



Contents lists available at ScienceDirect

Physical Therapy in Sport

journal homepage: www.elsevier.com/ptsp

Literature Review

The effect of limb dominance on change of direction biomechanics: A systematic review of its importance for injury risk

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ARTICLE INFO

Article history:

Received 4 April 2019

Accepted 6 April 2019

Keywords:

Asymmetries

Anterior cruciate ligament

Cutting

Limb preference

ABSTRACT

Objective: To critically evaluate the effect of limb dominance on change of direction (COD) biomechanics associated with increased ACL injury-risk.**Methods:** A systematic review of the literature was conducted using Medline and Sport DISCUS databases. Studies that compared COD biomechanics (lower-limb/whole-body kinetics/kinematics) between limbs, contained an approach run, and included physically active participants were included.**Results:** Of the 456 articles identified, six were included. All studies investigated a cutting action, while the majority defined limb dominance as the preferred kicking limb, whereas one study defined limb dominance as preferred push-off cutting limb. Conflicting observations were found, with one study indicating the non-dominant and one study indicating the dominant limb displayed biomechanical deficits associated with increased non-contact ACL injury-risk during COD. Conversely, the remaining studies demonstrated no significant or substantial differences in COD biomechanics between limbs.**Conclusions:** Female soccer players, male rugby players, and female handball players exhibit subtle side-to-side differences when performing cutting manoeuvres. However, the limb displaying high-risk mechanics is inconsistent within and between studies and populations. Thus, it remains inconclusive for COD that limb dominance is an ACL injury-risk factor and whether a particular limb is of heightened injury-risk.**Level of evidence:** Level 2, Systematic review

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1. Introduction

Central to the success of many multidirectional sports, the ability for athletes to change direction quickly and safely is of great importance (Bloomfield, Polman, & Donoghue, 2007; Faude, Koch, & Meyer, 2012; Karcher & Buchheit, 2014; Nimphius et al., 2014; Robinson, O'Donoghue, & Nielson, 2011; Sheppard, Dawes, Jeffreys, Spiteri, & Nimphius, 2014; Sweeting, Aughey, Cormack, & Morgan, 2017; Young, Dawson, & Henry, 2015). Change of direction (COD) actions such as side-steps, crossover cuts, and pivots are regularly performed in multidirectional sports (Bloomfield et al., 2007; Green, Blake, & Caulfield, 2011; Sayers & Washington-King, 2005; Sweeting et al., 2017; Taylor, Wright, Dischiavi, Townsend, &

Marmon, 2017; Wheeler, Askew, & Sayers, 2010; Zahidi & Ismail, 2018), and are often linked to decisive moments such as, evading an opponent to penetrate the defensive line in rugby (tackle-break success in rugby) (Nedelec et al., 2014; Wheeler et al., 2010; Zahidi & Ismail, 2018), getting into space to receive a pass in netball (Fox, Spittle, Otago, & Saunders, 2014), or creating goals in soccer (Faude et al., 2012). However, of concern, directional changes are inciting events associated with non-contact anterior-cruciate ligament (ACL) injury (Boden, Dean, Feagin, & Garrett, 2000; Brophy, Stepan, Silvers, & Mandelbaum, 2015; Cochrane, Lloyd, Buttfield, Seward, & McGivern, 2007; Faude, Junge, Kindermann, & Dvorak, 2005; Koga et al., 2010; Montgomery et al., 2018; Olsen, Myklebust, Engebretsen, & Bahr, 2004; Walden et al., 2015). This occurrence could be explained by the fact that COD actions have the propensity to create hazardous multiplanar knee joint loading when the foot is planted, such as high knee abduction moments (KAMs) and internal rotation moments (IRMs) (Besier, Lloyd, Ackland, & Cochrane,

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2001; Dempsey et al., 2007, 2009; Jones, Herrington, & Graham-Smith, 2016a, 2016b); both of which can increase ACL strain (Bates, Myer, Shearn, & Hewett, 2015; Kiapour et al., 2016; Markolf et al., 1995; Oh, Lipps, Ashton-Miller, & Wojtys, 2012; Shin, Chaudhari, & Andriacchi, 2011). Importantly, knee joint loading during directional changes is exacerbated when biomechanical deficits and 'high-risk' mechanics such as lateral trunk flexion (Dempsey et al., 2007; Frank et al., 2013; Jamison, Pan, & Chaudhari, 2012; Jones, Herrington, & Graham-Smith, 2015), knee valgus (Jones et al., 2015, 2016b; Kristianslund, Faul, Bahr, Myklebust, & Krosshaug, 2014; McLean, Huang, & van den Bogert, 2005; Sigward, Cesar, & Havens, 2015), extended knee positions (Dai et al., 2014; Koga et al., 2010), wide foot plants (Dempsey et al., 2007; Havens & Sigward, 2015a; Jones et al., 2015; Kristianslund et al., 2014), and high GRFs (Jones et al., 2016; Sell et al., 2007; Sigward et al., 2015; Sigward & Powers, 2007) during weight acceptance of COD tasks are exhibited. As such, ensuring athletes have the capability to change direction safely (i.e. optimal mechanics/frontal plane alignment) from both limbs by avoiding these 'high-risk' postures is a viable strategy to reduce ACL injury-risk (Dos'Santos, Thomas, Comfort, & Jones, 2018; Fox, 2018; Hewett, 2017; Padua et al., 2018).

Anterior cruciate ligament injury is a serious, potentially career-threatening injury with negative health (Hewett, 2017; Lohmander, Englund, Dahl, & Roos, 2007), psychological (Hewett, 2017; Langford, Webster, & Feller, 2009), and economic (Cumps, Verhagen, Annemans, & Meeusen, 2008; Hewett, 2017; Quatman & Hewett, 2009) implications for athletes and the general population. Although the mechanisms of non-contact ACL injury are multifactorial (Hewett, 2017; Quatman, Quatman-Yates, & Hewett, 2010), strength, neuromechanical, and dynamic control between-limb differences (side to side differences/asymmetries), and overall lower-limb dominance has been suggested to be a potential ACL injury risk factor (Brophy, Silvers, Gonzales, & Mandelbaum, 2010; Hewett et al., 2005, 2010; Maulder, 2013; Pappas & Carpes, 2012; Pappas, Shiyko, Ford, Myer, & Hewett, 2016; Paterno et al., 2010). Limb dominance, also known as lateral preference or laterality (Carpes, Mota, & Faria, 2010; Maloney, 2018), refers to the concept that humans will preferentially use one side of the body when performing a motor task, typically resulting in a more skilful and therefore dominant side (Carpes et al., 2010; Maloney, 2018). A preferred leg to kick a ball is typically used to indicate limb/skill dominance and as such, practitioners and researchers are interested whether a particular leg is at a heightened injury risk. For example, seminal work from Hewett et al. (Hewett et al., 2005) found significantly greater asymmetries (dominant [D] vs non-dominant [ND]) in landing peak KAM in nine youth females athletes (soccer, basketball, volleyball) who injured their ACL compared to uninjured. Notably, six of the nine athletes injured their D limb, defined as their preferred kicking leg. Additionally, prospective research by Paterno et al. (Paterno et al., 2010) reported athletes with a previous ACL injury that sustained a second ACL injury exhibited greater asymmetries (4.1 times) in landing knee extensor moments between limbs. Moreover, Kyritsis et al. (Kyritsis, Bahr, Landreau, Miladi, & Witvrouw, 2016) showed previously injured athletes that did not meet return to play criteria in 6 tests (three of which required >90% limb symmetry indexes in hopping tasks) were four times more likely to sustain a second ACL rupture. Therefore, reducing between-limb biomechanical deficits could be a potential training strategy to reduce the relative risk of non-contact ACL injury.

Retrospective analysis of ACL injuries (i.e., questionnaires and interviews) report conflicting findings regarding whether the D or ND limb is at a greater risk of ACL injury. For example, previous studies have refuted the connection between limb dominance and

ACL injury in athletes from multiple sports (Matava, Freehill, Grutzner, & Shannon, 2002; Negrete, Schick, & Cooper, 2007), whereas limb dominance may serve as an aetiological risk factor regarding non-contact ACL injuries in soccer players and skiers (Brophy et al., 2010; Ruedl et al., 2012). Previously, researchers reported a greater occurrence of ACL injuries in the D limb compared to the ND limb (18 vs 8) in female soccer players (Faude, Junge, Kindermann, & Dvorak, 2006); however, they did not delineate between non-contact and contact ACL injuries. In contrast, Brophy et al. (Brophy et al., 2010) demonstrated 74% (20/27) of males sustained a greater proportion of non-contact ACL injuries to the D limb, compared to 32% (10/31) in females. Thus, female soccer players were more likely to injure their ACL in the ND (supporting/stance) limb, whereas males demonstrated the opposite and a greater trend in the kicking limb. Corroborating the aforementioned findings, Boden et al. (Boden et al., 2000) found 68% of female athletes from multiple sports sustained a non-contact ACL injury in their ND limb, with a similar trend documented for female skiers compared to males (63% vs. 45%, $p = 0.020$) (Ruedl et al., 2012). As such, arguably, limb dominance may play a gender-based role in non-contact ACL injury in soccer players and female skiers; however, it is important to note that the retrospective analysis ACL injuries do not imply cause and effect; thus, further prospective research is required to confirm the role of limb dominance as an ACL injury risk factor.

While biomechanical investigations into COD biomechanics have considered the effect of sex (Beaulieu, Lamontagne, & Xu, 2009; Cronstrom, Creaby, Nae, & Ageberg, 2016; Fedie, Carlstedt, Willson, & Kernozeck, 2010; McLean et al., 2004, 2005a, 2005b; Sigward et al., 2012, 2015), approach velocity (Dai et al., 2016; Kimura & Sakurai, 2013; Kristianslund et al., 2014; Nedergaard, Kersting, & Lake, 2014; Vanrenterghem, Venables, Pataky, & Robinson, 2012), anticipation (Besier et al., 2001a; Collins, Almonroeder, Ebersole, & O'connor, 2016; Cortes, Blount, Ringleb, & Onate, 2011; Dempsey et al., 2009; Khalid, Ian Harris, Michael, Joseph, & Qu, 2015; Kim et al., 2014; Lee, Lloyd, Lay, Bourke, & Alderson, 2013; Park, Lee, Ryue, Sohn, & Lee, 2011), and COD angle (Cortes et al., 2011b; Hader et al., 2015, 2016; Havens and Sigward, 2014, 2015b; Schot, Dart, & Schuh, 1995; Schreurs, Benjaminse, & Lemmink, 2017; Sigward et al., 2015), an emerging area of research is the effect of limb dominance on COD biomechanics (Bencke et al., 2013; Brown, Brughelli, & Hume, 2014; Greska, Cortes, Ringleb, Onate, & Van Lunen, 2016; Marshall et al., 2015; Mok, Bahr, & Krosshaug, 2018; Pollard et al., 2018). Research into between-limb differences during COD provides further insight into the potential mechanisms of non-contact ACL injury. From both performance and risk of injury perspectives, it would be advantageous for athletes to have the capacity to change direction safely and quickly from both limbs, given the unpredictable nature of multidirectional sports (Dos'Santos, Thomas, Jones, & Comfort, 2018a, 2018b). However, as athletes can display strength, neuromechanical, and dynamic control deficits between limbs (Bishop, Turner, & Read, 2017; Brown, 2018; Del Bel, Fairfax, Jones, Steele, & Landry, 2017; Hewett et al., 2005, 2010; Jones & Bampouras, 2010; McGrath et al., 2016; Mendiguchia et al., 2017; Paterno et al., 2010; Thomas, Comfort, Dos'Santos, & Jones, 2017), these deficits, hypothetically, could lead side-to-side asymmetries in COD biomechanics, whereby a particular limb could display 'higher-risk' mechanics, thus increased injury risk. Several studies have examined the effect of limb dominance on COD biomechanics (Bencke et al., 2013; Brown et al., 2014b; Greska et al., 2016; Marshall et al., 2015; Mok et al., 2018; Pollard et al., 2018) in an attempt to establish whether a particular limb displays greater biomechanical deficits associated with increased ACL injury risk. To the best of our knowledge, however, a systematic review and

critical evaluation of the literature that has examined the effect of limb dominance on COD biomechanics does not exist.

The purpose of this systematic review, therefore, was to critically evaluate the literature to date, which has examined the effect of limb dominance on COD biomechanics associated with increased risk of injury, and to highlight the limitations, considerations, and future directions for research to improve our understanding regarding the effect of limb dominance and biomechanical asymmetries during COD. For the purpose of the review, limb dominance is defined as the leg which an athlete would prefer to a kick a ball with (unless stated otherwise) and is synonymous with previous studies that used the terms limb preference (Brown, Donelon, Smith, & Jones, 2016; Thomas et al., 2017b), leg preference (Brown, 2018; Brown et al., 2014b; Condello, Kernozek, Tessitore, & Foster, 2016), and leg dominance (Greska et al., 2016). Moreover, in this review, KAM and knee abduction angle (KAA) are synonymous with knee valgus moment and knee valgus.

2. Methods

2.1. Literature search strategy

A literature search was performed using Medline and Sport DISCUS databases. Fig. 1 provides a schematic of the search methodology in accordance to Prisma guidelines (Moher, Liberati, Tetzlaff, Altman, & Group, 2009). Search terms were as follows:

- 1; “limb dominance”, or “leg dominance”, or “leg preference”, or “limb preference”, or “asymmetries” or “side to side differences”, or “symmetry” AND
- 2; “change of direction”, or “cutting”, or “cut”, or “sidestep”, or “turning”, or “side-step”, or “agility”, “or multidirectional speed”

Bibliographies of potentially eligible studies were hand searched to identify any additional studies and citation tracking on Google Scholar was used to identify any additional material. Following the search, two authors from the current review independently screened each article for inclusion. The screening process consisted of: 1, screening for duplicates; 2, screening the title; 3, screening

the abstract; and 4, screening the full paper using the inclusion and exclusion criteria. If the two authors were not in agreement with the inclusion/exclusion criterion of the study, a third author independently reviewed the study and a discussion occurred until consensus was reached. The final search date was January 10th, 2019.

2.2. Study selection

Studies were included if they met the following criteria:

1. Investigated preplanned or unplanned cutting or turning tasks that contained an approach run
2. Compared COD biomechanics between D and ND limbs
3. Investigated lower-limb and/or whole-body kinetics/kinematics
4. Included participants who participated in sport or physical activity
5. Full-text in a peer reviewed journal, in English

Studies that failed to meet the abovementioned criteria were subsequently removed.

2.3. Assessment of study quality

Following the article search and examination, a methodological quality assessment was performed based on the scale (Table 1) created by Brown et al. (Brown et al., 2014a) which conducted a similar systematic review regarding the effect of anticipation on knee mechanics during side-stepping. The scale by Brown et al. (Brown et al., 2014a) is argued to be more specific for evaluating COD biomechanical studies in contrast to the Delphi, Physiotherapy Evidence Database, or Cochrane scales, because a large proportion of studies would fail to achieve many of the criteria of the aforementioned scales such as random allocation, assessor blinding, and subject blinding. As such, each article was assessed against a nine-item scale (Table 1) comprising of an 18 point-scoring system (ranging from 0 to 18) where 0 = clearly no; 1 = maybe or inadequate information; and 2 = clearly yes.

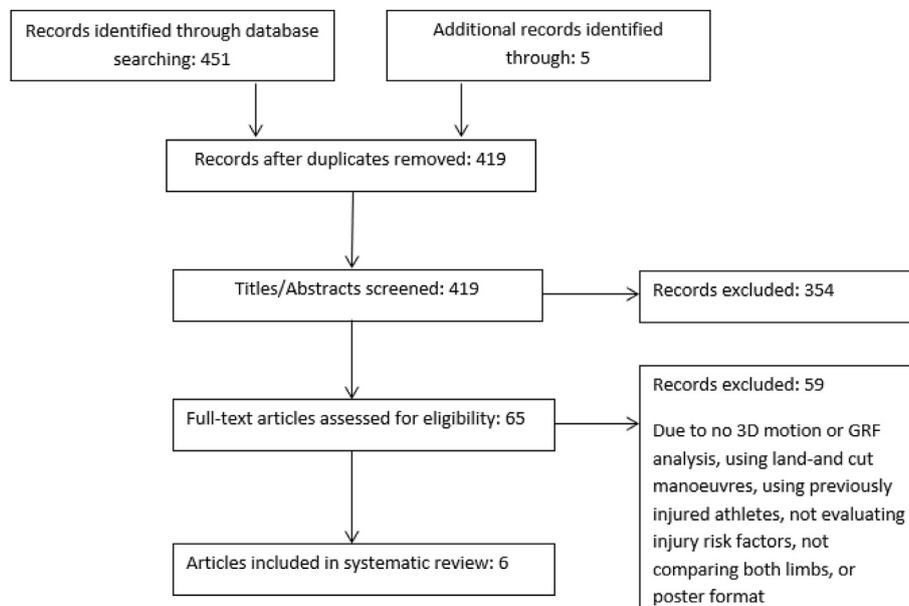


Fig. 1. Flow diagram illustrating the different phases of the systematic review; based on PRISMA recommendations. 3D: Three-dimensional; GRF: Ground reaction force.

Table 1
Methodological quality assessment of limb dominance COD studies.

Question	Criteria	Bencke et al. (Bencke et al., 2013)	Brown et al. (Brown et al., 2014b)	Marshall et al. (Marshall et al., 2015)	Greska et al. (Greska et al., 2016)	Pollard et al. (Pollard et al., 2018)	Mok et al. (Mok et al., 2018)
1	Power analysis was performed and justification of study sample size	0	2	0	2	0	0
2	Athlete demographics were clearly defined: gender, age, body height, and body mass at time of test	2	2	2	2	2	2
3	Athlete characteristics were clearly defined: sport, experience or activity level and level of play	1	2	2	2	2	2
4	Inclusion and exclusion criteria were clearly stated for athletes	0	2	1	2	2	0
5	Proper training and practice trials of the test were given to the athletes allowing for adequate familiarisation	1	2	1	1	1	2
6	Methods were described in great detail to allow replication of the test. Testing devices, n of trials, n and duration of rest, speed, angle of COD	1	2	2	2	2	1
7	Test-retest reliability of measurement device reported	0	0	2	0	0	2
8	Outcome variables clearly defined	1	2	2	2	2	1
9	Statistical analyses were appropriate	1	2	2	2	1	1
	Total score (maximum 18)	7 (39%)	16 (89%)	14 (78%)	15 (83%)	12 (67%)	11 (61%)

Key: n: number; COD: Change of direction; 0: clearly no; 1: maybe or inadequate information; 2: clearly yes.

3. Results

Initial database searches resulted in the identification of 451 articles, with an additional 5 articles through bibliographies, citation tracking, and hand searching (Fig. 1). After removing duplicates, 419 articles were retained for initial screening. Title and abstract screening resulted in 354 articles excluded. The remaining 65 articles were further examined using the inclusion/exclusion criteria, and 59 studies were excluded, resulting in six studies included to examine the effect of limb dominance on COD biomechanics (Bencke et al., 2013; Brown et al., 2014b; Greska et al., 2016; Marshall et al., 2015; Mok et al., 2018; Pollard et al., 2018) (Fig. 1 and Table 1). Methodology quality scores ranged from seven (39%) to sixteen (89%) (Table 1).

Four studies examined female athletes (Bencke et al., 2013; Brown et al., 2014b; Greska et al., 2016; Mok et al., 2018), one study examined male athletes (Marshall et al., 2015), and one study used a mixed cohort (Pollard et al., 2018). In addition, sporting populations varied with two studies investigating female collegiate soccer players (Brown et al., 2014b; Greska et al., 2016), one study investigating male international rugby players (Marshall et al., 2015), one study investigating (mixed) recreationally active (Pollard et al., 2018), one study in female handball (Bencke et al., 2013), while one study examined a mixture of elite female soccer and handball players (Mok et al., 2018). The most common angle of COD was 45° (Brown et al., 2014b; Greska et al., 2016; Pollard et al., 2018), followed by 75° (Marshall et al., 2015), while two studies used a sports-specific cut (Bencke et al., 2013; Mok et al., 2018) but did not specify COD angle. The majority defined limb dominance as the preferred kicking limb, whereas one study (Bencke et al., 2013) defined limb dominance as preferred push-off cutting limb (Table 2).

In terms of the effect of limb dominance on COD biomechanics associated with increased injury-risk, conflicting observations were found (Table 2). One study indicated that the ND (Brown et al., 2014b) limb and one study indicated the D (Marshall et al., 2015) limb displayed biomechanical deficits associated with increased non-contact ACL injury risk during COD. Conversely, the remaining studies (Bencke et al., 2013; Greska et al., 2016; Mok et al., 2018; Pollard et al., 2018) demonstrated no significant or substantial differences in COD biomechanics between limbs (Table 2).

4. Discussion

The aim of this systematic review was to critically evaluate the literature to date, which has examined the effect of limb dominance

on COD biomechanics associated with increased risk of injury. A secondary aim was to highlight the limitations, considerations, and future directions for research to improve our understanding regarding the effect of limb dominance and biomechanical asymmetries during COD. As six studies were included in the final analysis, the effect of limb dominance on COD biomechanics will be discussed in sport-specific sections, relative to the sample in the included studies.

4.1. Soccer players

Given the findings from Brophy et al. (Brophy et al., 2010) that limb dominance may play a gender-based role in non-contact ACL injury risk in soccer players, two studies have compared COD biomechanics between limbs for a greater understanding into the potential mechanisms of ACL injury which met the criteria for this review (Table 2). Brown et al. (Brown et al., 2014b) conducted a comprehensive comparison of knee kinetics and kinematics between limbs during a pre-planned 45° cut in female collegiate soccer players. The authors observed subtle differences in knee kinematics and kinetics (Table 2) between limbs, reporting small differences in knee flexion angle, and slightly greater KAAs, knee internal rotation angle, and KAMs during weight acceptance in the ND limb. In addition, slightly lower knee extensor moments and knee IRMs were reported in the ND limb, while peak power absorption and peak knee flexion velocity in the ND leg were slightly greater than the D limb (Table 2). Moreover, peak power production and peak knee extension velocity in the ND limb were slightly lower than those in the D limb (Table 2), indicating that the push-off was executed faster in the D limb. Unfortunately, the authors did not examine centre of mass velocity at toe-off; therefore, it is uncertain whether the athletes displayed superior exit velocity, thus performance from the D limb. Collectively, these results indicate that the ND limb exhibits biomechanical deficits associated with greater risk of non-contact ACL injury, which may partially support the greater ND limb ACL incidence rates in female soccer players reported by Brophy et al. (Brophy et al., 2010).

Investigating an unanticipated 45° cut in female collegiate soccer players, Greska et al. (Greska et al., 2016) demonstrated no significant differences between limbs in hip and knee moments, GRFs, and peak electromyography activation (Table 2). Interestingly, based on the effect sizes (Table 2), differences in neuro-mechanical characteristics were inconsistent between limbs. For example, the D limb displayed greater peak knee flexion angles,

Table 2

Summary of research that has examined the effect of limb dominance on COD biomechanics in multidirectional athletes.

Study	Subjects	COD task	Results
Bencke et al. (Bencke et al., 2013)	24 young female handball athletes	Handball specific cut – 5 step run up (COD angle not provided) D limb – based on preferred push-off limb	D vs ND <ul style="list-style-type: none"> ↔ ($p > 0.05$) hip and knee joint angles at IC; but small differences in D GCT (ES = 0.22), hip adduction angle (ES = -0.33), hip internal rotation angle (ES = 0.30), and knee flexion (ES = -0.33) ↔ ($p > 0.05$) hip and knee joint moments 100 ms after IC; but small differences in hip flexion moment (ES = 0.20), hip extension moment (ES = 0.27), hip adduction moment (ES = 0.54), and knee flexion moment (ES = -0.20) Trivial differences (ES = 0.00) for hip internal rotation, KAM, and knee internal rotation moment (only 1 d.p provided)
Brown et al. (Brown et al., 2014b)	16 female collegiate soccer NCAA Division 1	Pre-planned 45° cut 5-m approach distance 4.5 ± 0.5 m s ⁻¹ approach velocity D limb – kicking	ND vs D <ul style="list-style-type: none"> Knee flexion angles: slightly smaller at IC (ES = 0.19, -5.3%), WA (ES = 0.28, -4.5%), PPO (ES = 0.36, -3.5%) KAA: slightly greater WA (ES = 0.10, +9.8%) Knee internal rotation angle: greater WA (ES = 0.64, +32%), slightly greater peak PO (ES = 0.58, +25%), and final PO (ES = 0.22, +20%) Knee extensor moments: slightly lower during peak PO (ES = 0.31, -5.8%) and final push-off (ES = 0.30, -22%) KAMs slightly greater WA (ES = 0.22, +19%) Knee IRM slightly lower during PPO (ES = 0.42, -19%) and final PO (ES = 0.18, -11%) Peak power absorption and peak knee flexion velocity slightly greater (ES = 0.14, +5.1% and ES = 0.09, +2.7%) Peak power production and peak knee extension velocity were slightly lower (ES = 0.34, -8.3% and ES = 0.21, -5.2%)
Marshall et al. (Marshall et al., 2015)	Twenty elite injury free international male rugby union players (11 forwards and 9 backs)	Pre-planned 75° cut (approach distance not provided)	<ul style="list-style-type: none"> ↔ 27/28 variables, but AI values ranged from 1 to 49% (ES = 0.02–0.60) ND ↑ ankle IRM ($p = 0.04$, 67%, ES = 0.75) D ↑ KAA (ES = 0.23, AI = 21%), ↑ KAM (ES = 0.23, AI = 8%), ↑ knee IRM (ES = 0.43, AI = 29%), ↓ knee flexion angle (ES = 0.35, AI = 5%), and ↓ GCT (ES = 0.60, AI = 9%) ND ↑ vGRF (ES = 0.48, AI = 11%), ↑ mlGRF (ES = 0.25, AI = 14%), ↑ longitudinal GRF (ES = 0.31, AI = 7%) ACP – across the whole waveform: <ul style="list-style-type: none"> ND ↑ ankle IRM ($p = 0.02$–0.04, ES = 0.52) from 23 to 38% of the movement. ND ↑ dorsi-flexion during the latter stages (78–94%) of the cut PO ($p = 0.011$, ES = 0.57) D ↑ peak knee flexion angle ($p = 0.034$, ES = 0.69) ↔ ($p > 0.05$) in hip and knee kinetics or kinematics, GRF, or EMG, but: <ul style="list-style-type: none"> D ↑ peak vGRF (ES = 0.39), but ND ↑ vGRF at peak KAM (ES = 0.60) ND ↑ KAA at IC and peak (ES = 0.21–0.23) D ↑ peak KAM (ES = 0.26) GCT between limbs ($p > 0.004$), D ↑ (ES = 0.45) ↔ Approach velocities (ES = 0.06) Trivial to small differences to EMG activation (%MVIC) pre-contact (ES = 0.02–0.55) and IC (ES = 0.04–0.40) Trivial to small differences to EMG activation time course pre-contact (ES = 0.13–0.30) and peak stance (ES = 0.10–0.56)
Greska et al. (Greska et al., 2016)	20 Female collegiate soccer players	Unanticipated 45° cut – 6-m approach distance Minimum 3m.s ⁻¹ approach velocity D limb – kicking	<ul style="list-style-type: none"> D ↑ peak knee flexion angle ($p = 0.034$, ES = 0.69) ↔ ($p > 0.05$) in hip and knee kinetics or kinematics, GRF, or EMG, but: <ul style="list-style-type: none"> D ↑ peak vGRF (ES = 0.39), but ND ↑ vGRF at peak KAM (ES = 0.60) ND ↑ KAA at IC and peak (ES = 0.21–0.23) D ↑ peak KAM (ES = 0.26) GCT between limbs ($p > 0.004$), D ↑ (ES = 0.45) ↔ Approach velocities (ES = 0.06) Trivial to small differences to EMG activation (%MVIC) pre-contact (ES = 0.02–0.55) and IC (ES = 0.04–0.40) Trivial to small differences to EMG activation time course pre-contact (ES = 0.13–0.30) and peak stance (ES = 0.10–0.56)
Pollard et al. (Pollard et al., 2018)	31 healthy participants (15 males and 16 females)	Pre-planned 45° cut (approach distance and velocity not provided) D limb – kicking	D vs ND <ul style="list-style-type: none"> D ↓ knee internal rotation angle from IC to 40% ($p < 0.05$, ES = 0.74) and IC to pk knee flexion ($p < 0.05$, ES = 0.61) ↔ hip and knee kinematics (sagittal, transverse, and frontal) ($p > 0.05$, ES ≤ 0.18) ↔ hip and knee kinematics (sagittal, transverse, and frontal) ($p > 0.05$, ES ≤ 0.39) (note some variables are presented to only 1 d.p)
Mok et al. (Mok et al., 2018)	19 elite Female handball and 22 female soccer	Sports- specific cut 6-m approach distance (COD angle not provided) Limb D - kicking	<ul style="list-style-type: none"> 4/33 variables significantly different ($p < 0.05$) Significant difference for peak hip abduction angle, peak knee internal rotation angle, peak knee valgus moment and peak knee flexion moment (Does not provide descriptive data for ND limb, thus direction of asymmetry cannot be established)

Key: ↔: no significant differences; ↑: greater; ↓: lower; D: Dominant; ND: Non-dominant; KAM: Knee abduction moment; KAA: Knee abduction angle; GRF: Ground reaction force; vGRF: Vertical GRF; hGRF: Horizontal GRF; mlGRF: Medio-lateral GRF; IC: Initial contact; PFC: Penultimate foot contact; FFC: Final foot contact; SS: Sidestep; ES: Effect size; WA: Weight acceptance; PO: Push-off; GCT: Ground contact time; EMG: Electromyography; MVIC: Maximum voluntary isometric contraction; COD: Change of direction; AI: Asymmetry index; ACP: Analysis of characterising phases; IC: Initial contact; d.p: decimal place; IRM: Internal rotation moment.

greater peak KAMs, and greater peak vertical GRFs, while the ND limb exhibited greater KAAs (IC and peak) and greater vertical GRF at peak KAM (Table 2). Moreover, the authors found the time course of muscle activation was also different between limbs (Table 2). These findings contrast to Brown et al. (Brown et al., 2014b) that found the ND to display potentially more hazardous knee kinetics and kinematics. However, it is worth noting that the conflicting and inconsistent findings between studies could be attributed to task differences because Brown et al. (Brown et al., 2014b) examined a pre-planned 45° cut, compared to an unanticipated 45° cut investigated by Greska et al. (Greska et al., 2016). Furthermore, greater approach velocities were reported by Brown et al. (Brown et al., 2014b) compared to Greska et al. (Greska et al., 2016) ($4.5 \pm 0.5 \text{ m s}^{-1}$ vs. $3.26 \pm 0.18 \text{ m s}^{-1}$), whereby velocities $\geq 4 \text{ m s}^{-1}$ have been recommended to screening and evaluating COD biomechanics in female athletes (Vanrenterghem et al., 2012). As such, further research is required examining between-limb differences in COD biomechanics during unanticipated cuts $\geq 4 \text{ m s}^{-1}$, in line with recommendations from Vanrenterghem et al. (Vanrenterghem et al., 2012).

4.2. Rugby players

Five of the six studies (Tables 1 and 2) have compared between-limb COD biomechanics based on discrete point analysis (DPA) (i.e. peak value during weight acceptance or push-off) (Table 2). This approach, however, leads to regional focus bias (focusing only on one aspect of the waveform) (Mullineaux et al., 2017; Pataky, 2010; Pataky et al., 2013, 2014; Robinson, Vanrenterghem, & Pataky, 2015), does not provide information regarding temporal differences (timing differences) (Richter et al., 2014a, Richter, Marshall, & Moran, 2014; Stergiou, Harbourne, & Cavanaugh, 2006), and a large proportion of potentially valuable and meaningful information of the waveform (i.e. moment, GRF, angle waveform) is left unexamined (Brown, Bowser, & Simpson, 2012; Preatoni et al., 2013).

In light of the issues with DPA, Marshall et al. (Marshall et al., 2015) compared between-limb biomechanics in male international rugby players during a 75° cut using not only DPA, but also compared the continuous data between limbs using a method known as analysis of characterising phases (ACP: a continuous data analysis techniques that detects and examines phases of variance within a sample a sample of curves utilising the time, magnitude, and magnitude-time domains) (Richter et al., 2014a, 2014b). Interestingly, based on DPA, ankle IRM was the only variable (1/28) that showed a significant difference between limbs (Table 2). Notably, however, when the full waveform for variables were compared between D and ND limbs, ACP revealed ankle IRM was significantly greater for the ND limb from 23 to 38% of the movement, while significantly greater ankle dorsi-flexion angles during the latter stages of push off (78–94%) were also observed for the ND limb. Although not significantly different, based on DPA, slightly greater KAAs (asymmetry index (AI = 8%), knee IRMs (AI = 29%), and lower knee flexion angles (AI = 5%), and greater vertical GRF (AI = 11%) were observed for the D limb (Table 2). These findings are concerning because multiplanar joint loading can increase ACL strain (Bates et al., 2015; Kiapour et al., 2016; Markolf et al., 1995; Oh et al., 2012; Shin et al., 2011), while model-based image-matching has revealed knee valgus, extended knee postures, and high vertical GRFs as characteristics of non-contact ACL injury during COD (Koga et al., 2010). Furthermore, Marshall et al. (Marshall et al., 2015) observed a slightly longer ground contact time (GCT) for the ND limb (ES = 0.60, AI = 9%), potentially indicating slower performance from that push-off limb (Dos'Santos, Thomas, Jones, & Comfort, 2017a; Maloney, Richards, Nixon, Harvey, & Fletcher, 2016; Marshall et al., 2014; Sasaki, Nagano,

Kaneko, Sakurai, & Fukubayashi, 2011). Therefore, rugby players may benefit from improving their unilateral reactive strength to improve COD speed performance from their ND limb (Bishop, Turner & Read, 2018; Maloney, Richards, Jelly, & Fletcher, 2019), though it is imperative that athletes have a solid foundation of strength to fully reap the benefits of unilateral reactive strength training (Dos'Santos, Thomas, Comfort, & Jones, 2018; Suchomel, Nimphius, Bellon, & Stone, 2018; Suchomel, Nimphius, & Stone, 2016).

4.3. Handball players and mixed cohorts

Only two studies have examined asymmetries in COD biomechanics in handball players (Table 2). Bencke et al. (Bencke et al., 2013) reported no significant asymmetries in knee and hip joint angles, and no significant differences in hip and knee moments (flexion, extension, abduction, and internal rotation) during a sports-specific cut in female handball players (Table 2). However, it should be noted that Bencke et al. (Bencke et al., 2013) failed to calculate AI values or effect sizes for the between-limb comparisons. Based on the descriptive data provided, though some data were presented only to one decimal place, small effect sizes would have been observed (Table 2), with the D limb displaying a slightly longer GCT, smaller knee and hip adduction angles, and a greater hip internal rotation angle. Furthermore, the D limb displayed slightly greater hip flexion, hip extension, hip adduction, and lower knee flexor moments; however, notably, trivial differences in KAM and knee internal rotation moments were observed. It is important to note, however, that Bencke et al. (Bencke et al., 2013) defined limb dominance as the preferred push-off leg which may not necessarily correspond to the D kicking limb (Dos'Santos, Thomas, Jones, & Comfort, 2017b) as used by the other limb dominance studies (Table 2).

Similarly, Mok et al. (Mok et al., 2018) also compared between-limb biomechanics during a sports-specific cut in elite female handball and soccer players, finding four of 33 variables displayed a significant difference (peak hip abduction angle, peak knee internal rotation angle, peak KAM, and peak knee flexion moment) between limbs. Unfortunately, the authors failed to provide the descriptive data for the ND limb; thus, it is unclear which limb displayed the greater biomechanical deficits, and the magnitude of the differences could not be established. Recently, Pollard et al. (Pollard et al., 2018) reported knee internal rotation angle at 40% of stance and internal rotation angle displayed significant difference between limbs during a 45° cut in a mixed cohort (Table 2). Although effect sizes were not calculated, the ND limb displayed greater knee internal rotation angles (ES = 0.61–0.74), while non-significant and trivial differences between limbs were observed for all other knee and hip kinematics (Table 2). In addition, the authors observed no significant differences in knee kinetics between limbs, though effect sizes ranged from trivial to small (Table 2); however, it is worth noting that values were only presented to one decimal place which may slightly alter effect size calculations.

5. Considerations, limitations, and future directions for research

Collectively, it remains inconclusive whether limb dominance has a direct association with COD biomechanics connected with non-contact ACL injuries and whether a particular limb displays mechanics associated with greater ACL injury risk, with conflicted findings reported in female soccer, male rugby, and female handball athletes (Table 2). It is worth noting that the published literature to date are limited to female soccer, male rugby, female handball, and physically active populations (Table 2); thus, these findings can

only be extrapolated within this context and cannot be generalised to other athletic populations. Further research is required exploring the effect of limb dominance on COD biomechanics from different athletic populations, such as netball, American football, and Australian rules football given the importance of COD actions from both performance and risk of non-contact ACL injury perspectives (Johnston et al., 2018; Montgomery et al., 2018; Stuelcken, Mellifont, Gorman, & Sayers, 2016; Sweeting et al., 2017; Wheeler et al., 2010). In addition, the published studies (Table 1) have only examined one COD task; thus, further research is required, investigating a greater range of COD tasks of different angles (i.e. 45° vs 90° vs 135 vs 180°) because the biomechanical demands of directional changes are angle-dependent (Cortes et al., 2011b; Dos'Santos, Thomas, Comfort, & Jones, 2018; Hader et al., 2016; Hader et al., 2015; Havens & Sigward, 2014; Havens & Sigward, 2015b; Schot et al., 1995; Schreurs et al., 2017; Sigward et al., 2015).

Although failing to achieve the eligibility criteria for this systematic review, two studies (Brown et al., 2016; Thomas et al., 2017b), presented as posters, observed greater KAAs in the ND limb during a 180° turn in female athletes (ES = 0.22–0.63), though trivial differences in peak KAMs (ES = 0.13) were observed. Furthermore, Brown et al. (Brown, 2018) compared sidestepping (COD angle not provided) biomechanics between D and ND limbs in thirty male academy rugby players. In contrast to Marshall et al. (Marshall et al., 2015), the ND limb displayed mechanics associated with increased risk of injury with 8% less knee flexion (ES = -0.26), 17% greater lateral trunk flexion (ES = 0.42), 11% greater COM distance relative to the joint centre (ES = 0.97), and 25% greater peak KAMs (ES = 0.43) observed (Brown, 2018). These results further highlight the inconsistency in 'high-risk' mechanics displayed by the D and ND limb, and demonstrate the individual variation regarding the relationship between limb dominance and ACL injury risk.

Specifically, all eligible studies investigated a cutting action $\leq 75^\circ$ (Table 2), while no published peer-reviewed study has examined the braking characteristics and braking strategy differences between limbs over the penultimate foot contact (PFC). The PFC has been recently highlighted as playing a pivotal role in deceleration prior to changing direction and is also considered a preparatory step in facilitating effective directional changes (Dos'Santos et al., 2017a; Dos'Santos, Thomas, Jones, & Comfort, 2019; Jones et al., 2016; Jones, Thomas, Dos'Santos, McMahon, & Graham-Smith, 2017). Although published in poster format only, Thomas et al. (Thomas et al., 2017b) found female soccer players displayed different braking strategies during a 180° turn between directions. Greater magnitudes of PFC horizontal braking forces (i.e., earlier braking with the ND limb) when changing direction from the D limb were demonstrated by the female soccer players and this also resulted in faster turning performance. Conversely, slower performance and greater emphasis and magnitudes of braking forces were displayed during the final foot contact when changing direction from the ND limb. The better performance and PFC dominant braking strategy demonstrated by the soccer players may be attributed to the similarities of the kicking action with their preferred leg, whereby the ND limb (i.e., stance) would experience greater eccentric and braking demands (Ball, 2011, 2013; Brophy, Backus, Pansy, Lyman, & Williams, 2007; Hart et al., 2018; McLean & Tumilty, 1993), and may therefore be a more skilful and efficient limb for braking. Consequently, further research is required exploring the between-limb differences in braking strategies during sharper directional changes, considering the PFC.

It should also be acknowledged that in order for an asymmetry to be deemed 'real', the between-limb difference must be greater than the variability for that variable (Bishop, Read, Chavda, & Turner, 2016; Exell, Irwin, Gittoes, & Kerwin, 2012). A

fundamental shortcoming of the COD limb dominance studies is the failure to report their variability statistics (i.e., coefficient of variation/typical error) (Table 2). Moreover, only one study has directly calculated AI values (Marshall et al., 2015), though the equation used was in contrast to the recent recommendations of Bishop et al. (Bishop et al., 2016; Bishop, Read, Lake, Chavda, & Turner, 2018) for quantifying asymmetries, and practitioners and researchers are encouraged to use these recommendations to correctly calculate between-limb percentage imbalances. Briefly, when calculating AI values, if imbalances are not calculated in respect to the maximum value, then the percentage is mathematically incorrect (Bishop et al., 2016, 2018a). Practitioners run the risk of incorrectly calculating AIs when defining the D limb as the kicking limb because the kicking limb may not necessarily be the limb that displays the greater value. Therefore, limb dominance should be defined as the limb that displays the highest value (i.e., highest peak KAM, KAA, vGRF, etc.) and subsequent AI and comparison between D and ND limbs should be based on this approach to nullify the inconsistencies based on kicking limb preference.

A problematic issue in the COD limb dominance literature (Tables 1 and 2), is no study has accounted for the effect of variability when interpreting between-limb differences. This absence has large implications because it is uncertain the between-limb differences presented in the aforementioned literature can be interpreted as 'real' (Bishop et al., 2016; Exell et al., 2012) (Table 2). Additionally, no study, to the best of our knowledge, has comprehensively examined the between-session reliability of the between-limb differences in COD biomechanics. It is not yet understood whether the magnitudes and directions of asymmetries between limbs are consistent between sessions (i.e. left limb consistently displays 15% AI for both session 1 and 2). This is important because if the magnitudes and directions of asymmetries are inconsistent between sessions, this could lead to different clinical diagnoses which could influence the future training for that athlete. Going forward, future research that investigates between-limb differences and asymmetries in COD biomechanics should account for the variability to establish 'significant' and 'real' differences between limbs.

While five of the six published studies have compared between-limb differences in COD biomechanics based on limb dominance (i.e., preferred leg to kick a ball), the assumption that the preferred kicking leg is a more coordinated and potentially stronger limb is flawed because previous studies have shown that the kicking limb may not necessarily be the stronger limb (Dos'Santos et al., 2017b; Jones & Bampouras, 2010; McGrath et al., 2016), or lead to superior functional performance from that limb (Bishop et al., 2017; Dos'Santos et al., 2017b; McGrath et al., 2016), with research indicating that the preferred kicking limb does not necessarily correspond to faster COD speed performance from the same push-off limb (Dos'Santos et al., 2017b). The published COD limb dominance studies have pooled their data with respect to limb dominance which can mask and conceal potentially meaningful between-limb differences because some athletes may display greater biomechanical deficits in the kicking limb, while the ND limb will display biomechanical deficits for other athletes. Going forward, it could more suitable to compare COD biomechanics between limbs between preferred and non-preferred turning (push-off) limbs to identify if a particular limb is a greater risk of injury, as done by Bencke et al. (Bencke et al., 2013) This recommendation is extremely pertinent when wanting to examine the effect of limb dominance in athletes from sports where kicking is not a regularly performed action such as handball, basketball, netball, and rugby.

To the best of our knowledge, no study has examined whether between-limb force asymmetries (muscle strength asymmetries) affect COD biomechanics. Moreover, it has been documented that

athletes display faster performance, based on completion times, from a push-off limb during cutting and turning tasks (Dos'Santos et al., 2017b, 2018a, 2018b; Hart, Spiteri, Lockie, Nimphius, & Newton, 2014; Maloney et al., 2016; Nimphius, Callaghan, Spiteri, & Lockie, 2016; Rouissi, Chtara, Berriri, Owen, & Chamari, 2016; Young, James, & Montgomery, 2002), yet the underpinning kinetic and kinematic mechanisms which explain the differences between faster cutting or turning performance to a side are yet to be established and warrant further investigation. As such, comparing COD biomechanics between stronger and weaker limbs, or faster and slower sides, may provide different between-limb differences and subsequent evaluations regarding an athlete's risk of injury and performance. Performing such investigations would improve our understanding regarding the effect of between-limb force asymmetries on COD biomechanics and mechanical differences that explain differences in COD performance between limbs.

Finally, the majority of studies have conducted DPA (Table 2); however, this method fails to account for the whole waveform for angle, moments, and GRF data whereby valuable information is left unexamined (Brown et al., 2012; Preatoni et al., 2013). Only one study (Marshall et al., 2015) has conducted statistical analysis across the whole waveform for kinetic and kinematic variables to provide greater insight into the temporal differences between-limbs. Thus, further research is warranted using temporal phase analysis (Cormie, McBride, & McCaulley, 2009; McMahan, Rej, & Comfort, 2017), ACP (Richter et al., 2014a, 2014b), or one-dimensional statistical parametric mapping (Pataky, 2010; Robinson et al., 2015; Vanrenterghem et al., 2012) to explore differences between limbs across the whole waveform. Furthermore, no study to our knowledge, has examined the joint-joint coordination differences (angle-angle plots) between-limbs during COD, which may provide insight into the coupling behaviours between multiple segments (Hamill et al., 2000, 2012; Mullineaux et al., 2001, 2017; Preatoni et al., 2013; Stergiou & Decker, 2011), and thus, is a recommendation for future research.

6. Conclusions

In conclusion, female soccer players, male rugby players, and female handball players, in general, exhibit subtle side-to-side differences when performing cutting manoeuvres, though the magnitude and direction of the differences are inconsistent within and between studies and populations. Based on the published literature to date, it remains inconclusive whether limb dominance is a risk factor associated with non-contact ACL biomechanical risk factors during COD. Studies to date have demonstrated conflicting results, indicating that the ND (Brown et al., 2014b) or D (Marshall et al., 2015) limb may display biomechanical deficits associated with increased non-contact ACL injury risk, whereas previous research have demonstrated no significant or substantial differences between limbs during COD (Bencke et al., 2013; Greska et al., 2016; Pollard et al., 2018), refuting the notion of limb dominance as a risk factor of non-contact ACL injury. However, a fundamental flaw of the majority of the studies is that limb dominance was defined as the preferred kicking limb, and thus the assumption that the kicking limb will be the more skilful and coordinated limb when changing direction is inherently incorrect. Nevertheless, practitioners are encouraged to screen COD biomechanics in both push-off limbs to identify biomechanical deficits associated with non-contact ACL injury risk, so informed individualised preventative training interventions can be created. Furthermore, as the aim of the sports medicine, sports science, and strength and conditioning is to improve athletic performance and minimise risk of injury, it would be advantageous that athletes have the capacity and are equally proficient in changing direction safely and quickly from

both limbs, due to the unpredictable nature of multidirectional sport.

Declarations of interest

None declared.

Conflicts of interest

None declared.

Ethical approval

None declared.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Ethical statement

None declared.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ptsp.2019.04.005>.

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