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Kinematics of 90° change of direction in young football players: Insights for ACL injury prevention from the *CUTtheACL* study on 6008 trials

Francesco Della Villa[1] | Stefano Di Paolo[2] | Matteo Crepaldi[1] | Piefrancesco Santin[1] | Ilaria Menditto[1] | Luca Pirli Capitani[1] | Lorenzo Boldrini[1] | Luca Ciampone[1] | Gabriele Vassura[1] | Antonio Bortolami[1] | Andrea Nicolò Bosi[1] | Alberto Grassi[2] | Stefano Zaffagnini[2,3]

[1]Education and Research Department, Isokinetic Medical Group, FIFA Medical Centre of Excellence, Bologna, Italy

[2]2nd Orthopaedic and Traumatologic Clinic, IRCCS Istituto Ortopedico Rizzoli, Bologna, Italy

[3]Department of Biomedical and Neuromotor Sciences, University of Bologna, Bologna, Italy

Correspondence

Stefano Di Paolo, 2nd Orthopaedic and Traumatologic Clinic, IRCCS Istituto Ortopedico Rizzoli, Via Giulio Cesare Pupilli, 1, Bologna 40136, Italy.
Email: stefano.dipaolo@ior.it

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Abstract

Purpose: To investigate the 90° change of direction (COD) task in an extensive cohort of competitive healthy football players within the *CUTtheACL* study and to provide normative values and differences between males and females for full-body kinematics based on two-dimensional (2D) video analysis and scoring system.

Methods: One-thousand-and-two competitive football (soccer) players (age 16.3 ± 2.8 years, 264 females) were prospectively enroled. Each player performed three preplanned 90° COD tasks per limb. The 2D evaluation was performed through objective measures (collected through three high-speed cameras) of frontal and sagittal plane joint kinematics at the cut initial foot contact (IC) and maximum knee flexion angle. A previously published scoring system was adopted to measure the movement quality of the COD task. The scoring system included five criteria (limb stability [LS], pelvis stability [PS], trunk stability [TS], shock absorption [SA], movement strategy [MS]) ranked from 0/2 (nonadequate) to 2/2 (adequate) with a maximum score of 10/10. Normative data were provided for all the variables; statistical differences between male and female players were investigated ($p < 0.05$).

Results: A total of 6008 valid attempts were included. Frontal plane knee projection angle (FPKPA) at initial contact was 24.4 ± 9.8° (95th percentile: FPKPA > 40°). The total score was ≤4/10 in 71.2% of the trials, the lowest subscores were LS and PS. Female players showed different movement patterns with lower hip and trunk flexion both at IC and maximum knee

Abbreviations: ACL, anterior cruciate ligament; BMI, body mass index; CMAS, cutting movement assessment score; COD, change of direction; DKV, dynamic knee valgus; FPA, foot projection angle; FPKPA, frontal plane knee projection angle; GRF, ground reaction force; ICC, intraclass correlation coefficient; IRB, International Review Board; KAA, knee abduction angle; KAM, knee abduction moment; LS, limb stability; MAT, movement analysis test; MS, movement strategy; NMT, neuromuscular training; PS, pelvis stability; RTS, return to sport; SA, shock absorption; TS, trunk stability.

flexion angle ($p < 0.01$, ES = 0.41–0.64). Female players also showed worse scores than males in SA, MS and total score ($p < 0.01$).
Conclusion: Female players seem more prone to stiffer lower limb strategy and greater pelvis–trunk frontal plane instability than males. Clinicians could adopt normative data and sex-specific differences in players' movement techniques to improve ACL injury risk mitigation protocols.

Level of Evidence: Level IV.

KEYWORDS
2D video-analysis, ACL, cut manoeuvre, injury prevention, return to sport

INTRODUCTION

In young football players, the implications of an anterior cruciate ligament (ACL) injury can be devastating: physical and psychological weakness, limited return to sport (RTS), high rate of reinjury risk and increased risk of early osteoarthritis onset [11, 17, 19]. For these reasons, prevention protocols targeting the modifiable risk factors for ACL injury have been deployed through neuromuscular training (NMT) in football academies.

Female players are usually considered at higher risk for ACL injury than males [14, 27]. Females also showed lower compliance with injury prevention programs and worse mitigation outcomes [3, 14, 27]. It should be noted that risk factors for ACL injury—and the dedicated testing methodologies historically developed—are almost exclusively based on male (or pooled) data. The latter aspect increases the risk of sex bias in the interpretation of the data and the development of targeted interventions.

Two-dimensional (2D) video analysis is a valuable solution in the assessment of the risk factors related to ACL injury [5, 7, 9, 29, 30]. Recent literature focused on the analysis of the change of direction task, considered the most informative and game-resembling movement to be performed in a controlled setting [5, 23, 24, 32]. Scoring systems based on 2D video analysis of cut manoeuvres kinematics such as the cutting movement assessment score (CMAS) and the movement analysis test (MAT) have been validated against marker-based three-dimensional (2D) motion capture, demonstrating high intra- and inter-rater reliability and discriminative power towards well-known risk factors for ACL injury, for example, the knee abduction moment [5, 8, 12, 13].

Despite the recent scientific progress in the 2D video analysis, the studies conducted so far were mainly cross-sectional with a limited sample size (<100 participants). Large prospective investigations would offer the unique opportunity to systematically inform cut manoeuvre screening through a strong benchmark of 2D kinematics data.

The purpose of the present study was to investigate the 90° change of direction task in an extensive cohort of competitive healthy football players within the *CUTtheACL* project, a prospective epidemiology and biomechanics investigation on risk factors for primary ACL injury mitigation, and to provide normative values and differences between males and females for full-body kinematics based on 2D video analysis and the MAT 2D scoring system.

MATERIALS AND METHODS

Study protocol and participants

The study was approved by the Bioethical Committee of the University of Bologna (International Review Board approval: n. 283861 of 04/11/2021). All the subjects or their legal tutor signed informed consent before entering the study.

The *CUTtheACL* study is a prospective epidemiology and biomechanics investigation on risk factors for primary ACL injury mitigation. The analysis was entirely conducted in the Education and Research Department of the Isokinetic Medical Group. The goal of the project is to prospectively assess the risk of ACL injury in young competitive football players after a baseline screening of cut manoeuvres through a qualitative 2D video analysis scoring system. The ultimate goal of the project is (I) to define a state-of-the-art ACL injury risk in the young and competitive football population (at the highest risk for ACL injury [15, 21, 22]) and (II) to provide an effective translational approach for the primary and secondary ACL injury prevention through a qualitative quick screening based on objective 2D biomechanical measurements. In the original study protocol, the players are prospectively followed for 2 years (two consecutive football seasons) after the baseline test to record the events of musculoskeletal injuries to the lower limbs (in particular, ACL injury).

A total of 1002 football players belonging to professional ($n = 286$) and amateur ($n = 716$) football team academies participated in the study. Inclusion criteria were age between 14 and 21 years old and Tegner activity level >6. Exclusion criteria were (1) evidence of musculoskeletal disorders or functional impairment; (2) body mass index (BMI) > 35; (3) cardiopulmonary or cardiovascular disorders; (4) inability to perform the required tasks.

For each player, the following information was collected before the change of direction tests: gender, age, weight, dominant limb, family history for ACL injury (only closest relatives), first team level (professional, amateur), position in the field and level of aggressiveness in the field (ranked through a Likert scale from 1 = *minimally aggressive* to 5 = *extremely aggressive*). The mean age was 16.3 ± 2.8 years; female players represented more than one-fourth of the cohort (n = 264, Table 1).

TABLE 1 Demographic data for the CUTtheACL study cohort.

	All (n = 1002)	Female (n = 264)	Male (n = 738)	Effect size[a]	p Value
Age	16.3 ± 2.8 [16.1; 16.5]	18.0 ± 3.2 [17.6; 18.4]	15.7 ± 2.3 [15.5; 15.9]	0.89	<0.01
Weight	62.9 ± 10.1 [62.2; 63.5]	59.4 ± 8.6 [58.4; 60.4]	64.1 ± 10.4 [63.4; 64.9]	0.47	<0.01
Height	169.9 ± 9.7 [169.3; 170.5]	162.1 ± 6.8 [161.3; 162.9]	172.7 ± 9.0 [172; 173.3]	1.25	<0.01
BMI	21.7 ± 2.8 [21.6; 21.9]	22.6 ± 2.9 [22.3; 22.9]	21.4 ± 2.7 [21.2; 21.6]	0.42	<0.01
Preferred limb[b]					
Left	162 (16.2)	33 (12.5)	129 (17.5)	3.56	n. s.
Right	840 (83.8)	231 (87.5)	609 (82.5)		
Team level[c]					
Professional	286 (28.5)	74 (28.0)	212 (28.7)	0.05	n. s.
Amateur	716 (71.5)	190 (72.0)	526 (71.3)		
Player position					
Goalkeeper	106 (10.6)	29 (11.0)	77 (10.4)	1.73	n. s.
Defender	343 (34.2)	92 (34.8)	251 (34)		
Midfielder	296 (29.5)	83 (31.4)	213 (28.9)		
Striker	257 (25.6)	60 (22.7)	197 (26.7)		
Aggressiveness					
1 (min)	26 (2.6)	9 (3.4)	17 (2.3)	5.84	n. s.
2	119 (11.9)	38 (14.5)	81 (11.0)		
3	440 (44.1)	102 (38.9)	338 (45.9)		
4	331 (33.2)	88 (33.6)	243 (33)		
5 (max)	82 (8.2)	25 (9.5)	57 (7.7)		
Family history of ACL injury					
No	830 (82.8)	219 (83)	611 (82.8)	0.01	n. s.
Mother	25 (2.5)	8 (3.0)	17 (2.3)		
Father	117 (11.7)	22 (8.3)	95 (12.9)		
Mother and father	6 (0.6)	3 (1.1)	3 (0.4)		
Sister	6 (0.6)	5 (1.9)	1 (0.1)		
Brother	18 (1.8)	7 (2.7)	11 (1.5)		

Note: Data are presented as mean ± standard deviation [95% confidence intervals] for the continuous variables, and count (percentage) for the categorical variables.
Abbreviation: ACL, anterior cruciate ligament.

[a]Effect size for continuous variables was Cohen's d, while effect size for categorical variables was χ^2.

[b]Preferred limb is intended as the kicking limb.

[c]First team level.

Change of direction acquisition protocol

Each football player was asked to perform a preplanned 90° change of direction task. The complete acquisition setting has been presented in a previous study [5]. In brief, each trial consisted of a frontal sprint followed by a 90° sidestep cut and a further frontal sprint in the new direction. Players were asked to complete the movements at the maximum speed possible (100%). Before the test, the subjects performed a 10-min dynamic warm-up (exercise bike and mobility) and a few repetitions of the movement to get confident with the environment and the motor task. All subjects performed three valid repetitions per lower limb. Full foot contact on the force platform and a subsequent sharp cut angle were required to consider a trial valid.

Three high-speed cameras placed frontally and bilaterally towards movement direction (VICON Nexus, Vicon Motion Systems Ltd. Sampling frequency: 100 Hz) were used to collect the videos used for the 2D video-analysis. A force platform embedded in the floor and synchronised with the cameras (AMTI 400 × 600, Sampling frequency: 1000 Hz) was also used as part of the scoring system (Section Data processing). The laboratory floor was equipped with artificial turf, the cut direction was traced with cones.

Data processing

The 2D joint kinematics was computed in dedicated software in the VICON environment through the recordings of the high-speed cameras. Frontal and lateral cameras were used to assess joint kinematics on the frontal and sagittal planes, respectively. Joint kinematics was evaluated at two frames: the initial foot contact (IC) on the force platform, that is, the beginning of the cut manoeuvre; and the frame of maximal knee flexion angle after the IC on the force platform. The two frames were chosen to present both the initial player's pose in contact with the ground, which is indicative of the motor strategy of the player while approaching the cut manoeuvre, and the kinematic response to the forces exchanged with the ground in the central phase of the cut manoeuvre, that is, after the load acceptance and the joint moment peaks [6, 18, 24]. The following 2D angles were computed through the stills of the frontal view: foot projection angle (FPA), knee abduction angle (KAA), frontal plane knee projection angle (FPKPA), ground reaction force vector distance from knee centre (V distance), pelvis tilt angle and trunk tilt angle. The following 2D angles were computed through the stills of the sagittal view: ankle flexion angle (γ), supplementary knee flexion angle (α), supplementary hip-to-trunk flexion angle (β), trunk flexion angle (δ), hip flexion angle [computed as $180° - (\beta + \delta)$]. The graphical and written explanation of each 2D joint angle is presented in Appendix A.

A 2D scoring system, validated for the change of direction task assessment, was adopted to rate each trial [5]. The scoring system is aimed at identifying biomechanical and neuromuscular control deficits through a synthetic and user-friendly interface in the context of ACL injury prevention and rehabilitation [5, 9, 10, 12, 31]. The score, based on the frontal and sagittal plane joint kinematics computed at the maximum knee flexion angle frame, is composed of five scoring criteria: *limb stability* (LS), *pelvis stability* (PS), *trunk stability* (TS), *shock absorption* (SA) and *movement strategy* (MS). For each criterion, a sub-score of 0/2 (nonadequate), 1/2 (partially adequate) or 2/2 (adequate) is attributed to the movement, based on objective 2D measurements [5]. A total score is also computed as the sum of the single subscores, with an optimal trial being ranked as 10/10. The scoring system has demonstrated fair-to-excellent intra-rater and inter-rater reliability (e.g., intraclass correlation coefficient [ICC] = 0.94 and ICC = 0.83 for the total score, respectively) and a strong association (large effect size) with the knee abduction moment [5, 9].

Statistical analysis

The normal distribution of the data for each variable was verified through the Shapiro–Wilk test and the homogeneity of variance was verified through Levene's test. Regarding the normative data, the continuous variables were presented as mean ± standard deviation (95% confidence interval [CI]), while the categorical variables were presented as a percentage over the total and median with interquartile range. Furthermore, the 25th, 75th and 95th percentiles were reported for each continuous variable for the overall data. The 95th percentile was reported alongside the common robust statistics as a measure of 'extreme values': since the present study involves baseline data only and no clear indication of ACL injury risk thresholds has already been provided for joint kinematics based on 2D video analysis, the use of 95th percentile surrogates a clinically relevant threshold that, if exceeded, might imply a greater risk for ACL injury (e.g., high dynamic knee valgus [DKV] [16, 26]).

Regarding the comparison between males and females, the two-tailed Student's t test was used to assess continuous 2D kinematics variables in the presence of normally distributed data. The Cohen's d effect size and the mean difference between the groups (with 95% CI) were reported alongside the p value. The effect size was considered trivial, small, medium and large for Cohen's d value of <0.2, 0.2, 0.5 and 0.8, respectively. The Mann–Whitney U test was used to investigate the differences in the total score and nonnormally distributed variables, and Rank Biserial Correlation was reported as an effect size measure. The χ^2 test in contingency tables was used to investigate the differences between males and females for each subscore of the 2D scoring system.

Differences were considered statistically significant for $p < 0.05$. The statistical analyses were conducted in SPSS (v26.0; IBM).

RESULTS

Overall, 6008 valid trials were included in the final analysis. Forty-five trials (0.7% of the total) were excluded due to technical reasons related to the force platform or the cameras during the data processing.

Male and female players differed in age and height with a large effect size and in weight and BMI with a small effect size. No other differences in demographics were identified (Table 1).

2D kinematics

In the overall population, FPKPA increased from 24.4 ± 9.8° (95th percentile: 40°) at IC to 43.6 ± 14.5° at maximum knee flexion angle (95th percentile: 64°). The V distance was 15.1 ± 9.1 cm (95th percentile: 31.6 cm) at IC and decreased to 6.2 ± 3.9 cm (95th percentile: 12.4 cm) at maximum knee flexion. The α (supplementary knee flexion angle) at the IC was 148.1 ± 11.0° (95th percentile: 163°) (Figure 1, Table 2).

Female players showed lower hip and trunk flexion both at IC ($p < 0.001$, $d = 0.41–0.64$, small-to-moderate effect) and maximum knee flexion angle ($p < 0.001$, $d = 0.42–0.61$, small-to-moderate effect) (Table 2). Statistically significant differences with trivial-to-small effects ($p < 0.01$, $d < 0.27$) were found for most of the other 2D variables (Figure 1, Table 2).

2D scoring system

The total score was 4/10 or lower (nonadequate) in 71.2% of the trials. The LS and PS subscores showed a prevalence of 0/2 (89.0% and 77.1%, respectively) with no differences between males and females (Table 3).

Female players were ranked as 0/2 more frequently than males in SA (7.7% more, $p < 0.001$) and MS (17.5% more, $p < 0.001$). Male players were ranked 0/2 more frequently than females in TS (9.8% more, $p < 0.001$). The total score was lower for females compared to males with a rate ≤4/10 in 76.0% and 69.5% of the trials, respectively ($p < 0.001$, Figure 2, Table 3).

DISCUSSION

The most important finding of the present study was the description of joint kinematics from 2D video analysis of the 90° change of direction in an extensive cohort of young football players and the identification of relevant

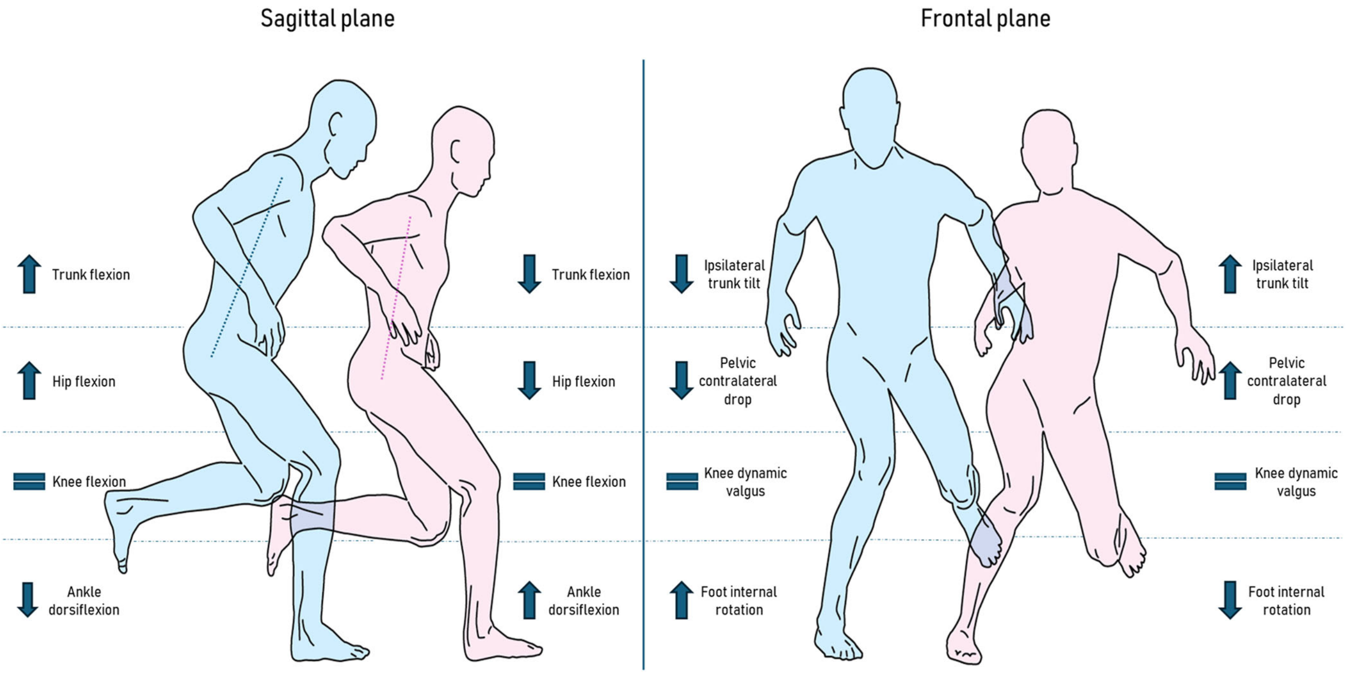

FIGURE 1 Summary of the salient differences between female (pink) and male (blue) players' two-dimensional kinematics on sagittal (left) and frontal plane (right) in the CUTtheACL study cohort.

TABLE 2 Results for 2D kinematics (°) for the overall population and separated for male and female players.

	All (n = 6008)	Female (n = 1584)	Male (n = 4424)	Diff [95% CI]	Effect size[a]	p Value
Initial contact						
Foot projection angle	−30.5 ± 24.1	−27.3 ± 24.7	−31.7 ± 23.7	4.4 [3.0; 5.8]	0.18	<0.01
Knee abduction angle	19.9 ± 6.3	20.8 ± 6.7	19.5 ± 6.1	1.3 [0.9; 1.6]	0.20	<0.01
Frontal plane knee projection angle	24.4 ± 9.8	25.0 ± 9.4	24.2 ± 9.9	0.9 [0.3; 1.4]	0.09	<0.01
GRF vector-knee distance	15.1 ± 9.1	15.1 ± 9.0	15.1 ± 9.2	−0.1 [−0.6; 0.5]	0.01	n. s.
Pelvis drop angle	−14.0 ± 7.4	−13.6 ± 7.7	−14.1 ± 7.3	0.6 [0.1; 1.0]	0.08	0.01
Trunk tilt angle	0.6 ± 8.0	1.2 ± 7.3	0.4 ± 8.2	0.8 [0.4; 1.3]	0.10	<0.01
γ (ankle dorsiflexion)	−11.6 ± 14.8	−12.1 ± 15.8	−11.4 ± 14.4	−0.7 [−1.6; 0.1]	0.05	n. s.
α (suppl. knee flexion)	148.1 ± 11.0	148.3 ± 10.3	148.0 ± 11.2	0.4 [−0.3; 1.0]	0.04	n. s.
β (180 − (hip flexion + trunk flexion)	103.8 ± 12.8	109.5 ± 12.0	101.7 ± 12.4	7.8 [7.1; 8.5]	0.64	<0.01
δ (trunk flexion)	21.9 ± 9.1	18.5 ± 8.3	23.1 ± 9.1	−4.6 [−5.1; −4.1]	0.52	<0.01
Hip flexion angle	54.4 ± 7.8	52.1 ± 7.4	55.2 ± 7.8	−3.2 [−3.6; −2.7]	0.41	<0.01
Maximum knee flexion angle						
Foot projection angle	−29.4 ± 21.7	−26.8 ± 21.8	−30.4 ± 21.6	3.6 [2.3; 4.8]	0.17	<0.01
Knee abduction angle	37.7 ± 9.1	38.0 ± 9.7	37.6 ± 8.9	0.4 [−0.1; 0.9]	0.05	n. s.
Frontal plane knee projection angle	43.6 ± 14.5	42.1 ± 13.7	44.2 ± 14.8	−2.0 [−2.9; −1.2]	0.14	<0.01
GRF vector-knee distance	6.2 ± 3.9	6.3 ± 3.9	6.2 ± 3.9	0.1 [−0.2; 0.3]	0.01	n. s.
Pelvis drop angle	−16.3 ± 7.9	−17 ± 8.2	−16.1 ± 7.8	−0.9 [−1.4; −0.5]	0.12	<0.01
Trunk tilt angle	−0.4 ± 11.9	0.4 ± 10.5	−0.7 ± 12.4	1.1 [0.4; 1.8]	0.09	<0.01
γ (ankle dorsiflexion)	1.5 ± 8.3	3.1 ± 9.8	0.9 ± 7.5	2.2 [1.7; 2.7]	0.27	<0.01
α (suppl. knee flexion)	119.5 ± 20.5	122.0 ± 34.6	118.6 ± 11.9	3.4 [2.3; 4.6]	0.17	<0.01
β (180 − (hip flexion + trunk flexion)	99.9 ± 15.6	106.7 ± 15.3	97.5 ± 14.9	9.2 [8.4; 10.1]	0.61	<0.01
δ (trunk flexion)	26.9 ± 10.3	23.8 ± 10.2	28.0 ± 10.1	−4.2 [−4.8; −3.6]	0.42	<0.01
Hip flexion angle	53.3 ± 9.3	49.7 ± 9.3	54.6 ± 9.0	−4.9 [−5.4; −4.4]	0.54	<0.01

Note: Data are presented as mean ± standard deviation. Colour code highlights differences between male and female players with $p < 0.001$, darker colours mean greater effect size.

Abbreviations: 2D, two-dimensional; CI, confidence interval; GRF, ground reaction force.

[a]Cohen's *d* effect size.

differences between male and female players, with the latter more prone to pelvis and trunk instability at IC and stiffer lower limb strategy. To the best of the authors' knowledge, this is the largest cohort assessing cut manoeuvre kinematics through a validated scoring system based on video analysis for both female (n = 264) and male (n = 738) players. Overall, more than 6008 trials were included in the analysis, thus providing a substantial benchmark for future assessments of cut manoeuvre 2D kinematics in ACL injury prevention testing (Figure 1, Appendix B).

Both frontal and sagittal plane kinematics were in line with current literature on 90° change of direction tasks [5]. Previous studies demonstrated the association between higher frontal plane kinematics, for example, the FPKPA and higher knee abduction moment [1, 5, 28]. Due to the prospective nature of the present study, the players were all free from musculoskeletal injuries at the time of the data collection. Therefore, inferences about the risk of ACL injury should be drawn with caution when referring to average outcomes. For this reason, robust statistics (interquartile ranges) for each variable including the 95th percentile are provided. The latter should be considered as an edge measure and might be used as a warning when assessing the results of the change of direction test: healthy players exhibiting kinematics close or over the 95th percentile (e.g., initial contact FPKPA > 40°, KAA > 30°, knee flexion angle <47°) might deserve attention and corrective intervention to

TABLE 3 Results for the 2D scoring system for the overall population and separated for male and female players.

	All (*n* = 6008)	Female (*n* = 1584)	Male (*n* = 4424)	Effect size[a]	*p* Value
Limb stability					
0/2	5346 (89.0)	1390 (87.8)	3956 (89.4)	19.2	<0.01
1/2	548 (9.1)	177 (11.2)	371 (8.4)		
2/2	114 (1.9)	16 (1.0)	98 (2.2)		
Pelvis stability					
0/2	4632 (77.1)	1234 (78)	3398 (76.8)	4.2	n. s.
1/2	1066 (17.7)	258 (16.3)	808 (18.3)		
2/2	310 (5.2)	91 (5.7)	219 (4.9)		
Trunk stability					
0/2	2214 (36.9)	469 (29.6)	1745 (39.4)	49.0	<0.01
1/2	2111 (35.1)	632 (39.9)	1479 (33.4)		
2/2	1683 (28.0)	482 (30.4)	1201 (27.1)		
Shock absorption					
0/2	975 (16.2)	346 (21.9)	629 (14.2)	61.8	<0.01
1/2	3817 (63.5)	984 (62.2)	2833 (64.0)		
2/2	1216 (20.2)	253 (16.0)	963 (21.8)		
Movement strategy					
0/2	1759 (29.3)	668 (42.2)	1091 (24.7)	242.4	<0.01
1/2	1860 (31.0)	519 (32.8)	1341 (30.3)		
2/2	2389 (39.8)	396 (25.0)	1993 (45.0)		
Total score					
0–4/10	4279 (71.2)	1203 (76.0)	3076 (69.5)	35.2	<0.01
5–7/10	1602 (26.7)	336 (21.2)	1266 (28.6)		
8–10/10	127 (2.1)	44 (2.8)	83 (1.9)		
Avg.	3.4 ± 1.9	3.2 ± 2.0	3.5 ± 1.9	0.18	<0.01

Note: Data are presented as count (percentage).

Abbreviation: 2D, two-dimensional.

[a] χ^2 effect size, Cohen's *d* for average total score.

mitigate the risk of knee overloading [1, 20]. The prospective analysis of the ACL-injured players' kinematics will be used to finetune such metrics.

Differences between male and female players had mainly trivial-to-small statistical effects (Table 2). Interestingly, female players seem more prone to DKV at the IC of the cut manoeuvre, while males at maximum knee flexion angle (Table 2). This finding might be related to a difference in sprint performance between males to females: on one hand, the kinematics at IC is indicative of the braking strategy while approaching the cut; on the other hand, the kinematics at maximum knee flexion angles are indicative of the kinematic response to the impact with the ground and prepares the body to the propulsion in the new direction. Higher approaching speed with a limited braking strategy has been shown to increase the occurrence of risk patterns and knee overload [6]. Therefore, female players seem to approach the cut with a worse strategy and male players seem more prone to injury-performance conflict as described by Dos'Santos et al. [13]. Moreover, female players showed a stiffer lower limb strategy (moderate effect size, Table 2): lower hip flexion angle was shown at both IC and maximum knee flexion angle, thus demonstrating a sex-specific cut strategy. Despite potential differences in playing level, years of playing and physical characteristics such as quadriceps and gluteus strength or general joint laxity, this finding suggests that female players might need different preventative approaches compared to males

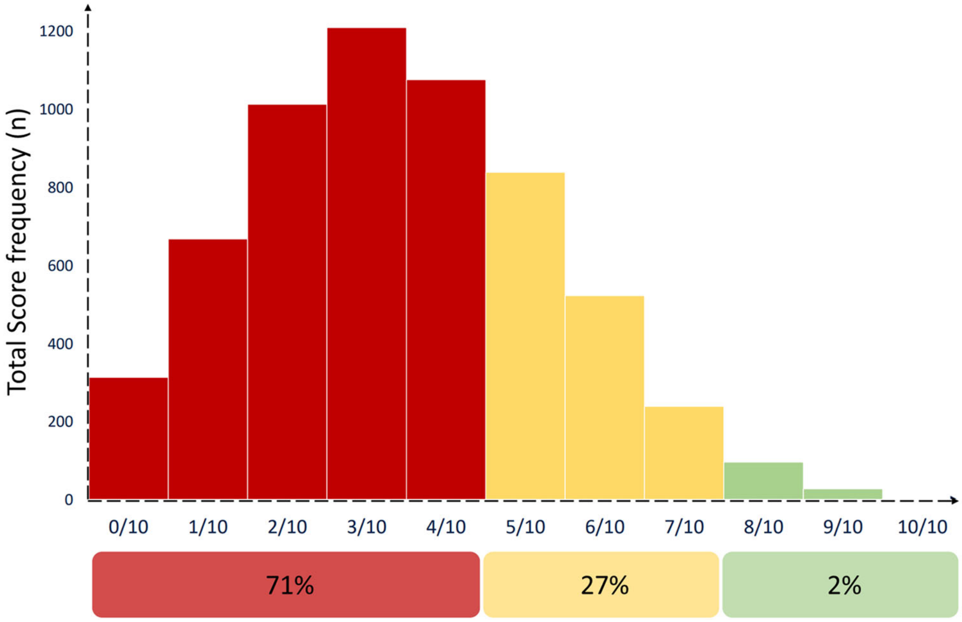

FIGURE 2 Two-dimensional total score frequency in the 6008 change of direction trials of the CUTtheACL study cohort. According to Della Villa et al. [5]., trials rated ≤4/10 (red), 5–7/10 (yellow) and ≥8/10 (green) are considered at high, mid and low risk of anterior cruciate ligament injury (high knee abduction moment), respectively.

in terms of lower limb sagittal plane and core stabilisation.

The 2D scores were overall low (prevalence of 0/2). Despite a floor effect that could be argued, this is in line with the findings of previous studies on poor movement quality in football players as well as the increasing occurrence of ACL injuries in the young population experienced in the last decade [2]. These aspects enforce the rationale for continuously promoting and optimising NMT protocols for ACL injury mitigation in football academies. In the present study, LS and PS subscores showed the highest prevalence of 0/2 (*nonadequate change of direction*). Previous literature demonstrated that poor frontal plane control of the lower limb and pelvis is associated with increased knee abduction moment and higher occurrence of ACL injury [1, 8, 28]. Male players showed lower TS scores than females (Table 3). This aspect could again be related to the injury-performance conflict: indeed, a trunk fully rotated into the direction of the cut is rated as 0/2 [5, 13, 29]. This intrarotation pattern is typical of anticipatory movement technique, that fosters a faster cut (greater performance) but can induce rotational components at knee level, too [4, 13, 25]. Female players performed worse than male players in the SA and MS subscores. These scores, based on sagittal plane analysis of knee and hip flexion and position to the foot clarify—in a more athlete- (or patient-) friendly fashion—the findings of the 2D kinematics regarding the stiffer lower limb strategy adopted by female players [5, 10, 20].

More than two-thirds of the trials were rated <4/10 in total score. The study by Della Villa et al. showed that a total score of 0–4/10 (*nonadequate change of direction*) implies up to 1 Nm/body weight (37%) higher knee abduction moment compared to a score of 8–10/10 (*high-quality change of direction*) [5]. In a prospective pilot study on female footballers, Di Paolo et al. showed that players sustaining a noncontact ACL injury in the two following seasons had a lower total score (average 2.4/10 vs. 4.6/10, moderate effect) at the time of the change of direction test compared to the noninjured ones [8]. The players with a total score of <4/10 in one or more trials should, therefore, deserve greater attention and could be potentially targeted for additional preventative training. The present study shows that female players are more likely to be ranked 0–4/10 than their male counterparts (Table 3). The 2D scoring system brings an easy-to-interpret coupling of clinically relevant variables in the assessment of the ACL injury risk while showing high intra- and inter-rater reliability [5, 12]. These aspects facilitate the use of such a scoring system in the RTS continuum.

The present study has some limitations. First, the task evaluated was a preplanned change of direction. The assessment of unplanned changes of direction has been proposed in both laboratory and on-field testing to better resemble game situations, although this implies a greater amount of variability in the data that could have flawed the repeatability of the protocol. A female-to-male sample size ratio of 1:3 should be acknowledged. Moreover, pooling the results could have flattened potential differences between males and females. Future sub-analyses of the present database could help stratify the players into (several) clinically relevant categories and inspect sex differences more in detail. The presence of such a wide cohort is indeed a strong strength of the *CUTtheACL* study. Moreover, the present database allows the adoption of statistical methods for dimensionality reduction and/or supervised and unsupervised machine learning algorithms to better inspect the key features involved in the description of change of direction kinematics.

The clinical relevance of the present study is that the kinematics of the change of direction technique, considered the most informative test to inspect the presence of biomechanical risk factors for ACL injury, was provided in a simple, cost-effective fashion through 2D video analysis for a wide cohort of male and female players. These results might help clinicians to further understand sex-specific differences in players' movement techniques and shape future testing protocols in daily clinical practice through the inspection of normative data. In particular, preventative approaches to mitigate the ACL injury risk in female football might be based on different cutoffs than male players for lower limbs and pelvis–trunk kinematics. Moreover, the *CUTtheACL* study will prospectively adopt these findings to provide evidence on the relation between poor biomechanics and ACL injury in young football players.

CONCLUSION

Joint kinematics from 2D video analysis of the 90° change of direction task was provided in an extensive cohort of young football players. Female players seem more prone than male players to pelvis and trunk instability at IC and stiffer lower limb strategy. Players exhibiting kinematics over the 95th percentile (e.g., FPKPA > 40° at initial contact, total 2D score ≤4/10) might deserve attention towards the risk of sustaining an ACL injury. The prospective investigation of ACL injuries in the *CUTtheACL* study cohort will provide evidence on the biomechanical risk thresholds of the 90° change of direction task and could help in the implementation of large screenings and ACL injury mitigation protocols.

AUTHOR CONTRIBUTIONS

Francesco Della Villa participated to study conceptualisation, methods development, data interpretation, supervision and coordination and drafted the manuscript. Stefano Di Paolo contributed to study conceptualisation, methods development and data interpretation, drafted the manuscript and performed statistical analyses. Matteo Crepaldi, Piefrancesco Santin, Ilaria Menditto, Luca Pirli Capitani, Luca Ciampone, Gabriele Vassura, Antonio Bortolami and Andrea Nicolò Bosi contributed to data collection. Alberto Grassi and Lorenzo Boldrini contributed to study design and data interpretation. Stefano Zaffagnini contributed to study design, coordinated activities and supervised the drafting of the manuscript. All the authors read the final manuscript and approved it.

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CONFLICT OF INTEREST STATEMENT

Each author certifies that he or she has no commercial associations (e.g., consultancies, stock ownership, equity interest, patent/licensing arrangements, etc) that might pose a conflict of interest in connection with the submitted article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, SDP, upon reasonable request.

ETHICS STATEMENT

This study obtained approval from the Institutional Review Board (IRB approval: n. 283861 of 04/11/2021) of the Bioethical Committee of the University of Bologna. All the subjects or their legal tutor signed informed consent before entering the study.

ORCID

Stefano Di Paolo http://orcid.org/0000-0002-1761-7352

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APPENDIX A

See Figure A1

See Table A1

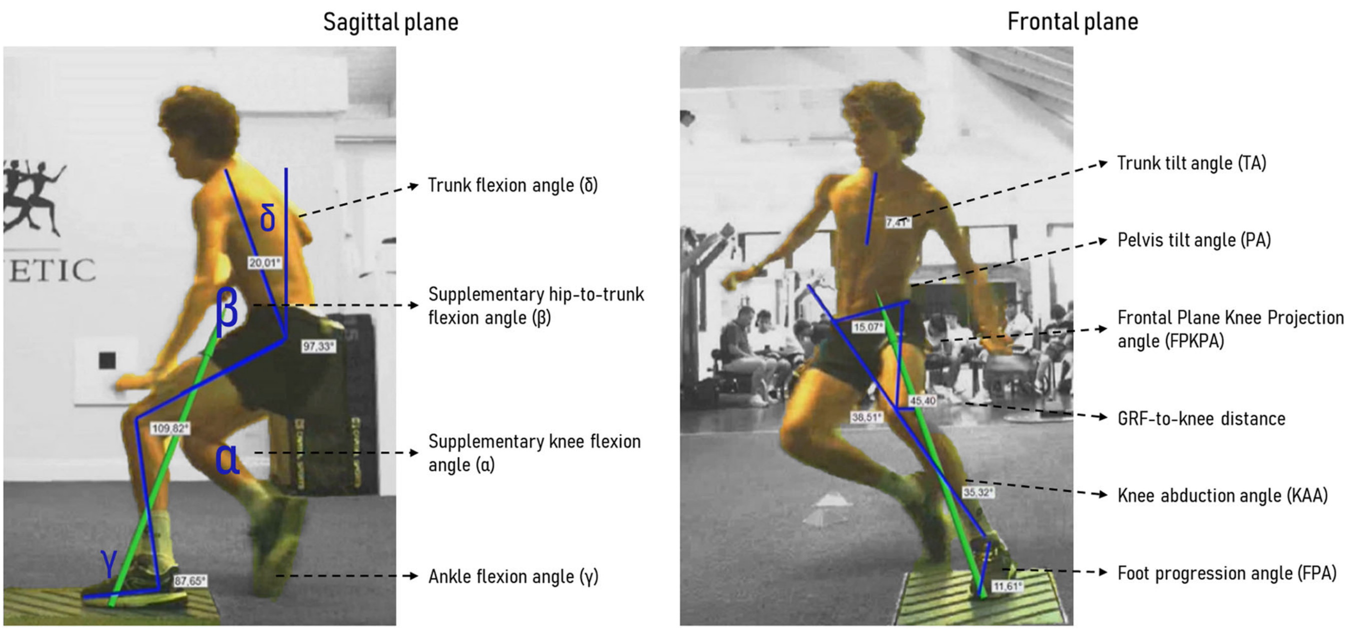

FIGURE A1 Graphical explanation of the two-dimensional variables composing the scoring system collected through sagittal (left) and frontal (right) plane.

TABLE A1 Written explanation of the 2D variables composing the scoring system.

Variable name	Acronym	Definition	Interpretation
Foot projection angle	FPA	The angle between the foot and the anterior-posterior direction of the initial sprint	External rotation (+) Internal rotation (−)
Knee abduction angle	KAA	The angle between AJC to KJC and vertical neutral reference	Abduction (+) Adduction (−)
Frontal plane knee projection angle	FPKPA	The angle between AJC to KJC line and ASIS to KJC line	Valgus (+) Varus (−)
GRF vector-knee distance	V distance	Horizontal distance between GRF vector and KJC	External to the KJC (+) Internal to the KJC (+)
Pelvis drop angle	PA	The angle between the ASIS-to-ASIS line and horizontal neutral reference	Contralateral hike (+) Contralateral drop (−)
Trunk tilt angle	TA	The angle between the clavicular notch to the midline pelvis line and vertical neutral reference	Ipsilateral tilt (+) Contralateral tilt (−)
γ (ankle dorsiflexion)	γ	The angle between LM to foot toe line and horizontal neutral reference	Dorsiflexion (+) Plantarflexion (−)
α (suppl. knee flexion)	α	The angle between the LM to LFC line and LFC to GT line	Lower knee flexion (») Greater knee flexion («)
β (180 − (hip flexion + trunk flexion)	β	The angle between the LFC to GT line and GT to SJC line	Hip extension (+) Hip flexion (−)
δ (trunk flexion)	δ	The angle between the GT to SJC line and vertical neutral reference	Flexion (+) Extension (−)
Hip flexion angle		$180°-\beta-\delta$	Hip flexion (+) Hip extension (−)

Abbreviations: 2D, two-dimensional; AJC, ankle joint center; ASIS, anterior superior iliac spine; GRF, ground reaction force; GT, greater trochanter; KJC, knee joint center; LFC, lateral femoral condyle; LM, lateral malleolus; SJC, shoulder joint center.

APPENDIX B

See Table B1

TABLE B1 Robust statistics for 2D kinematics (°) in the overall population and separated for female and male players.

	5th percentile			25th percentile			50th percentile			75th percentile			95th percentile		
	All	Female	Male	All	Female	Male	All	Female	Male	All	Female	Male	All	Female	Male
Initial contact															
Foot projection angle	**−67**	−65	−67	−48	−45	−49	−32	−28	−33	−14	−11	−16	10	12	9
Knee abduction angle	10	10	10	16	17	16	20	21	20	24	25	23	**30**	32	29
Frontal plane knee projection angle	8	10	8	18	18	18	24	25	24	31	32	31	**40**	40	40
GRF vector-knee distance	2.1	2	2.2	8.3	8.4	8.3	14	14	14	20.7	20.8	20.7	**31.6**	31.3	31.7
Pelvis drop angle	**−26**	−26	−26	−19	−19	−19	−14	−14	−14	−9	−8	−9	−3	−2	−3
Trunk tilt angle	**−14**	−12	−14	−5	−3	−5	2	3	2	6	6	6	**12**	11	**12**
γ (ankle dorsiflexion)	−36	−38	−35	−21.5	−22	−21	−10	−11	−9	−2	−2	−1	**7**	9	**7**
α (suppl. knee flexion)	133	134	133	142	142	142	148	148	148	155	155	155	**163**	163	**163**
β (180 − (hip flexion + trunk flexion)	84	91	83	95	102	93	104	110	101	112	117	109	**125**	129	**122**
δ (trunk flexion)	**7**	6	8	16	13	17	22	18	23	28	24	29	36	31	37
Hip flexion angle	**43**	40	44	50	48	51	54	52	55	59	57	59	65	63	66
Maximum knee flexion angle															
Foot projection angle	**−61**	−57	−63	−46	−43	−47	−31	−29	−32	−15	−12	−16	8.6	12	7
Knee abduction angle	23	22	23	32	32	32	38	39	38	44	44.2	43	51	52	51
Frontal plane knee projection angle	18	18	17	35	34	36	45	43	45	53	51	54	64	61	65
GRF vector-knee distance	0	0	0	3.6	3.5	3.6	6.1	6.1	6.2	8.8	9	8.8	12.4	12.6	12.3
Pelvis drop angle	**−29**	−29	−29	−22	−23	−21	−16	−17	−16	−11	−11	−11	−4	−4	−5
Trunk tilt angle	**−21**	−19	−22	−9	−7	−10	2	3	2	7	7	7	**17**	15	17
γ (ankle dorsiflexion)	−10	−9	−11	−3	−1	−3	2	3	1	6	7	5	**12**	14	11
α (suppl. knee flexion)	103	104	102	111	113	111	118	120	118	126	129	126	**140**	142	138.9
β (180 − (hip flexion + trunk flexion)	76	83	74	90	98	88	100	107	97	110	116	107	**126**	130.8	122
δ (trunk flexion)	**11**	9	12	20	17	21	27	23	28	33	30	34	44	39	45
Hip flexion angle	**39**	35	41	48	44	49	53	50	55	59	55	60	66	63	66

Note: Bold characters represent the extreme values (5th and/or 95th percentile) for the variables of interest towards the risk of ACL injury.
Abbreviations: 2D, two-dimensional; ACL, anterior cruciate ligament.