinematic and kinetic variables was examined using linear regression models. Kinematic and kinetic inter-limb differences were adjusted for inter-limb differences in approach velocity and CoM deflection angle. Adjusted and unadjusted inter-limb differences were submitted to one sample t-tests.

Results: Inter-limb differences in approach velocity and centre of mass deflection angle explained 3 – 60% of the variance in kinematic and kinetic inter-limb differences. Statistical inferences remained consistent between adjusted and unadjusted conditions with the exception of hip flexion angle.

Significance: Inter-limb differences in task-level features explain a large proportion of the variance in inter-limb differences in several kinematic and kinetic variables. Accounting for this variation reduced the magnitude of kinematic and kinetic inter-limb differences comparable to those previously observed in normative cohorts.

1. Introduction

Quantifying inter-limb differences in kinematic and kinetic variables during change of direction (CoD) is proposed as a means of monitoring rehabilitation and informing return to play decision making following anterior cruciate ligament reconstruction (ACLR) [1–4]. CoD is the most common mechanism of non-contact anterior cruciate ligament (ACL) injury and a major component of post-ACLR rehabilitation is the reintroduction of these movements in the period preceding return to sport [5,6]. Approach velocity and centre of mass (CoM) deflection angle are fundamental CoD task descriptors that reflect the whole body demands of every CoD movement, influencing both technique and knee joint loading [7–9]. In an attempt to control for the effect of approach velocity and CoM deflection angle, studies examining inter-limb differences in kinematics and kinetics during CoD typically instruct participants to change direction at maximal velocity and through the same

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pre-defined angle when turning off each limb [1,2,10–12].

In ACLR patients, inter-limb differences in kinematics and kinetics during CoD are interpreted as reflecting altered limb-level differences during the completion of equivalent CoD tasks on both limbs. For example, King et al. (2018) identified multiple kinematic and kinetic inter-limb differences associated with reduced knee joint loading on the ACLR limb during 90° CoD tasks. Smaller knee flexion angles as well as smaller tri-planar knee joint moments were noted when changing direction from the ACLR limb, despite no statistically significant difference in task completion times between sides. This has been viewed as evidence that, when completing equivalent CoD tasks on both limbs, i.e. at the same velocity and through the same angle, ACLR patients reduce the magnitude of knee joint loading when changing direction from their ACLR limb via modifications to their movement patterns during CoD stance phase, likely as a compensatory mechanism in response to reduced physical capacity and/or psychological deficits that may be present following injury and rehabilitation [1,13,14].

Assumptions of task equivalency during CoD may be unfounded, as recent evidence demonstrates that individuals systematically modify task constraints during CoD after ACLR. Inter-limb differences in both approach velocity and CoM deflection angle during stance have been observed in ACLR patients during pre-planned CoD tasks [1,15]. When turning off their ACLR limb, individuals change direction with slower approach velocities and smaller CoM deflection angles compared to when turning off their non-ACLR limb despite being given identical task instructions. Slower approach velocities require smaller posteriorly-directed GRFs and impulses to decelerate, while smaller CoM deflection angles necessitate smaller horizontally-directed GRFs and impulses to redirect the CoM in the intended direction of travel. Changing direction at slower velocities and through smaller angles has been associated with smaller ground reaction forces (GRFs) [9], smaller knee flexion angles [8] and smaller knee joint moments during stance phase in uninjured cohorts [8,16]. Task-level modifications to approach velocity and CoM deflection angle may thus be an additional method used by ACLR patients to reduce the magnitude of knee joint loading when changing direction from the ACLR limb.

It is possible that inter-limb differences in approach velocity and CoM deflection angle during CoD contribute, at least in part, to the presence of inter-limb differences in kinematics and kinetics commonly observed following ACLR. Studies examining inter-limb differences in kinematics and kinetics in ACLR patients during CoD report differences consistent with those which would be expected to arise from slower approach velocities and smaller CoM deflection angles when changing direction from the ACLR limb. Smaller GRFs, knee flexion angles and knee joint moments have been identified when turning off the ACLR limb compared to the non-ACLR limb [1,15]. Inter-limb differences in kinematics and kinetics thus likely reflect a combination of task and limb-level modifications following ACLR, although the extent to which inter-limb differences in approach velocity and CoM deflection angle contribute to inter-limb differences in kinematics and kinetics during CoD is currently unknown. Failing to incorporate the effect of task level inter-limb differences on kinematic and kinetic inter-limb differences, may see kinematic and kinetic inter-limb differences incorrectly attributed solely to limb-level compensations, when actually reflecting a combination of task and limb-level differences.

The aim of this study was to determine the proportion of variance in inter-limb differences in kinematics and kinetics during a 90° CoD task that can be explained by task-level inter-limb differences 6-months post ACLR. We hypothesized that inter-limb differences in approach velocity would be associated with inter-limb differences in kinematics and kinetics during CoD, and that adjusting for these differences would reduce the magnitude of joint level differences by a clinically meaningful extent.

2. Methods

A cohort of 192 male participants aged 18–35 years (23.8 ± 3.6) approximately 6 months (6.3 ± 0.4) post primary ACLR were recruited consecutively from the case load of two orthopaedic surgeons based in the Sports Surgery Clinic, Dublin, Ireland. All patients underwent either bone-patellar tendon-bone or hamstring tendon autograft procedures. Inclusion criteria were male, aged 18–35, participation in multi-directional field-based sports prior to injury and the intention to return to the same level of participation post rehabilitation. Exclusion criteria were a history of concurrent ligament reconstructions, previous ACL surgery, meniscal repair, full-thickness chondral injury, or no intention to return to the same level of multi- directional sport. Ethical approval was received from the University of Roehampton, London (LSC 15/122) and the Sports Surgery Clinic Hospital Ethics Committee (25AFM010). Participants gave informed, written consent prior to participation in the study.

Data collection took place in a biomechanics laboratory using a 10-camera motion analysis system (200 Hz; Bonita-B10, Vicon, UK), synchronized with two force platforms (1000 Hz BP400600, AMTI, USA), recording the positions of 28 reflective markers (14 mm diameter). Markers were secured at bony landmarks on the lower limbs, pelvis and trunk according to a modified Plug-in-Gait marker set [17]. Each participant completed a pre-planned 90° CoD task which followed a wider testing battery that formed part of a larger on-going study. The CoD task involved the participant running straight towards the force platforms positioned 5 m from the starting point, planting their outside foot on the force platform to cut right or left (i.e. planting their right foot to turn left), turning and running towards the finish line positioned 2 m from the centre of the force platform at 90° angle to the start line (Fig. 1A). Participants were instructed to complete the task as quickly as possible. Trials were considered successful if the participant made a full foot contact with the force platform when turning. Three successful trials were collected when turning off the non-ACLR limb, followed by three successful trials turning off the ACLR limb. A rest period of 30 s was given between trials. A fourth order zero-lab Butterworth filter (cut-off frequency 15 Hz) was used to filter marker trajectory and force data [18].

2.1. *Task-level variables*

Task-level variables analysed were horizontal approach velocity at initial contact and CoM deflection angle during CoD stance phase. Initial contact and toe-off were identified in each trial from when vertical GRF went above and below 20 N. Horizontal velocity was defined as CoM resultant velocity at initial contact in the horizontal plane using a moving average filter (5 frame span). CoM deflection angle during stance was calculated as the difference between the orientation of the velocity vector at initial contact and at toe-off in the horizontal plane (Fig. 1B). Mean values for ACLR and non-ACLR limbs were calculated using the three trials collected on each limb.

2.2. *Kinematic and kinetic variables*

Kinematic and kinetic variables analysed were vertical GRF, braking impulse, propulsion impulse, medio-lateral impulse, tri-planar joint angles at the hip, knee and ankle as well as tri-planar knee joint moments. GRF data were rotated to align with the body's local co-ordinate system before analysis [9]. Medio-lateral and anterior-posterior impulses were calculated by integrating the rotated medio-lateral and anterior-posterior GRFs respectively. Braking impulse was determined as negative anterior-posterior impulse and propulsion impulse as positive anterior-posterior propulsion impulse.

Joint level kinematic and kinetic variables were extracted during the deceleration phase of the CoD task. Non-contact ACL injuries occur within this phase and it is widely studied in CoD and ACLR literature

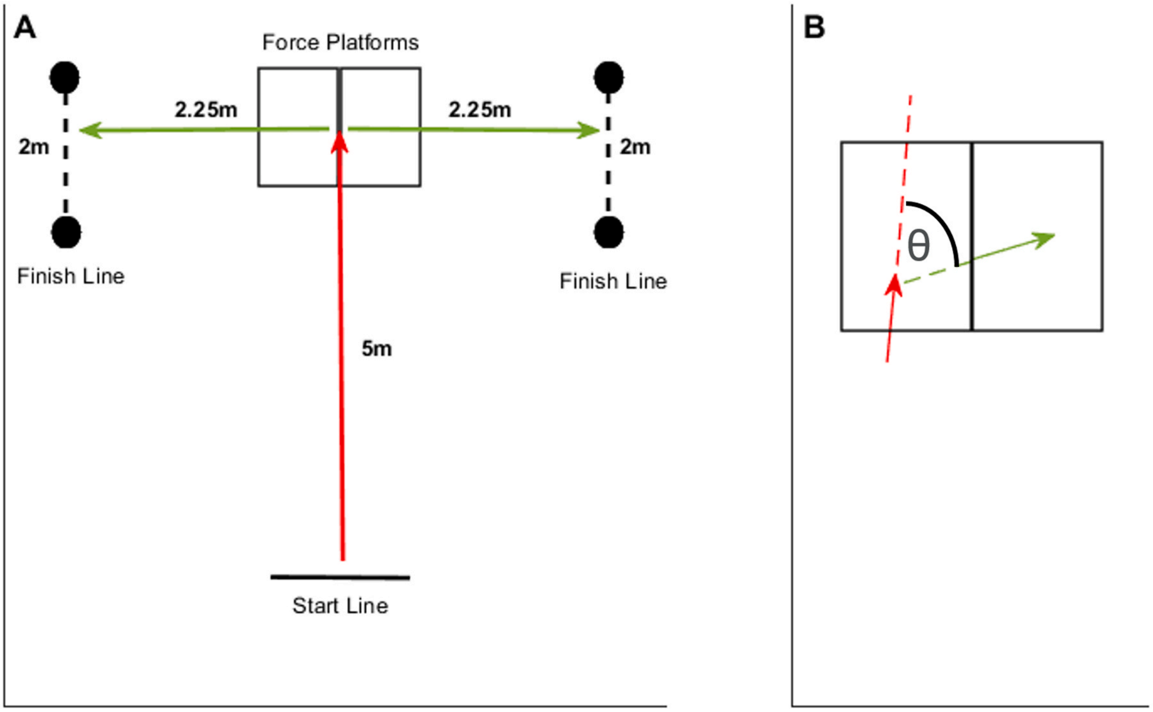

Fig. 1. Diagram of diagram of the 90° CoD task (Fig. 1A). Participants ran 5 m towards the laboratory force platforms before turning to either their right or left and running a further 2.25 m from the centre of the force platforms to the finishing line, denoted by timing gates positioned 2 m apart. Depiction of CoM deflection angle during stance phase for a change of direction planting on the left limb and turning to the right (Fig. 1B). This was calculated as the difference between the orientation of the velocity vector of the centre of mass at initial contact (red vector) and the orientation of the velocity vector at toe-off (green vector). Figure not to scale.

[16,19–21]. The deceleration phase was defined as from initial contact to the point of maximal knee flexion. Peak vertical GRF (vGRF), peak joint angles in each plane at the hip, knee and ankle, as well as peak tri-planar knee joint moments, were extracted from this phase. Mean values for the ACLR and non-ACLR limbs were calculated using values from the three trials collected on each limb.

2.3. Regression analysis

Inter-limb differences were calculated for both task variables and kinematic and kinetic variables as:

$$NonACLR \quad Limb - ACLR \quad Limb$$

Kinematic and kinetic inter-limb differences were submitted to a simple linear regression model against approach velocity and CoM deflection angle inter-limb differences separately. Kinematic and kinetic inter-limb differences with no significant linear regression coefficients for either approach velocity or CoM deflection angle inter-limb differences were excluded from further analysis as this indicated they were not affected by velocity or CoM deflection angle inter-limb differences. For kinematic and kinetic inter-limb differences with significant regression coefficients for either approach velocity or CoM deflection angles, the corresponding linear regression model produced was used for further analysis. Lastly, kinematic and kinetic inter-limb differences with significant linear regression equations for both approach velocity and CoM deflection angle inter-limb differences were submitted to a multiple linear regression model with inter-limb differences in approach velocity entered first, followed by inter-limb differences in CoM deflection angle. This mirrored the mechanistic sequence of the CoD task where the approach velocity preceded CoM deflection angle.

The intercept value for each variable was taken as the predicted value of joint level inter-limb differences if the corresponding inter-limb difference in approach velocity and/or CoM deflection angle was equal to 0. Each individual kinematic and kinetic inter-limb difference was then adjusted by removing the variance explained by the predictor variable(s). Inter-limb differences were adjusted using:

$$ILD_{adj} = ILD_{org} \quad - \left(ILD_{pv1} \times \beta_1\right) - \left(ILD_{pv2} \times \beta_2\right)$$

where ILD_{org} is the individual's original inter-limb difference for the kinematic or kinetic variable, ILD_{pv} is the individual's inter-limb difference for the predictor variable (approach velocity and/or CoM deflection angle and β is the beta-coefficient from the model between the predictor variable(s) inter-limb difference(s) and the kinematic or kinetic inter-limb difference (Fig. 2). Adjusted and unadjusted joint level inter-limb differences were submitted to one-samples t-tests against a value of 0 and Cohens' d effect sizes were calculated for both conditions.

3. Results

Mean approach velocities and CoM deflection angles are presented in Figs. 3A and 3B respectively. Inter-limb differences in 11 variables were found to have significant regression equations with CoD approach velocity and/or CoM deflection angle inter-limb differences. These variables and the corresponding predictor variable(s) and r^2 values are presented in Fig. 3C.

Regression models and results from one-sample t-tests for adjusted and unadjusted inter-limb differences are presented in Fig. 4 (GRF-derived variables), Fig. 5 (joint angle variables), and Fig. 6 (joint moment variables).

Inter-limb differences in approach velocity explained 21% of the variance in vGRF inter-limb differences (Fig. 3C), while inter-limb differences in approach velocity and CoM deflection angle explained 60%, 55% and 49% of the variance in braking, medio-lateral and propulsion impulse inter-limb differences respectively (Fig. 3C). Unadjusted inter-limb differences in each variable were statistically significant ($p < 0.05$) with the direction of inter-limb differences demonstrating lower values when turning off the ACLR limb (Fig. 4B, Fig. 4D, Fig. 4F, Fig. 4H). Adjusting for inter-limb differences in approach velocity and/

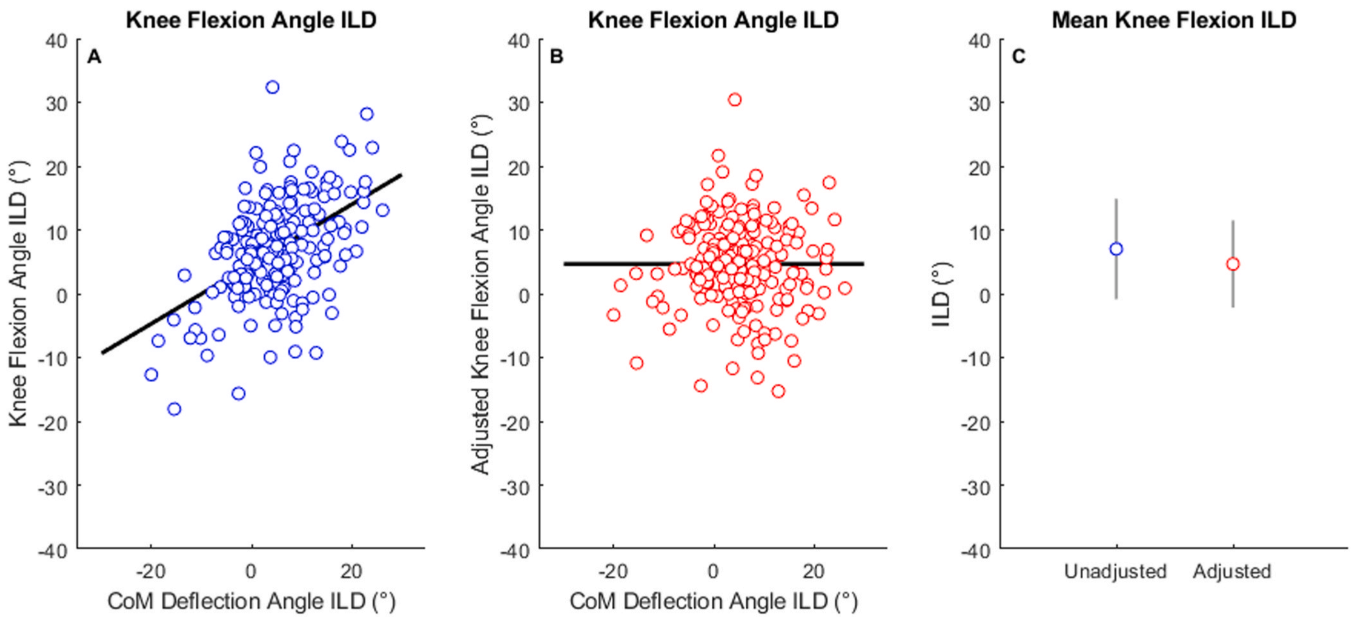

Fig. 2. Example of adjustment process. Fig. 2A depicts the linear regression model for CoM deflection angle inter-limb differences and knee flexion angle inter-limb differences. Fig. 2B depicts knee flexion angle inter-limb differences after the variance attributed to CoM deflection angle inter-limb differences was removed from each data point. Lastly, Fig. 2C depicts the mean and standard deviation of the original unadjusted knee flexion angle inter-limb differences and the adjusted knee flexion angle inter-limb differences.

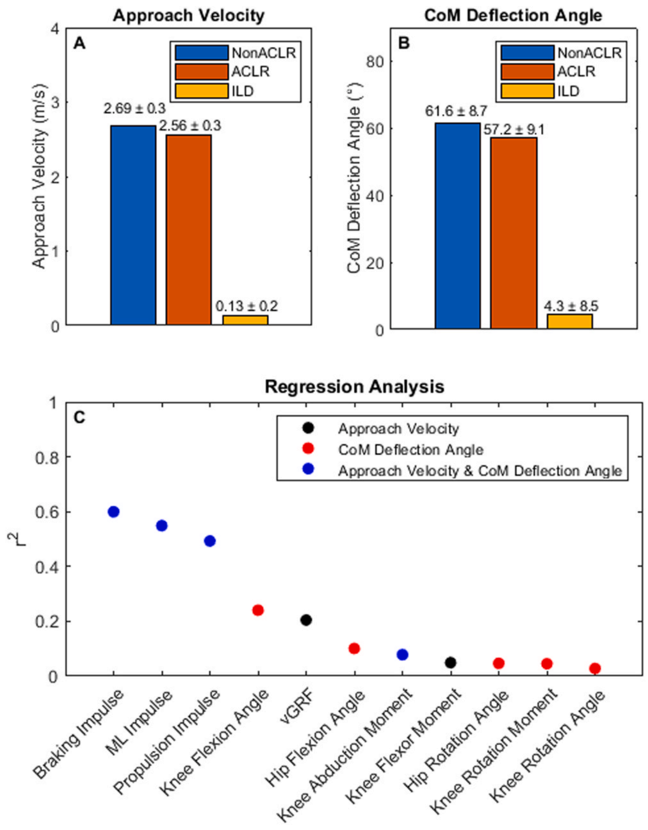

Fig. 3. Mean approach velocities and CoM deflection angles for the NonACLR and ACLR limbs as well as the corresponding inter-limb difference (ILD) (Fig. 3A, Fig3B). Fig. 3C depicts r^2 values for all variables which had significant regression coefficients for approach velocity and/or CoM deflection angle inter-limb differences.

or CoM deflection angle reduced the magnitudes of inter-limb differences by 0.68 N/kg (GRF), 0.03 kg·m/s (braking impulse), 0.03 kg·m/s (medio-lateral impulse) and 0.01 kg·m/s (propulsion impulse). Though the interpretation of statistical significance remained consistent when inter-limb differences were adjusted for approach velocity and CoM deflection angle, inter-limb differences in braking impulse were found to be significant in the opposite direction, i.e. a greater value on the ACLR limb.

Inter-limb differences in CoM deflection angle explained 10% of the variance in hip flexion angle inter-limb differences, 5% in hip rotation angle inter-limb differences, 24% in knee flexion angle inter-limb differences and 3% in knee rotation angle inter-limb differences (Fig. 3C). Unadjusted inter-limb differences in hip flexion, hip rotation, knee flexion and knee rotation angles were all found to be statistically significant ($p < 0.05$), with the direction of the inter-limb differences indicating smaller values when turning off the ACLR limb. Adjusting for inter-limb differences in CoM deflection angle reduced the magnitudes of inter-limb differences by 1.2° (hip flexion), 2° (knee flexion) and 1° (knee rotation) but increased the magnitudes in hip rotation angle by 0.9°. When adjusted for inter-limb differences in CoM deflection angles, the interpretation of statistical significance changed from significant to non-significant for hip flexion angle inter-limb differences (Fig. 5B) but remained consistent for the other kinematic variables (Fig. 5D, Fig. 5F and Fig. 5H).

Inter-limb differences in approach velocity explained 5% of the variance in knee flexor moment inter-limb differences (Fig. 6A), while inter-limb differences in approach velocity and CoM deflection angle explained 8% of the variance in knee abduction moment inter-limb differences (Fig. 3C). Inter-limb differences in CoM deflection angle explained 5% of the variance in knee rotation moment (Fig. 3C). Unadjusted inter-limb differences in knee flexor moment, knee abduction moment and knee rotation moment were all found to be statistically significant ($p < 0.05$). Adjusting for inter-limb differences in approach velocity and/or CoM deflection angle reduced magnitudes by 0.08 Nm/kg (knee flexor moment), 0.14 Nm/kg (knee abduction moment) and 0.02 Nm/kg (knee rotation moment). Initial interpretations of statistical significance remained consistent for all three variables when adjusted.

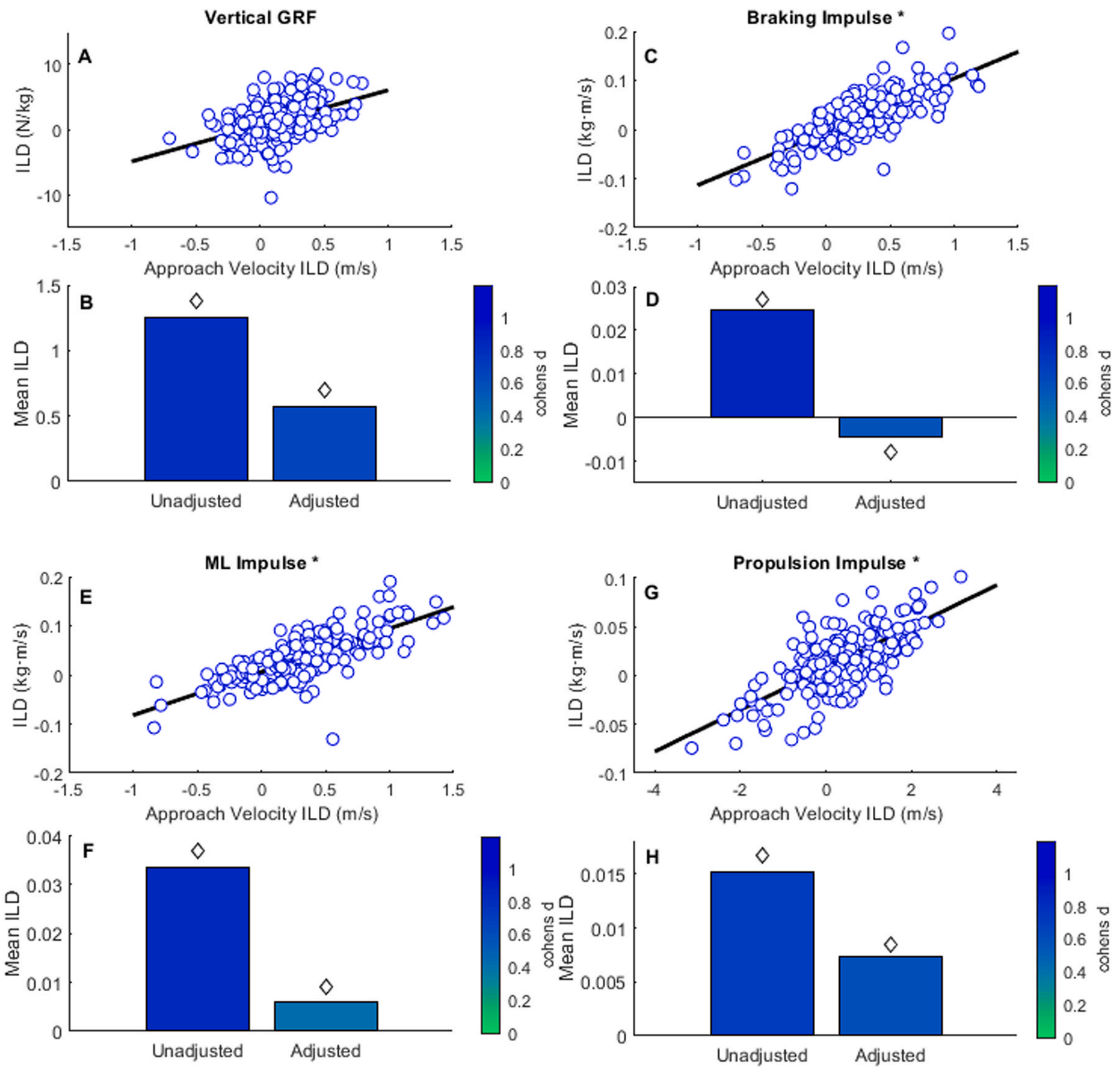

Fig. 4. Relationship between approach velocity and/or CoM deflection angle inter-limb differences and vertical GRF (Fig. 4A), braking impulse (Fg. 4 C), medio-lateral impulse (Fig. 4E) and propulsion impulse (Fig, 4D) inter-limb differences. * in title indicates that a multiple regression model containing both approach velocity and CoM deflection angle was used. Figs. 4B, 4D, 4F and 4H depict the mean inter-limb difference for vertical GRF, braking impulse, medio-lateral impulse and propulsion impulse respectively, in both unadjusted and adjusted conditions.◆ indicates statistical significance ($p < 0.05$) and bar face colour corresponds to Cohens' d effect size.

4. Discussion

Approach velocity and CoM deflection angle are fundamental task descriptors that characterise the whole-body demands of CoD movements. Our results demonstrate that task level inter-limb differences in approach velocity and CoM deflection angle explained between 3% and 60% of the variance in kinematic and kinetic inter-limb differences during a pre-planned 90° CoD task (Fig. 3C). Incorporating the effect of inter-limb differences in task-descriptors into analyses involving kinematic and kinetic inter-limb differences during CoD will provide a better understanding of the primary drivers of inter-limb differences in specific kinematic and kinetic variables, i.e. primarily driven by task or by limb-level modifications, or a combination of both.

Inter-limb differences in velocity and CoM deflection angle were consistent with those previously published, both in terms of magnitude and direction [1,15]. When turning off their ACLR limb, participants changed direction with slower approach velocities and smaller CoM deflection angles compared to when turning off their non-ACLR limb (Fig. 3A, Fig. 3B). Task modifications of this manner appear to be a means of reducing the mechanical demands imposed on the ACLR limb during CoD. For example, the direction of the inter-limb difference for braking impulse switched when adjusted for inter-limb differences in approach velocity and CoM deflection angle, suggesting that the primary mechanism by which ACLR patients reduce deceleration demands during CoD is via task level modifications. (Fig. 4C). While it has been thought that ACLR patients principally control mechanical loading by performing motor tasks with altered movement patterns [22–24], our findings, combined with previous observations of modifications to approach velocity and CoM deflection angles during CoD, demonstrate that ACLR patients also manipulate task constraints as a means of reducing the mechanical demands imposed on their operated limb.

Inter-limb differences in eleven kinematic and kinetic variables were found to have a significant relationship with inter-limb differences approach velocity and/or CoM deflection angle (Fig. 3). The largest r^2 values were observed in GRF impulse, sagittal plane knee angles and vertical GRF. Slower approach velocities and smaller CoM deflection angles on the ACLR limb means that deceleration and redirection demands are less than those imposed on the non-ACLR limb. These

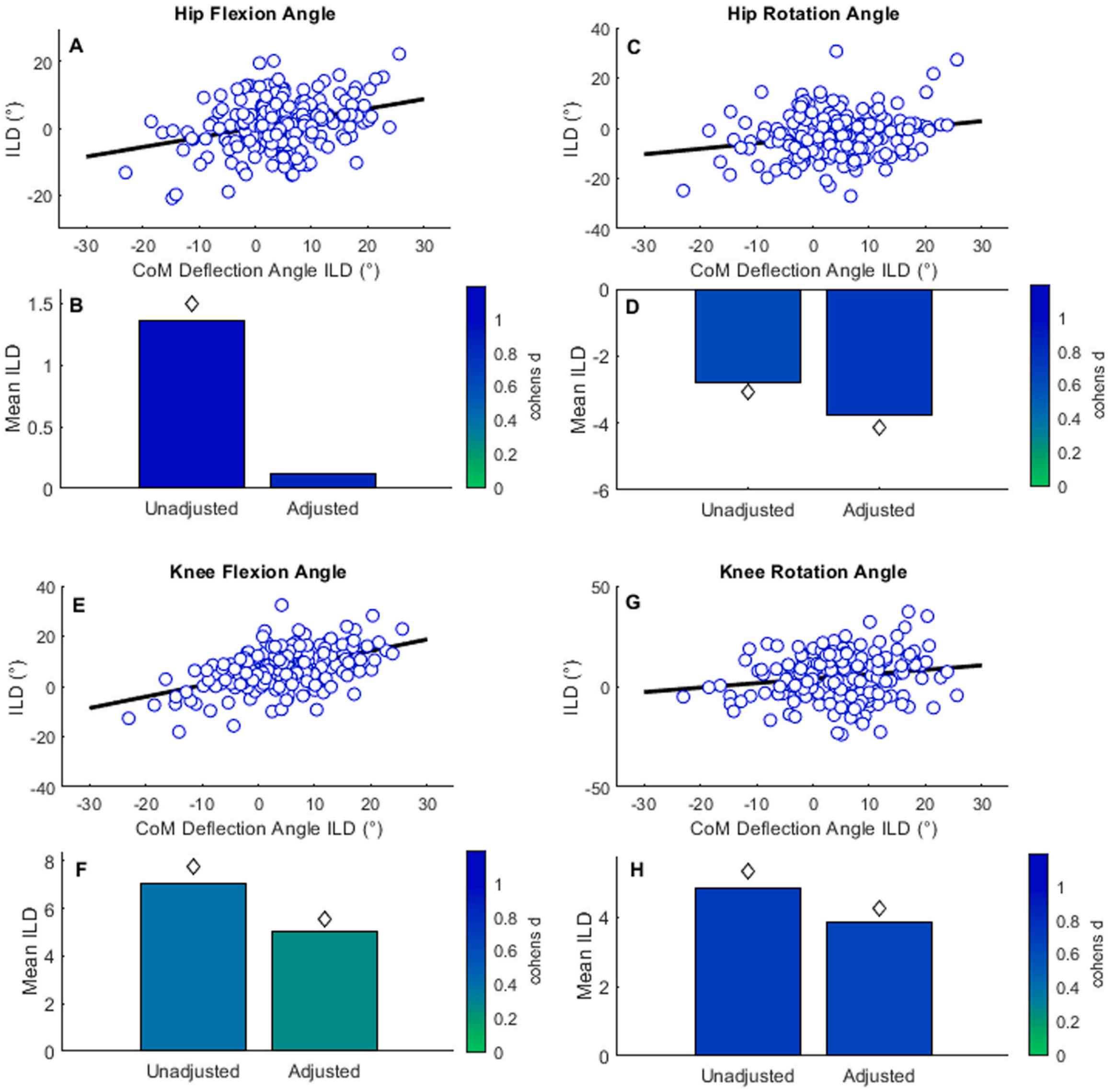

Fig. 5. Relationship between approach velocity and/or CoM deflection angle inter-limb differences and hip flexion angle (Fig. 5A), hip rotation angle (Fig. 5C), knee flexion angle (5E) and knee rotation angle (Fig, 5D) inter-limb differences. * in title indicates that a multiple regression model containing both approach velocity and CoM deflection angle was used. Figs. 5B, 5D, 5F and 5H depict the mean inter-limb difference for hip flexion angle, hip rotation angle, knee flexion angle and knee rotation angle respectively, in both unadjusted and adjusted conditions. ◆ indicates statistical significance ($p < 0.05$) and bar face colour corresponds to Cohens' d effect size.

alterations are associated with smaller GRFs, impulses and knee flexion angles which in turn influences the magnitude of inter-limb differences in these variables.

Adjusting limb-level inter-limb differences for task-level inter-limb differences reduced magnitudes considerably in several variables. For example, mean inter-limb differences of 0.8 N/kg and 5° in GRF and knee flexion angle respectively have been previously identified during CoD tasks in ACLR cohorts [1,15]. Such differences are interpreted as clinically meaningful and thought to be indicative of incomplete rehabilitation as they are greater than those observed in non-injured cohorts. Our data indicate that adjusting inter-limb differences in GRF and knee flexion angle for task level inter-limb differences would reduce their magnitudes to 0.12 N/kg and 3° respectively. For context, these magnitudes are comparable to those observed in normative cohorts, where inter-limb differences of 0.1 N/kg and 3° have been reported during CoD tasks [12,25]. This means that without alterations to approach velocity and CoM deflection angle, ACLR participants would be expected to demonstrate inter-limb differences in these variables comparable to those in normative cohorts. Clinical assessments may thus falsely conclude that patients are exhibiting clinically meaningful inter-limb differences in kinematics and kinetics when completing identical CoD tasks on both limbs, when in fact they are manipulating task constraints in a manner which alters the mechanical demands of the task such that inter-limb comparisons are not valid. Prior to any such inter-limb comparison, researchers should first establish whether inter-limb differences in task completion influence inter-limb differences in kinematic and kinetic variables.

Visual inspection of r^2 values (Fig. 3C) indicated a clear differentiation in the magnitude of r^2 between braking impulse, medio-lateral impulse, propulsion impulse, vGRF and knee flexion ($r^2 > 0.21$) and hip flexion, hip rotation, knee rotation, knee flexor moment, knee abduction moment and knee rotation moment inter-limb differences ($r^2 < 0.1$). While mechanistically it would be expected that GRF and impulse variables would be more sensitive to task-level inter-limb differences than joint angles and moments, the observed weak relationship with angle and moment inter-limb differences was unexpected.

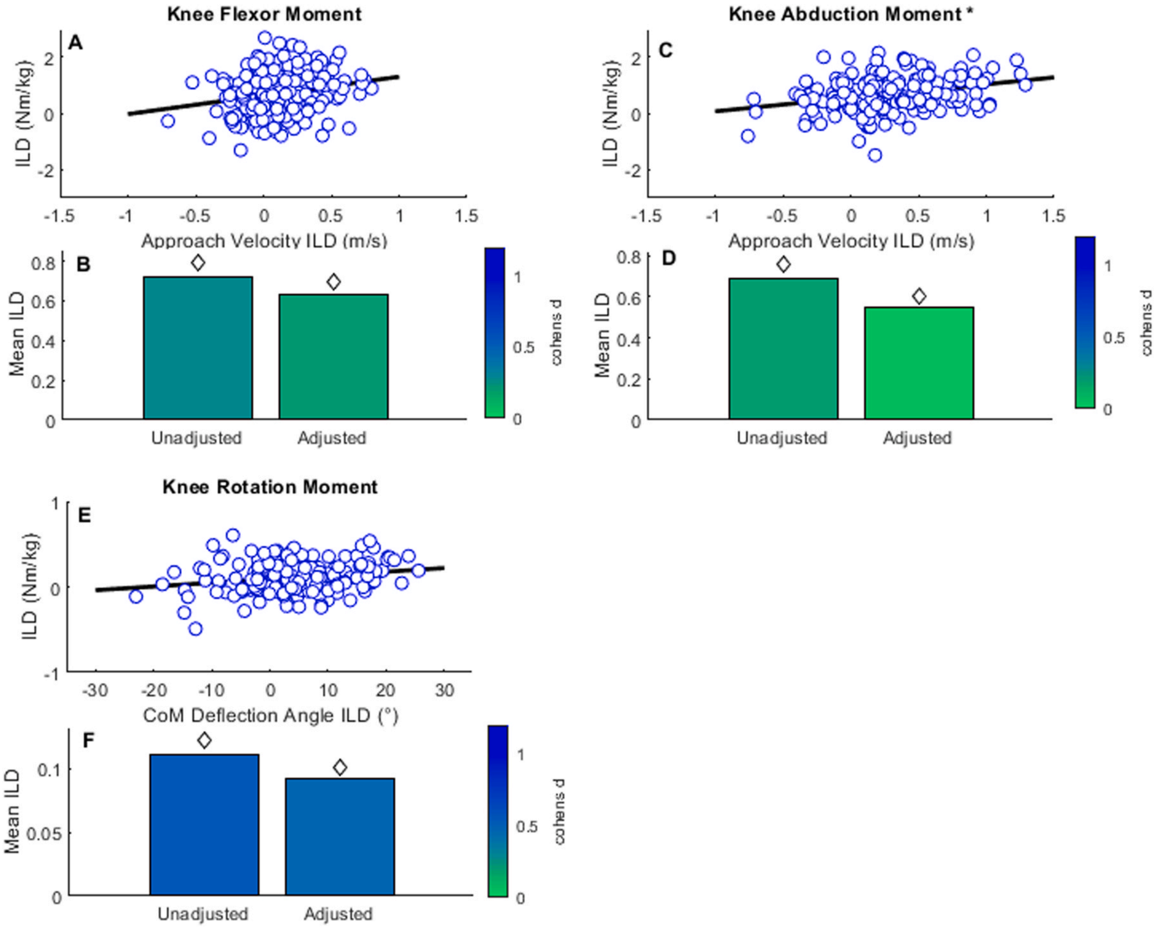

Fig. 6. Relationship between approach velocity and/or CoM deflection angle inter-limb differences and knee flexor moment (Fig. 6A), knee abduction moment (Fig. 6C) and knee rotation moment (Fig. 6E) inter-limb differences. * in title indicates that a multiple regression model containing both approach velocity and CoM deflection angle was used. Figs. 6B, 6D and 6F depict the mean inter-limb difference for knee flexor moment, knee abduction moment and knee rotation moment, in both unadjusted and adjusted conditions. ◆ indicates statistical significance ($p < 0.05$) and bar face colour corresponds to Cohens' d effect size.

Significant differences have been observed in hip, knee and ankle kinematics, as well as knee joint moments when changing direction at different velocities and through different angles [8,16] suggesting that these variables are influenced by velocity and angle. One explanation for the low r^2 values observed for joint angle and moment inter-limb differences may be the sensitivity of these variables to methodological sources of error such as marker placement. Inter-limb differences in joint angles and moments, particularly those in the frontal and transverse planes, are highly sensitive to marker placement, evidenced in our analyses by the high variability observed in these measures (Fig. 5, Fig. 6) [26,27]. The joint level inter-limb differences which did demonstrate relatively high r^2 values -namely hip and knee flexion angle - were both sagittal plane variables, which are less sensitive to marker placement. Thus, our results may indicate that the variation in these metrics explained by task-level inter-limb differences is masked by the variance explained by marker-placement error and the inability to measure these variables accurately and reliably.

It is important to note several limitations within the current study design. Firstly, our specific findings are limited to the 90° CoD task used in this study. It is likely that inter-limb differences in approach velocity and CoD angle are reduced at smaller CoD angles and thus have a lesser effect on kinematic and kinetic variables. Secondly, we only utilised male participants who were approximately six months post-surgery. It is unclear currently whether these differences persist in later stage rehabilitation, and whether female patients exhibit the same inter-limb differences in approach velocity and CoM deflection angle. Lastly, the CoD task itself was a pre-planned movement. A more reactive CoD task, such as is common in many real-world sporting contexts, may reduce the scope for anticipatory limb-specific task modifications and/or alter the modifications observed during CoD stance phase.

5. Conclusion

During pre-planned CoD tasks ACLR participants reduce approach velocity and CoM deflection angles as a means of reducing the mechanical demands imposed on the ACLR limb. These task modifications in turn contribute to the presence of inter-limb differences in several kinematic and kinetic variables, primarily those related to GRF and impulse. Where kinematic and kinetic inter-limb differences during CoD have previously been attributed solely to altered limb level differences arising from the ACLR procedure, our study demonstrates that a combination of task and limb level alterations are likely responsible. Task and limb level difference should be considered in tandem when examining and interpreting inter-limb differences in kinematic and kinetic variables in post-ACLR cohorts during CoD.

Declaration of Competing Interest

The authors confirm that there is no financial or personal relationship with other individuals or organisations that could inappropriately influence this work.

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