Article:

Montgomery, C, Blackburn, J, Withers, D et al. (3 more authors) (2018) Mechanisms of ACL injury in professional rugby union: a systematic video analysis of 36 cases. British Journal of Sports Medicine, 52 (15). pp. 994-1001. ISSN 0306-3674

https://doi.org/10.1136/bjsports-2016-096425

British Journal of
Sports Medicine

Mechanisms of Anterior Cruciate Ligament injury in Professional Rugby Union: A Systematic Video Analysis of 36 cases

Journal:	*British Journal of Sports Medicine*
Manuscript ID	bjsports-2016-096425.R1
Article Type:	Original Research
Date Submitted by the Author:	n/a
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Keywords:	ACL, Rugby, Anterior cruciate ligament, Knee injuries, Contact sports

Mechanisms of Anterior Cruciate Ligament injury in Professional Rugby Union: A Systematic Video Analysis of 36 cases

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Key Words: ACL, Rugby, Video Analysis,

Word Count: 3508

The word limit has been exceeded in an attempt to satisfy the reviewer comments for more detail in particular in the areas of the introduction and discussion.

ABSTRACT:

Background: ACL injury is a major issue in Rugby.

Aim: Use of systematic video analysis to investigate ACL injury mechanisms in Rugby.

Methods: Thirty-Six cases from games played in top professional leagues and international matches were available for analysis in our series. Five analysts independently assessed all videos to record the estimated frame/time of initial ground contact, frame/time of ACL tear and a range of play specific variables. This included Contact versus Non-Contact ACL injuries, injury timing, joint flexion angles and foot contact with the ground. Thirty-seven side-stepping manoeuvres from a control game were analysed to allow comparison of non-injury versus injury situations.

Results: Fifty-seven percent of ACL injuries occurred in a Contact manner. Two main scenarios were identified as offensive running and being tackled, indicating that the ball carrier is at higher risk of ACL injury. The majority of Non-Contact ACL injuries resulted from a side-stepping manoeuvre. In most Non-Contact cases, initial ground contact was through Heel Strike. Heel Strike was significantly associated with injury outcome. Non-Contact ACL injuries had lower median knee flexion angles and a more dorsiflexed ankle when compared to a control group (10°vs 20°, $p=0.000218$ and 10°vs 0°, $p=0.033$ respectively).

Conclusion: In our video analysis of ACL injuries in rugby, most injuries resulted from Contact mechanisms. For Non-Contact injuries, lower knee flexion angles and heel first ground contact in a side-stepping manoeuvre are also risk factors.

INTRODUCTION

Rugby Union (hereafter referred to as Rugby) turned professional in 1995. As the rate of injury has increased since this time, it is important that we understand this process with a view to reducing risk.[1-5] Knee injuries result in the most days absent from playing in professional Rugby.[6] Anterior cruciate ligament (ACL) injuries account for 29% of days missed due to knee injuries, on average 271 days absence per ACL rupture.[6] However, little is reported about the mechanisms of ACL injuries in rugby.

Mathematical modelling, laboratory motion analysis and cadaveric studies have helped in understanding the possible mechanisms of ACL injury.[7-9] However these studies are limited by their challenges in assessing real injury scenarios and therefore sport specific injury mechanisms. Retrospective interviews are limited by the athlete or coach's ability to comprehend, recall and articulate what occured.[10] In contrast, video analysis allows researchers to study playing situations preceding and during injury, as well as comparisons between injury and control groups. Several video analysis studies of ACL rupture in Football,[11 12] Handball,[13] Basketball,[14] Australian Rules Football,[15] Alpine Skiing,[16] and Netball[17] have been reported, but not for Rugby. Accordingly, the aim of this study was to use retrospective video analysis to describe ACL injury mechanisms in Rugby. The focus was on comparing Contact versus Non-Contact injuries, the timing of the injury, joint flexion angles and the nature of foot contact with the ground. We hypothesised that ACL injuries in Rugby would occur predominantly in a Non-Contact manner through side stepping and landing mechanisms similar to what has been previously reported for other team sports.

MATERIALS AND METHODS

Research Design

A semi-quantitative observational cohort study design was used to identify phase-of-play specific variables relating to ACL injuries in Men's Professional Rugby using video evidence. No personal player information was accessed and therefore ethical permission was not required.

Data Collection

A database of ACL injuries from Rugby games from January 1st 2014 to December 31st 2015 was compiled using Google News. Tournament specific searches (eg "ACL injury Six Nations") and club specific searches (eg "ACL injury Ulster Rugby") were applied, see Appendix 1 for a list of all teams and tournaments searched. A total of 54 ACL injuries were identified in training, preseason and competitive matches, see Figure 1. Only competitive matches were included for analysis.

Of the 54 injury cases identified, video footage for 36 competitive match injuries were obtained for analysis using (Optapro Rugby, London, UK) (Figure 1). No medical information was available apart from media reports of an injury. Fourteen cases were available with 3 camera views, 8 with 2 camera views and 14 cases had 1 camera view. Where possible, composite videos were created by manual synchronization using visual clues (eg initial foot ground contact).

Video processing

Injury sequences were cut and processed using Sportscode Elite version 9.8.3 software with all files converted to QuickTime (.mov), allowing frame-by-frame navigation using QuickTime player (version 7.7.9, Apple, Cupertino, California, USA). All videos were de-interlaced using the progressive scan feature of Elgato Turbo .264. Cases were cut as a sequence containing approximately 10s before the injury event and 2-3s after the injury to assess the specific match situation, as proposed by Walden et al.[11] Another sequence was cut with 1-2s before injury and 1-3s after injury to analyse biomechanical variables.

Video analysis

Five analysts (an international rugby analyst with a background in bioengineering, orthopaedics/sports medicine specialist, a chartered muskuloskeletal physiotherapist, orthopaedic surgeon and a bioengineer) independently assessed all videos in real time and frame-by-frame to record the estimated frame/time of Initial Contact (IC) as well as the frame/time of ACL tear, referred to as the Index Frame (IF).[11 14] A meeting was held to established a consensus for IC and IF for all cases, with consensus defined as 4 out of 5 analysts agreeing. The mean absolute deviation of the analysts individual estimates of IC and IF were 6ms and 8ms respectively. Thereafter all videos were categorised independently by the analysts using a form (Appendix 2) adapted from protocols for other sports.[18 11 14 16] This included categorical variables on injury circumstance and estimated flexion angles for the hip, knee and ankle (to the nearest 10°) for both IC and IF for all Non-Contact injury cases.

A Non-Contact injury was defined as occurring with no bodily contact with another player in the IF (Figure 2). Contact to any body part other than the injured leg was defined as Indirect Contact, while contact to the injured leg was defined as Direct Contact.[12 13 15]

Player velocities in the vertical and horizontal directions were categorised as high, low, zero or unsure. Low horizontal speeds refer to walking and jogging while high refer to running/sprinting. Low vertical speeds refer to running, stopping and cutting, while high refer to a distinct jump.

Knee valgus of the injured leg at either IC or the IF was recorded where possible. One case was excluded from joint flexion angle analysis due to inconclusive camera angles and in one case it was not possible to distinguish between a Non-Contact injury and a Contact Injury.

The categorical variables were established by consensus. The analysts also performed visual inspection for joint flexion angles in line with previous video analysis protocols.[11 14 15] No measurement tools were used to aid the visual inspection estimates of the experts.[14] The median joint flexion angles estimated by the five analysts were recorded along with the interquartile range.

Control group for Non-Contact Injuries

The most common Non-Contact Injury was due to a side-stepping motion. To study these in more detail, we identified a control group where side-stepping did not lead to an ACL injury. A randomly chosen game in the RWC 2015 (including a Northern and a Southern hemisphere team) was used to assess every sequence in which a ball carrier performed a side-stepping manoeuvre: 51 cases were identified, 14 of which were excluded due to inconclusive camera angles to assess joint flexion. The joint flexion angles of the remaining 37 cases at IC were estimated as previously described. These cases were then statistically compared to the side-stepping injury cases.

Statistical Analysis

All statistics were calculated using SPSS (IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp.). Knee and hip flexion angles were reported as positive numbers, ankle flexion angles were reported as negative numbers for plantarflexion and positive for dorsiflexion. Normal versus non-normal distributions were assessed using the Shapiro-Wilk test and results for non-normal distributions were reported as median and interquartile range. The Mann-Whitney U test was performed on the hip, knee and ankle angles of the Non-Contact side-stepping injury cases compared to the Control cases. Statistical significance was set at the 5% level. Fisher's exact test was used to assess the association of Heel strike or non-heel strike on side-stepping injury versus non-injury outcome (a Chi-Square test was not suitable as the sample size was too small). Inter-rater reliability for joint flexion angle estimations was assessed using the Intraclass Correlation Coefficient (ICC). An ICC score of >0.75 was regarded as excellent.[19]

RESULTS

General

The injury rate was 0.43 ACL injuries per 1000 player hours under match conditions. Of the 36 cases for which analysis was possible, 35 could be categorised into Contact and Non-Contact cases: 15 (43%) were Non-Contact and 20 (57%) were Contact cases. Contact cases were further subdivided into 8 (23%) Indirect Contact and 10 (29%) Direct Contact cases; 2 cases were Contact injuries but could not be subdivided into Direct/Indirect Contact. The majority of ACL injuries occurred in an Offensive playing situation (63%,n=22). Injuries were spread evenly over the pitch locations, with 13 occurring in the Offensive 3rd, 11 in the Defensive 3rd and 12 in the Middle 3rd. Only 3 matches (8%) had precipitation at the time of injury. There were 21 right knee injuries and 15 left knee injuries. Centres and Hookers obtained the most ACL injuries (Figure 3).

Playing situations for Non-Contact and Contact Injury cases

Non-Contact and Contact cases were further categorised by playing situation in which the injury occurred. Five categories were observed for 20 Contact Injuries: Rucking (n=4), Tackling (n=5), being Tackled (n=9), Set Play (n=1) and Kicking (n=1). Three categories were observed for the 15 Non-Contact Injury cases: Offensive Running (n=11), Defensive Running (n=3) and Set Play (n=1). See Tables 1-3.

Contact injury mechanisms

The majority of Contact cases fell into 3 categories accounting for 90% of all Contact injuries (n=18/20), see Table 3. The most common cause of contact ACL injury was to tackled players, termed Scenario A (Supplementary Video 1). The injured player was always in possession of the ball. A combination of both high (n=6) and low (n=3) speeds were observed. In the majority of cases the players were moving forwards or in a combination of forward and sideways at the time of contact (n=6). Contact was evenly distributed between Direct (n=5) and Indirect Contact (n=4) with one unsure. Rucking cases occurred predominantly to defensive players who were either stationary or moving at low speed (n=3). Tackling Contact injuries occurred at both high (n=2) and low (n=3) speeds. The remaining 2 cases occurred during a set play and to a player kicking the ball.

Table 1: Rugby–specific variables recorded for 36 ACL injury cases analysed using systematic video analysis

Case	Precipitation	Playing situation	Field Location	Player action	Duel type	If tackled what direction	Player contact preceding injury	player contact at injury	Time in match	Injured Knee
Offensive Running										
#1	No	Offence	Midfield Zone	Side step	Not being tackled		No	No	61-80	Left
#2	No	Offence	Offensive 3rd	Passing	Not being tackled		No	No	61-80	Right
#5	No	Offence	Offensive 3rd	Side step	Not being tackled		No	No	21-40	Right
#6	No	Offence	Offensive 3rd	Side step	Not being tackled		No	No	41-60	Right
#7	No	Offence	Offensive 3rd	Side step	Not being tackled		No	No	41-60	Right
#10	Unsure	Offence	Offensive 3rd	Stopping	Running		No	No	1-20	Left
#11	Unsure	Offence	Offensive 3rd	Side step	Not being tackled		No	No	41-60	Right
#12	Unsure	Offence	Midfield zone	Side step	Not being tackled		No	No	1-20	Left
#13	No	Offence	Midfield Zone	Side step	Not being tackled		No	No	61-80	Right
#15	Yes	Offence	Defensive 3rd	No possession	Running		Yes - Indirect	No	21-40	Right
#36	No	Offence	Defensive 3rd	Side step	Not being tackled		No	No	61-80	Right
Defensive Running										
#4	No	Defence	Midfield zone	Side step	Running		No	No	61-80	Right
#14	Unsure	Defence	Defensive 3rd	Side step	Not tackling		No	No	61-80	Left
#17	No	Defence	Defensive 3rd	Cross over cut	Not tackling		No	No	61-80	Right
Set Play										
#3	No	Set play	Midfield zone	Single leg landing	Competing for high ball		Yes - Indirect	No	1-20	Left
Rucking										
#8	No	Offence	Defensive 3rd	No possession	Rucking		Yes - Indirect	Yes - Direct	61-80	Left
#9	No	Defence	Offensive 3rd	No possession	Rucking		Yes - Indirect	yes -Indirect	61-80	Left
#18	Yes	Defence	Midfield zone	No possession	Rucking		Yes - Indirect	Yes - Indirect	21-40	Left
#34	Unsure	Defence	Midfield zone	No possession	Rucking		Yes - Indirect	Yes - Direct	61-80	Right
Tackling										
#22	No	Defence	Defensive 3rd	No possession	Tackling		Yes - Indirect	Yes - Indirect	61-80	Left
#23	No	Defence	Defensive 3rd	No possession	Tackling		Yes - Indirect	Yes - indirect	21-40	Right
#24	No	Defence	Midfield zone	No possession	Tackling		Yes - Indirect	Yes - Direct	1-20	Left
#29	No	Defence	Midfield zone	No possession	Tackling		No	Yes - Indirect	1-20	Right
#33	No	Defence	Offensive 3rd	No possession	Tackling		Yes - Indirect	Yes	21-40	Right
Tackled										
#19	No	Offence	Offensive 3rd	Other	Tackled	Side- above waist	Yes - Indirect	Yes - Indirect	1-20	Right
#20	No	Offence	Offensive 3rd	Other	Tackled	Front - Below waist	Yes - Indirect	Yes	1-20	Left
#21	No	Offence	Midfield zone	Running	Tackled	Behind - below waist	Yes - Indirect	Yes - Direct	21-40	Left
#25	No	Offence	Midfield zone	Side step	Tackled	Front and Side - above waist	Yes - Indirect	Yes - Direct	61-80	Right
#26	Unsure	Offence	Offensive 3rd	Receiving	Tackled	Behind and side - above and below	Yes - Indirect	Yes - Direct	1-20	Right
#27	No	Offence	Offensive 3rd	Side step	Tackled	Side and Below waist	Yes - Direct	Yes - Direct	61-80	Left
#28	unsure	Offence	Defensive 3rd	Receiving	Tackled	Front and above waist	Yes - Indirect	Yes - Indirect	21-40	Left
#32	Unsure	Offence	Midfield zone	Receiving	Tackled	Front and Side - above waist	Yes - Indirect	Yes - Direct	1-20	Right
#35	Yes	Offence	Offensive 3rd	Side step	Tackled	Behind - above waist	Yes - Indirect	Yes - Indirect	1-20	Right
Kicking										
#30	No	Offence	Defensive 3rd	Kicking	Collision	Side and Below	No	Yes - Direct	61-80	Right
Set Play										
#31	Yes	Set play	Defensive 3rd	Scrum	Scrum		Yes - Indirect	Yes - Direct	61-80	Right
Other										
#16	Unsure	Defence	Defensive 3rd	No possession	Unsure		Unsure	Unsure	61-80	Left

Non-Contact Injury Mechanisms

For the 15 Non-Contact injury cases (Tables 1&2), 67% (n=10) occurred while a player performed a side-stepping (evasive) manoeuvre. The remaining cases occurred through landing, crossover cut, stopping, passing and running without possession. Foot contact at IC was Heel Strike in 67% (n=10) of all Non-Contact cases, with 90% (n=9/10) of the side-stepping cases having Heel Strike at IC. Thus Heel Strike occurred over three times more often than either Flat or Toe strike for the Non-Contact injury cases. Furthermore, 80% (n=8) of the Heel Strike cases occurred in the second half of the game and 50% (n=5) occurred in the last quarter (Figure 4). Eleven Non-Contact Injuries (73%) occurred to a knee which appeared to be fully load-bearing.

The most frequent Non-Contact injury situation was Offensive Running, termed scenario B (Figure 2 and Supplementary Video 2). In 9 of these 11 cases the attacking player was the Ball Carrier and in 8 of the 11 he was performing a side-stepping manoeuvre. The foot plant at IC was Heel Strike in 8 of these Offensive Running cases, Flat in 2 cases and Toe Strike in 1 case. The flexion angles at IC all were ≤40° for the Hip (n=9) and ≤20° for the knee.

Table 2: Biomechanical variables recorded for 15 non-contact ACL injury cases analysed using systematic video analysis

Case	In balance	Movement	Cutting angle	Leg loading	Horizontal speed at IC	Vertical speed at IC	Trunk rotation at IF	Foot rotation at IC	Foot strike
Offensive Running									
#1	Yes	Forward + Sideways	30-90°	One	High	Zero	Neutral	External	Heel
#2	Yes	Forward	0-30°	One	High	Zero	Towards injured leg	External	Heel
#5	Yes	Forward + Sideways	30-90°	One	High	Zero	Neutral	External	Heel
#6	Yes	Forward + Sideways	0-30°	One	High	Zero	Towards injured leg	External	Heel
#7	Yes	Forward	30-90°	One	High	Zero	Neutral	External	Heel
#10	Yes	Forward + Sideways	0-30°	One	Low	Zero	Neutral	External	Flat
#11	Yes	Forward + Sideways	30-90°	One	High	Zero	Neutral	Unsure	Heel
#12	Yes	Forward + Sideways	30-90°	One	High	Zero	Neutral	External	Heel
#13	Yes	Forward	30-90°	2 legs - main load on injured leg	High	Low	Towards injured leg	External	Heel
#15	No- Backwards	Backwards + sideways	0-30°	2 legs - main load on injured leg	Low	Zero	Towards injured leg	Unsure	Toe
#36	Yes	Forward + Sideways	30-90°	One	High	Low	Neutral	External	Flat
Defensive Running									
#4	No - sideways	Forward	30-90°	2 legs - main load on injured leg	High	Zero	Neutral	External	Heel
#14	Yes	Sideways	>90°	2 legs - main load on injured leg	High	Zero	Neutral	Internal >45°	Heel
#17	No - sideways	Forward + Sideways	30-90°	One	Low	Zero	Towards injured leg	Neutral	Flat
Set Play									
#3	No	Downward + Sideways	0-30°	One	Zero	High	Towards injured leg	External	Toe

Table 3: Biomechanical variables recorded for 20 contact ACL injury cases analysed using systematic video analysis

Case	In balance	Movement	Cutting angle	Leg loading	Horizontal speed at IC	Vertical speed at IC
Rucking						
#8	Yes	Stationary	0-30°	2 legs -equal load	Zero	Zero
#9	Yes	Stationary	0-30°	2 legs -equal load	Zero	Zero
#18	Unsure	Unsure	0-30°	Unsure	Unsure	Unsure
#34	Yes	Unsure	0-30°	Unsure	Zero	Unsure
Tackling						
#22	Unsure	Forwards	0-30°	Unsure	Low	Unsure
#23	No - Forwards	Backwards	0-30°	One	High	Zero
#24	No -Backwards and Sideways	Unsure	0-30°	Unsure	Low	Low
#29	Unsure	Unsure	0-30°	One	High	Zero
#33	Unsure	Forwards and Down	0-30°	Unsure	Low	Unsure
Tackled						
#19	No - Forward and Sideways	Forwards and Sideways	0-30°	One leg	High	Zero
#20	No - Forward	Forward	0-30°	Unsure	Low	Zero
#21	Yes	Forward	0-30°	Unsure	High	Zero
#25	No - Forwards and Sideways	Forward and Sideways	0-30°	One leg	High	Zero
#26	Yes	Unsure	0-30°	2 legs -main load injured leg	High	Zero
#27	No - Forward	Forwards and Sideways	0-30°	Unsure	High	Zero
#28	Unsure	Unsure	0-30°	Unsure	Low	Zero
#32	No - Backwards	Backwards and Down	0-30°	Unsure	Low	Unsure
#35	No - Forwards	Forward and Sideways	30-90°	One	High	Zero
Kicking						
#30	Yes	Forwards	0-30°	One leg	Low	Zero
Set Play						
#31	Unsure	Unsure	0-30°	Unsure	Low	Zero

Control Study

From the 37 cases of side-stepping manoeuvres involving no injury identified in the Control game, only 22% (n=8) had a Heel Strike at IC, with the remaining 78% (n=29) Flat or Toe Strike. All Heel Strike cases occurred in the second half. Shapiro Wilk assessments showed the distributions of hip, knee and ankle angles at IC were not normally distributed. The flexion angles for the control cases were compared to the side-stepping injury cases (Supplementary Tables 1 & 2). The median hip flexion was 30° for injury cases versus 30° in non-injury cases (Figure 5). The median knee flexion angle was 10° for injury cases versus 20° in non-injury cases (Figure 6). The median ankle flexion ankle was 10° for injury cases versus 0° in non-injury cases (figure 7). Mann Whitney U tests showed the differences for knee and ankle flexion angles for the injury and non-injury cases to be both statistically significant ($p=0.000218$ and $p=0.033$ respectively). However, the hip flexion angle differences were not statistically significant ($p=0.261$). The Inter-rater reliability for joint flexion angles across the 5 analysts was ICC=0.9745, ICC=0.9619 and ICC=0.9268 for the hip, knee and ankle angles respectively. The Fisher's Exact test for Heel Strike versus non-Heel Strike at IC when comparing injury to non-injury yielded a p value of = 0.000145 and the effect size (Phi and Cramer's V) was 0.582, indicating a large effect size.[20]

DISCUSSION

This is the first reported video analysis of the circumstances of ACL injuries in men's professional Rugby. The ACL injuries evaluated were from the available videos obtained from leading international and club teams over a recent two-year period (2014-2015). We identified two main scenarios: being tackled (scenario A) – a Contact injury mechanism and offensive running (scenario B) – a Non-Contact injury mechanism. These scenarios accounted for 56% of all ACL injuries in this study. The results did not support the proposed hypothesis with 57% of ACL injuries occurring as a result of Contact scenarios in rugby. A valgus force was present in 80% of the Contact injuries. Side-stepping was the mechanism of injury in 67% of all Non-Contact injuries.

Contact versus Non-Contact ACL injuries

The results show that the proportion of ACL injuries due to Contact in rugby is substantial (57%, n=20/35). Rugby is a full contact sport which probably explains the increased proportions of Contact injuries compared to football and basketball (36% and 28% respectively).[11 14] Similar rates of Direct Contact injuries were found when compared to AFL (29% vs 32%) and these are higher than for football (15%), handball (5%) and basketball (10%), as expected.[11 13-15] Rucking and scrummaging are unique to Rugby and these accounted for 25% (n=5) of Contact cases.

Playing situations associated with Contact ACL injury

The unpredictable nature of Contact situations may contribute to the lack of clearly defined injury patterns. For example Contact cases were evenly distributed between Defensive (n=8) and Offensive situations (n=11), with the remaining case occurring during Set Play. Contact injuries were often associated with a knee under valgus loading (80%, n=16). A valgus force was present in 7/10

Direct Contact injuries, and these results show a similar trend to football where 5/6 Direct Contact injuries occurred under a valgus force.[11] Further research with a larger sample size may determine if any of the Contact categories result in a significant increase in ACL risk.

Playing situations associated with Non-contact ACL injury

Side-stepping injuries accounted for 36% (n=13) of cases overall, and for 67% (n=10) of all Non-Contact ACL injuries. This is higher than in AFL, where only 37% of Non-Contact ACL injuries resulted from side-stepping.[15] This may be because AFL has higher incidences of injuries resulting from players competing for a high ball. This is an integral part of AFL but is much less common in Rugby and Landing accounted for only one case in our study.

Sixty-one percent (n=22) of all ACL injury cases occurred during Offensive situations and these accounted for 73% (n=11) of the Non-Contact cases. The opposite was found in football.[11 12] This is most likely because rugby encourages ball carriers to perform evasive manoeuvres to avoid contact.

Knee and Ankle flexion and Foot strike

The median knee flexion angle for Non-Contact injury cases (10°, range 10-20°) was statistically lower than for non-injury cases (20°, range 10-60°). The median difference is small, but the injury cases have a small spread around the median, whereas the non-injury cases have a much larger spread, suggesting that these injuries are much more likely to happen at a lower knee flexion angle. These findings are similar to previous studies of AFL and football where all injury cases in both studies were found to occur ≤30°,[11 15] while a detailed study estimating joint kinematics in ACL injury in basketball and handball reported a median knee flexion angle of 23°.[21] Three dimensional joint angle analysis should be applied to ACL rugby injuries in future. However, since anterior shear force on the ACL at low knee flexion angles is known to be a contributing factor in ACL rupture,[22-24] it is anticipated that such a detailed analysis would corroborate the results presented here.

The median ankle flexion angle for Non-Contact injury cases (10°, range -10-10°) was statistically higher than for non-injury cases (0°, range -20-20°). This indicates that injury cases are more likely to have a dorsiflexed ankle at IC when compared to non-injury cases which present with a neutral ankle. This is what would be expected to be seen with the predominance of Heel strike cases occurring in the injury cases versus non-injury cases. Boden et al. reported that in cases with Flat or Heel Strike landings the calf musculature may be unable to absorb the ground-reaction forces adequately, which are then transmitted directly to the knee.[25] Boden et al. further surmised that landing on the forefoot may be crucial to preventing ACL injury,[7] our study found a significant association between Heel strike and ACL injury when comparing injury to non-injury cases. The high proportion of Heel strike cases seen in Non-Contact ACL injuries in Rugby may prove to be an important factor to target when creating rugby specific ACL prevention programmes. High knee abduction moments have been shown to predict ACL injury.[26] Kristianslund et al. showed that a sidestep cut with toe planting decreased knee abduction moments and therefore an improvement in side-stepping technique reduced ACL risk. [27]

Fatigue

Forty-seven percent of Non-Contact cases (n=7) and 42% (n=15) of all cases occurred in the last 20 minutes of the match, similar to Dallalana et al who found that 29% of all ACL injuries occurred in the last quarter of a match.[6] Eighty-nine percent (n=16) of Heel Strike cases for both injury cases and controls occurred in the second half of the match. The authors hypothesise that irrespective of injury, fatigue plays an important role in determining the nature of foot strike, which then predisposes players to ACL rupture. Important limitations to note are that substitutions and preceding training load and match congestion for the injured players was not assessed. Fatigue has been previously shown to significantly increase tibial anterior shear force and decrease knee flexion angles when performing stop-jump tasks.[28] Similarly, McLean et al concluded that under fatigue conditions changes in lower limb control may increase the risk of Non-Contact ACL injuries during landing.[29]

Limitations

The analysis is based on 36 cases, but these are all of the ACL injuries identified in the major league rugby tournaments over a two-year period for which analysis was possible, see Figure 1. This is a similar sample size to equivalent studies in other sports.[11 13 14 15 16] The cases were evenly distributed amongst all of the leagues and test matches, with at least seven cases in each competition. We also observed an almost identical injury rate to that reported in a two-season study of English professional Rugby Union performed in 2002/2003 (0.43 vs 0.42 per 1000 player hours) and conclude that the results should be representative.[6] In addition we used the same methodology as used by the majority of previous systematic video analysis studies on ACL injury mechanisms in other sports.[11 14 15] The cases only included injuries which occurred in men's competitive games, it is unknown whether training injuries and injuries sustained by amateur and female players occur as a result of the same mechanisms or playing situations.

The database was collected by a structured search of worldwide media, and it was not possible to confirm independently that ACL rupture occurred, or the extent of associated injuries or the history of previous injuries. However, there is no reason to suspect any selection bias in the reported results, and it is assumed that media reports of ACL injuries are generally reliable due to the long injury absences involved.

Video analysis studies are dependent on the quality and resolution of the images and the number of camera angles available. The exact moment when the ACL tear occurred could not be accurately determined, so the time point identified as the index frame is an estimate based upon the subjective observations of the five experienced analysts. A high degree of agreement was seen in their initial IF and IC estimations. In this study one injury case and 13 control group cases were removed from flexion analysis due to poor video quality or inconclusive camera angles. The remaining 14 injury cases and 37 non-injury cases had a varying number of camera angles. Krosshaug et al noted that accuracy and precision of video assessment of joint angles was limited. [30] However a strength of this study was that an excellent inter-rater reliability (all ICC values >0.9268) was shown for joint flexion angle estimations for both injury and control cases. This allowed for identification of trends rather than attempting to identify a precise flexion angle associated with injury. Future studies would benefit from using Model Based Image Matching techniques when analysing joint flexion angles,[31 32] but this is a highly time-consuming process and requires multiple camera angles.

Conclusions

Two scenarios were identified in rugby which accounted for 56% of all ACL injuries: a player being tackled and offensive running. Over half (57%) of the ACL injuries observed occurred in a Contact manner. The majority of Non-Contact ACL injuries resulted from a side-stepping manoeuvre by a Ball Carrier. In most of these Non-Contact cases, initial foot contact with the ground was through a Heel Strike. Heel strike was significantly associated with injury outcome. Furthermore, Non-Contact ACL injuries occurred with lower knee flexion angles compared to the control group. Future research of a prospective cohort of male subjects addressing prevention programmes aimed at the risk factors outlined in our study would be most beneficial.

What this study adds:

- **Offensive running and being tackled accounted for the majority of ACL injuries indicating that the ball carrier is at most risk of ACL injury in professional Rugby Union.**
- **A large number of all ACL injuries arise from Contact situations**
- **Heel strike during side stepping is significantly associated with Non-Contact ACL injuries in Rugby**

Acknowledgements

The authors would like to thank Dr Mathew Lyons for advice with the statistical analysis and Mr Paul Ryan for acting as a collaborator and one of the analysts for this research.

Author Contributions

All authors were involved in the research concept and design, as well as data analysis and paper writing. Mr Montgomery, Mr Blackburn, Mr Tierney and Dr Withers also performed the analysis. (The fifth analyst was Mr Paul Ryan, acknowledged above)

Conflicts of Interests

The authors report no conflicts of interest

Funding

No funding was received for this study

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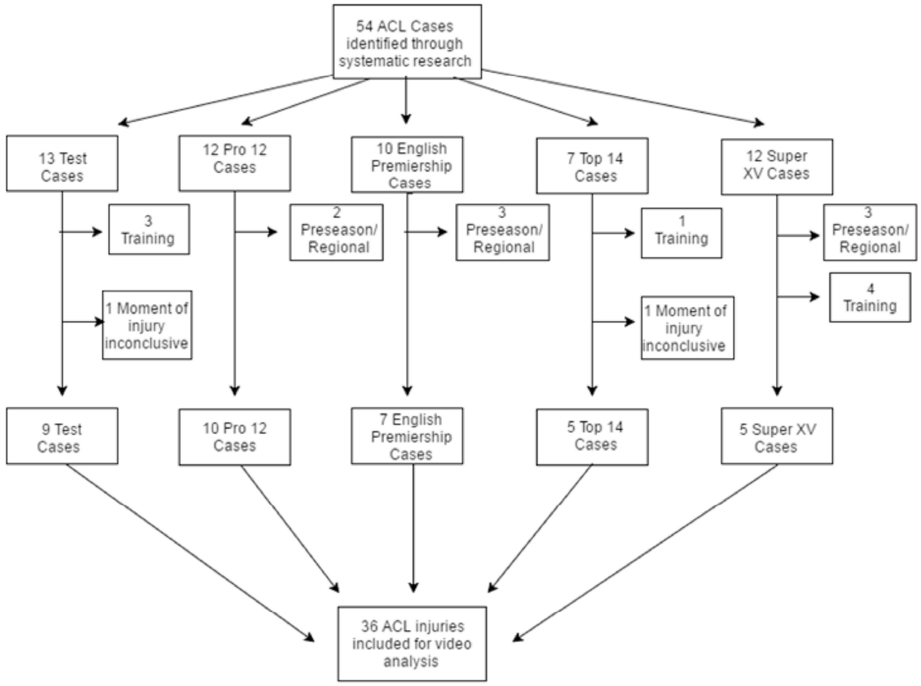

Figure 1. Flowchart indicating the 54 ACL ruptures identified and the screening process to make up the 36 cases of competitive match injuries used for video analysis.

130x97mm (300 x 300 DPI)

Figure 2: Scenario B, Non-contact offensive running: a side-stepping manoeuvre leading to ACL injury. A) IC: player makes contact with the ground with his heel while performing a side-stepping manoeuvre. B) IF: knee valgus is apparent as player attempts to complete manoeuvre

130x97mm (300 x 300 DPI)

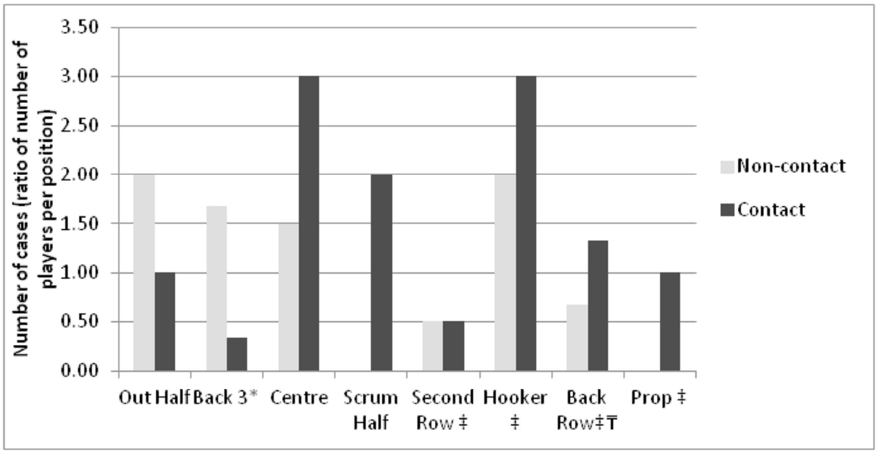

Figure 3: Break down of ACL injury by position (all positions of multiple players calculated as a ratio for comparative purposes) ‡Denotes Forwards, *Back 3 includes: Full back and 2 Wings, ₸ Back row includes: Number 8 and 2 Flankers

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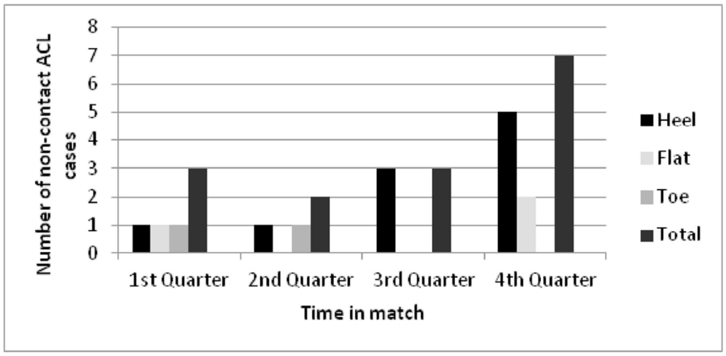

Figure 4: Non-Contact ACL injuries in relation to when they occur and the category of foot strike at IC

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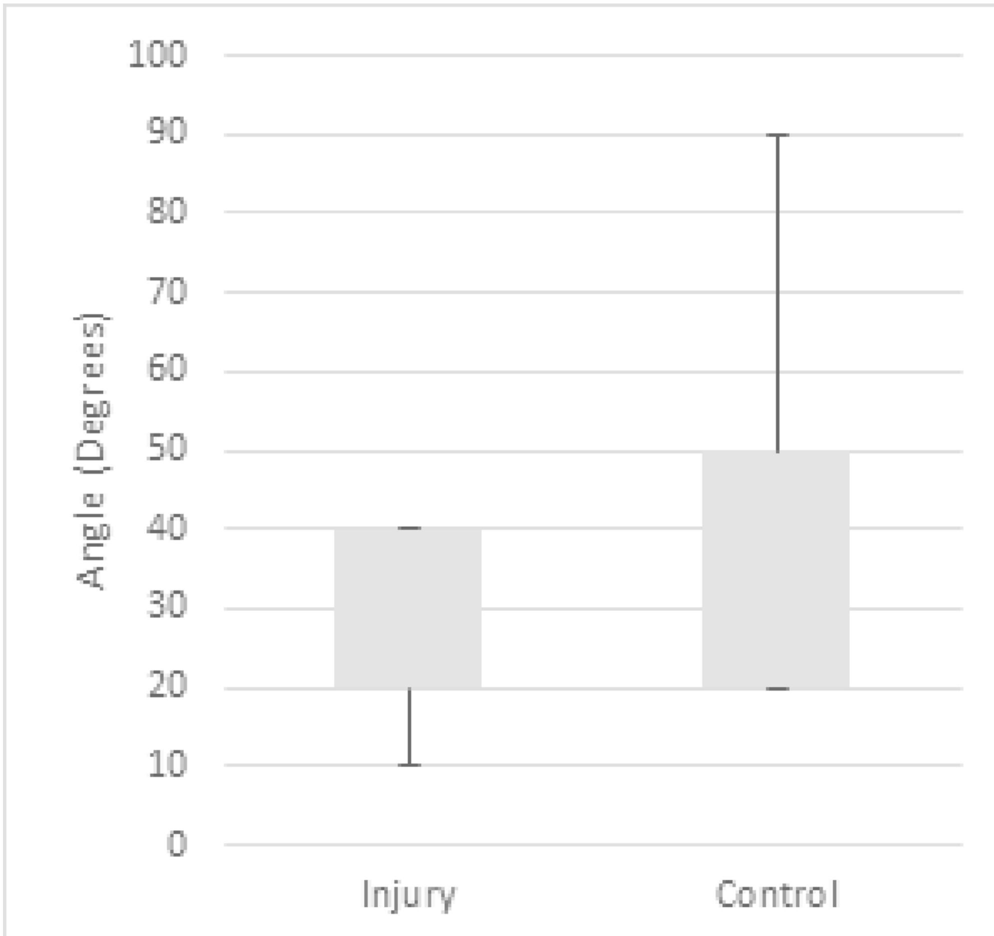

Figure 5: Box plot of Hip Flexion Angles: Injury cases vs Non-injury cases

163x153mm (300 x 300 DPI)

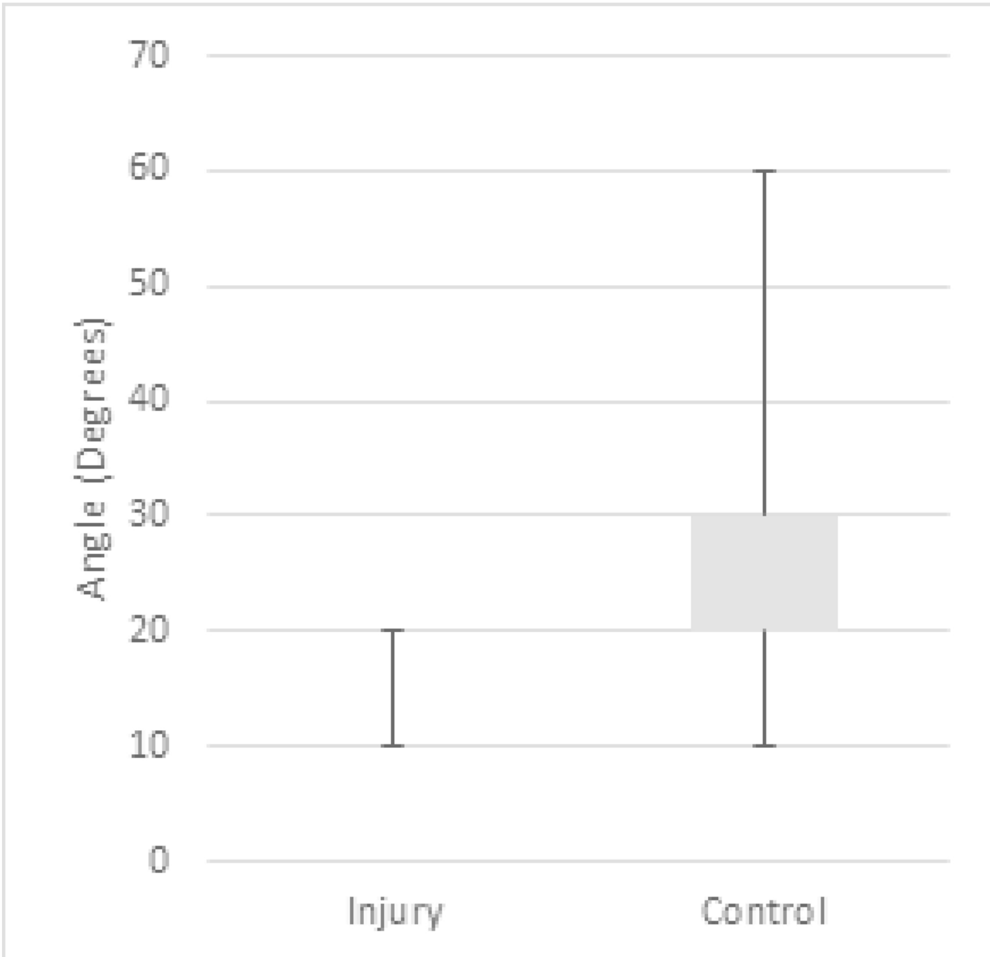

Figure 6: Box plot of Knee Flexion Angles: Injury vs Non-injury cases

167x162mm (300 x 300 DPI)

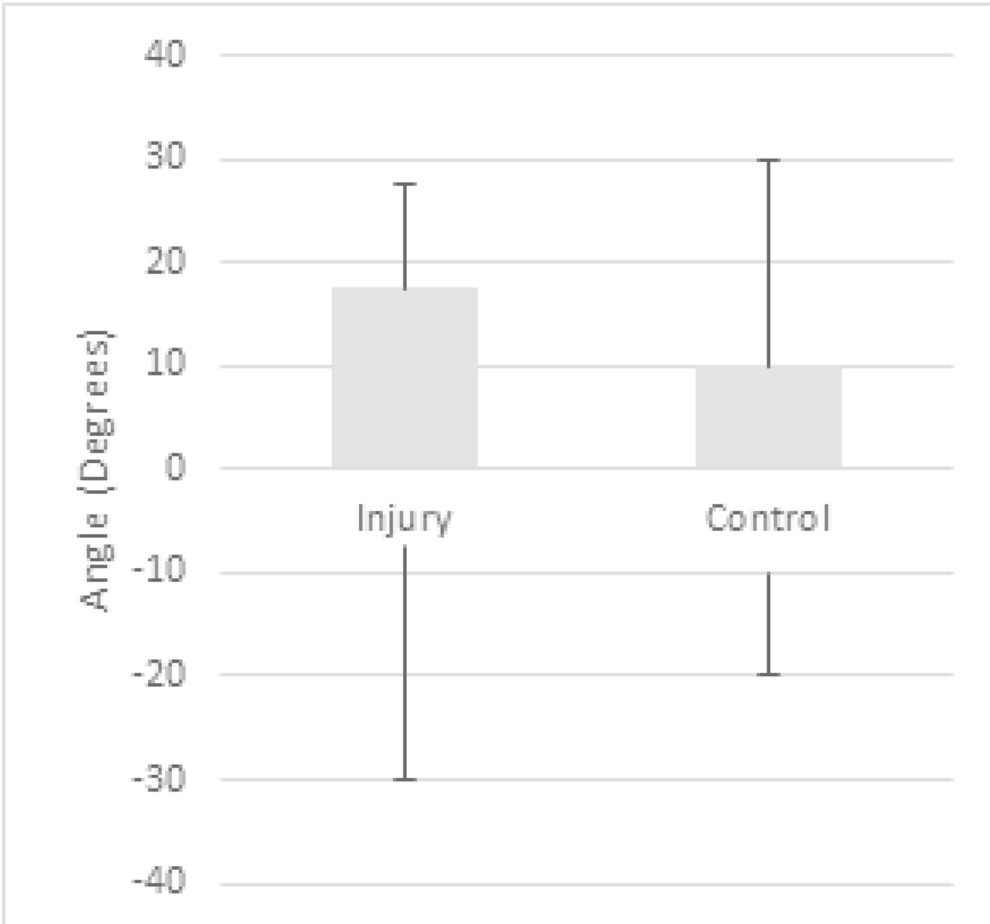

Figure 7: Box plot of Ankle Flexion Angles: Injury vs Non-injury cases

161x151mm (300 x 300 DPI)

Appendix 1: Google news searches, Club and tournament specific

Tournament specific searches	Club Specific Searches				
Rugby World Cup	Leinster Rugby	Agen	Saracens	Blues	New Zealand Rugby
Six Nations	Munster Rugby	Bordeux Begles	Exeter Chiefs	Brumbies	Australia Rugby
Rugby Championship	Connacht Rugby	Brive	Northampton Saints	Bulls	South Africa Rugby
Pro 12	Ulster Rugby	Castres	Leicester Tigers	Cheetahs	England Rugby
Top 14	Cardiff Blues	Clermot	Bath Rugby	Chiefs	Ireland Rugby
Aviva English Premiership	Newport Gwent Dragons	Grenoble	Worcester Warriors	Crusaders	Scotland Rugby
Super Rugby	Llanelli Scarlets	La Rochelle	Harlequins Rugby	Western Force	Wales Rugby
	Ospreys	Montpellier	Sale Sharks	Highlanders	France Rugby
	Edinburgh Rugby	Racing Metro	Wasps	Hurricanes	Italy Rugby
	Glasgow Warriors	Toulon	Gloucester Rugby	Lions	Japan Rugby
	Zebre	Pau	London Irish	Melbourne Rebels	Samoa Rugby
	Treviso Rugby	Stade Francais	Newcastle Falcons	Queensland Reds	Tonga Rugby
		Toulouse		Sharks	Fiji Rugby
		Oyonnax		Stormers	USA Rugby
				New South Wales Waratahs	Canada Rugby
					Argentina Rugby
					Uruguay Rugby
					Romania Rugby
					Georgia Rugby
					Namibia Rugby

Appendix 2: Video analysis questionnaire used to describe ACL injury circumstances and biomechanics

Weather Condition	
Precipitation preceding injury	Yes
	No
	Unsure
Rugby specific variables	
Playing position proceeding injury	Offensive
	Defensive
	Set play
	Unsure
	Other
Field location at injury	Defensive third
	Offensive third
	Midfield zone
	Unsure
Player action proceeding injury	Passing
	Receiving
	Stopping
	Landing (single or double leg) or Land and step
	Kicking
	Turning (Side step or Cross over)
	No ball possession
	Unsure
If kicking which leg	Right
	Left
	Unsure
Duel type proceeding injury	Collision (unintentional)
	Tackling (other player)
	Tackled (by other player)
	Not tackling (involving defending player that is not tackling)
	Not being tackled (involving attacking player which is not being tackled)
	Competing for a high ball
	Running
	Rucking
Time in Match (minutes)	1 - 20
	21 - 40
	41 - 60
	61 - 80
If tackled from what direction	Front
	Behind
	Side
	Unsure
If tackled what type	Above waist

	Below waist
	Unsure
Player contact proceeding injury	Yes
	No
	Unsure
If contact what type	Direct (to injured knee or leg)
	Indirect (to uninjured leg, trunk, head/neck or arm)
	unsure
Player contact at injury	Yes
	No
	Unsure
If contact what type	Direct (to injured knee or leg)
	Indirect (to uninjured leg, trunk, head/neck or arm)
	Unsure
Biomechanical variables	
In balance at IC	Yes
	No
	Unsure
If out of balance what direction	Forward
	Backward
	Sideways
	Combined directions
	Unsure
Player movement at IC	Forward
	Backwards
	Sideways
	Upward
	Downward
	Combined directions
	Unsure
Cutting angle at IC	Intended change of direction 0-30°
	Intended change of direction 30-90°
	Intended change of direction >90°
	Unsure
Leg loading at IF	One leg
	Two legs with equal load
	two legs with main load on injured leg
	Two legs with main load on uninjured leg
	Unsure
Horizontal speed at IC	High
	Low
	Zero
	Unsure
Vertical Speed	High
	Low
	Zero

	Unsure
Trunk rotation at IF†	Toward injured leg
	Toward uninjured leg
	Neutral
	Unsure
Foot rotation at IC*	Internal 0-45°
	Internal >45°
	External
	Neutral
	Unsure
Foot strike at IC	Heel
	Toe
	Flat
	Unsure
Hip Flexion Angles (nearest 10°)	IF
	IC
Knee Flexion Angles (nearest 10°)	IF
	IC
Ankle Flexion Angles (nearest 10°)	IF
	IC
Varus/valgus	IC

ACL, Anterior Cruciate Ligament; IC, Initial contact; IF, Index frame

†Trunk rotation denotes the position in relation to foot position

* Foot rotation denotes the position in relation to the players direction of movement

SUPPLEMENTARY TABLE 1: Joint flexion angles of the hip, knee and ankle joints for the 15 non-contact ACL injury mechanisms

	Hip Flexion (°)*		Knee Flexion (°)*		Ankle Flexion (°)*	
Case	**IC**	**IF**	**IC**	**IF**	**IC**	**IF**
Offensive Running						
#1	40 (±5)	40 (±10)	10 (±10)	30 (±10)	-10 (±0)	-20 (±5)
#2	40 (±5)	40 (±5)	20 (±15)	30 (±20)	10 (±10)	-10 (±10)
#5	20 (±15)	10 (±0)	20 (±10)	30 (±10)	20 (±5)	-10 (±0)
#6	40 (±5)	30 (±0)	10 (±5)	30 (±10)	10 (±15)	0 (±15)
#7	40 (±15)	40 (±10)	10 (±15)	30 (±10)	0 (±10)	-10 (±0)
#10	10 (±10)	10 (±15)	10 (±10)	30 (±10)	-10 (±10)	0 (±10)
#11	30 (±25)	20 (±15)	10 (±5)	30 (±15)	-10 (±15)	10 (±0)
#12	40 (±10)	40 (±5)	10 (±10)	30 (±20)	10 (±10)	0 (±10)
#13	10 (±15)	10 (±20)	10 (±5)	20 (±20)	10 (±15)	0 (±10)
#15	Unsure	Unsure	Unsure	Unsure	Unsure	Unsure
#36	Unsure	Unsure	10 (±10)	20 (±30)	10 (±0)	-10 (±5)
Defensive Running						
#4	20 (±10)	20 (±10)	10 (±0)	20 (±10)	10 (±5)	20 (±15)
#14	30 (±5)	20 (±0)	10 (±15)	10 (±20)	0 (±10)	-10 (±0)
#17	20 (±10)	20 (±10)	10 (±10)	20 (±15)	10 (±10)	30 (±15)
Set Play						
#3	20 (±15)	90 (±5)	20 (±15)	110 (±20)	-30 (±10)	30 (±20)

ACL, Anterior Cruciate Ligament; IC, Initial Contact; IF, Index Frame

*Flexion angles are reported as the median of individual estimates along with the interquartile range. Positive values mean flexion and negative values mean extension

SUPPLEMENTARY TABLE 2: Joint flexion angles of the hip, knee and ankle joints for the non-injury side stepping cases indentified from the control study.

	Hip Flexion (°)*	Knee Flexion (°)*	Ankle Flexion (°)*
Case	**IC**	**IC**	**IC**
Heel Strike			
#1	30 (±15)	10 (±5)	0 (±10)
#2	30 (±0)	20 (±20)	10 (±15)
#3	30 (±15)	10 (±5)	20 (±15)
#4	80 (±15)	20 (±15)	10 (±15)
#5	20 (±10)	10 (±10)	0 (±10)
#6	40 (±5)	20 (±10)	10 (±20)
#7	90 (±10)	30 (±0)	0 (±15)
#8	20 (±15)	30 (±15)	0 (±5)
Other			
#9	50 (±15)	40 (±5)	-10 (±10)
#10	30 (±20)	20 (±20)	-10 (±5)
#11	30 (±10)	10 (±10)	-10 (±5)
#12	30 (±20)	30 (±10)	10 (±10)
#13	50 (±10)	60 (±10)	-20 (±15)
#14	40 (±15)	30 (±157)	-10 (±10)
#15	20 (±5)	10 (±10)	0 (±5)
#16	60 (±10)	60 (±5)	0 (±10)
#17	60 (±5)	50 (±10)	-10 (±5)
#18	50 (±10)	40 (±0)	-10 (±5)
#19	30 (±10)	10 (±0)	-10 (±10)
#20	80 (±10)	10 (±5)	-10 (±10)
#21	60 (±10)	20 (±10)	-10 (±10)
#22	50 (±20)	60 (±20)	-10 (±10)
#23	60 (±5)	20 (±0)	0 (±5)
#24	40 (±15)	20 (±0)	-10 (±0)
#25	20 (±5)	20 (±0)	0 (±5)

#26	40 (±0)	20 (±10)	0 (±0)
#27	20 (±15)	20 (±20)	-10 (±0)
#28	40 (±0)	40 (±5)	0 (±0)
#29	60 (±10)	20 (±0)	0 (±5)
#30	70 (±15)	40 (±10)	-10 (±10)
#31	30 (±15)	20 (±5)	-10 (±10)
#32	20 (±10)	30 (±15)	-10 (±5)
#33	20 (±0)	20 (±0)	0 (±0)
#34	20 (±10)	30 (±5)	20 (±25)
#35	20 (±15)	20 (±5)	-10 (±15)
#36	20 (±10)	20 (±5)	0 (±10)
#37	30 (±5)	10 (±5)	0 (±0)

ACL, Anterior Cruciate Ligament; IC, Initial Contact

*Flexion angles are reported as the median of individual estimates along with the interquartile range. Positive values mean flexion and negative values mean extension