Original Research

Two-Dimensional and Three-Dimensional Biomechanical Factors During 90° Change of Direction are Associated to Non-Contact ACL injury in Female Soccer Players

Stefano Di Paolo[1] [a], Alberto Grassi[2], Filippo Tosarelli[3], Matteo Crepaldi[3], Laura Bragonzoni[1], Stefano Zaffagnini[2], Francesco Della Villa[3]

[1] Life Quality Studies, University of Bologna, [2] 2nd Orthopaedic and Traumatologic Clinic, Istituto Ortopedico Rizzoli, [3] Education and Research Department, Isokinetic Medical Group

Keywords: ACL, female football, biomechanics, 2D video-analysis, injury prevention, change of direction

https://doi.org/10.26603/001c.84308

Background

The two-dimensional (2D) video-analysis of the change of direction (COD) technique has never been used to attempt to predict the risk of ACL injury in female football players.

Hypothesis/Purpose

The purpose of the present pilot study was to prospectively investigate the biomechanical predictors of ACL injury during a COD task in female football players using both gold standard 3D motion capture and a qualitative scoring system based on 2D video-analysis.

Study Design

Prospective cohort study

Methods

Sixteen competitive female football (soccer) players (age 21.4 ± 4.3) performed a series of pre-planned 90° COD tasks. 3D motion data was recorded through 10 stereophotogrammetric cameras and a force platform. 2D frontal and transverse plane joint kinematics were computed through video-analysis from three high-speed cameras. A scoring system based on five criteria was adopted: limb stability, pelvis stability, trunk stability, shock absorption, and movement strategy. The players were prospectively followed for the next two consecutive football seasons and the occurrence of severe knee injuries was registered.

Results

Four players (25%) experienced an ACL injury. In 3D analysis, ACL-injured players showed greater knee valgus, knee internal rotation, and lower knee flexion (p= 0.017 – 0.029). Lower hip flexion coupled with greater external rotation (p= 0.003 – 0.042), ankle eversion, and contralateral pelvic drop (p<0.001) were also noted. In 2D analysis, ACL-injured players showed greater internal foot rotation, contralateral pelvic drop, lower knee flexion, and contralateral trunk tilt (moderate-to-large effect size). Pelvis stability and trunk stability showed the highest predictive value towards ACL injury. Total score was significantly lower in ACL-injured players with a moderate effect size (d=0.45).

a   Corresponding author
     Stefano Di Paolo
     Department for Life Quality Studies QUVI
     Università di Bologna
     Via Giulio Cesare Pupilli, 1, 40136 Bologna (BO), Italy
     ORCID ID: 0000-0002-1761-7352

Conclusions

Both 3D and 2D methodologies depicted biomechanical risk factors and offered predictive insights towards the ACL injury risk. Awareness should rise in women's football regarding the high risk of ACL injury and the strategies to assess and mitigate it.

Level of Evidence

3

INTRODUCTION

The rapid growth of women's football (soccer) participation is bringing about increasing rates and earlier occurrence of primary Anterior Cruciate Ligament (ACL) injury.[1,2] Several authors have demonstrated that female footballers are at overall higher risk of ACL injury than their male counterparts[1,3,4] and are less responsive to targeted preventative interventions e.g., the FIFA 11+ program.[1,5,6]

Therefore, a deeper comprehension of modifiable risk factors, such as ACL injury biomechanics, has been advocated to mitigate the injury risk in female football academies.[7,8] Standardized methodologies are crucial to obtain objective measurements of players' movement quality and identify ACL injury predictors in a user- and athlete-friendly fashion.

The 3D motion capture is the gold standard for biomechanical assessment of high-demanding tasks and has been used in prospective investigations of ACL injury predictors.[7,9] Recently, 2D video-analysis has been proposed as a cost-effective alternative to 3D motion capture for high-demand tasks. Promising results have reported regarding the association between 2D angles (frontal plane knee, pelvis, and trunk angle; limited knee and hip flexion) and scoring systems (Movement Analysis Test, Cutting Movement Assessment Score) based on video-analysis and well-known ACL risk factors such as the knee abduction moment (KAM) and high vertical and posterior ground reaction forces (GRF).[10-13] Such 2D scoring systems allow for simpler movement analysis for the raters and quicker feedback to the athletes, making them an attractive solution to implement large screenings in young population.[12-14]

However, the efficacy of 2D video-analysis in determine the risk of the occurrence of ACL injury has never been assessed prospectively in male nor female football players. The efficacy of 2D video-analysis and its agreement with 3D motion capture would support the use of dedicated methodologies to test female football players in primary ACL injury prevention.

The purpose of the present pilot study was to prospectively investigate the biomechanical predictors of ACL injury during a COD task in female football players using both gold standard 3D motion capture and a qualitative scoring system based on 2D video-analysis. The hypothesis was that both the 3D motion capture and the 2D scoring system would detect clinically-relevant biomechanical differences between non-injured and ACL-injured players such as shallower lower limb flexion and dynamic valgus.

MATERIALS AND METHODS

The study was approved by the Institutional Review Board (IRB approval ID number: 555/2018/Sper/IOR of 12/09/2018) of Area Vasta Emilia Romagna Centro (AVEC, Bologna, Italy) and registered on ClinicalTrials.gov (Identifier: NCT03840551). Signed informed consent were collected from all participants before enrollment.

PARTICIPANTS

This represents a secondary analysis of a larger cross-sectional study aimed to investigate the concurrent validity of different methodologies (wearable inertial sensors and 2D video-analysis) for examining high-demand motion tasks for ACL injury prevention and rehabilitation.[10,15] The analysis was conducted in the Education and Research Department of the Isokinetic Medical Group during the regular football season (February 2019). Sixteen young competitive (first-to-third Italian Football division) female football (soccer) players (age 21.4 ± 4.3, range 18-31) were enrolled in the study. Exclusion criteria were: evidence of previous severe injury (> 28 days recovery time); previous surgery to the lower limbs; body mass index (BMI) > 35; and cardiopulmonary or cardiovascular disorders.

DATA COLLECTION

Each player performed a series of pre-planned 90° COD tasks at maximum speed possible in a specialized laboratory equipped with artificial turf. The players wore their own running shoes and clothes. The COD task consisted of a 6-meter frontal sprint followed by a 90° sidestep cut with foot strike on a force platform and a further 3-meter sprint. The complete acquisition setting was previously described.[10] In brief, a 10-minute dynamic warm-up and few unrecorded repetitions of the movement were performed by each player to get confident with the setting. The players were instructed by a single sport & exercise medicine physician specialized in sports biomechanics (*F.D.V.*), who also verified the validity of each trial. Full foot contact on the force platform was required to consider a trial valid. Each player performed six valid trials with three right and three left strikes.

3D motion data and 2D video-analysis data were collected simultaneously. 3D Motion data were recorded through a set of 10 stereophotogrammetric cameras (VICON Nexus, Vicon Motion Systems Ltd, Oxford, UK) and a force platform embedded in the floor (AMTI 400*600, Watertown, MA USA), and three high-speed cameras placed frontally and bilaterally towards movement direction to

capture 2D data. The systems were synchronized for direct data comparison. The sampling rate was 120 Hz for cameras and force platform, and 100 Hz for the high-speed cameras.

The system calibration was performed at the beginning of the acquisition and repeated periodically during the session. Forty-two retroreflective markers were placed on each participant by a single expert user according to the full-body Plug-in Gait protocol. Anthropometric data were collected for each participant and model calibration was performed before data acquisition.

DATA PROCESSING – 3D MOTION CAPTURE

Marker trajectories were collected through the stereophotogrammetric cameras and interpolated through a spline-based algorithm. The lower limb and pelvis kinematics were computed through VICON Nexus software using the Cardan angles. The frontal, transverse and sagittal plane kinematics waveforms were extracted for the stance phase of the foot on the force platform. The positively defined rotations (+) were: knee varus and internal rotation, hip adduction and internal rotation, ankle inversion and internal rotation, and pelvis contralateral drop and rotation.

DATA PROCESSING – 2D VIDEO ANALYSIS

The 2D frontal and transverse plane joint kinematics was computed through video-analysis. The evaluation was performed in a specific VICON software environment through the recordings of the three high-speed cameras. Joint kinematics was evaluated at the frame of maximal knee flexion angle after the foot contact on the force platform. For each trial, the following 2D angles were calculated: Foot Projection Angle (FPA), Frontal Plane Knee Projection Angle (FPKPA), Pelvis tilt Angle (PA), and Trunk tilt Angle (TA). Furthermore, a scoring system was adopted based on the 2D kinematics.[10,16] Five scoring criteria were used to evaluate each COD trial: *limb stability* (LS), *pelvis stability* (PS), *trunk stability* (TS), *shock absorption* (SA), and *movement strategy* (MS). The detailed description of each criteria was reported in a previous study.[10] In brief, a score from 0/2 to 2/2 (non-adequate to adequate) was attributed to the trial for each criterion based on objective 2D measurements by a single sports physician. The total score was computed as the sum of each criterion sub-score (maximum total score: 10/10).

PROSPECTIVE FOLLOW-UP

The players were prospectively followed for the next two consecutive football seasons through regular phone calls. The occurrence of severe knee injuries (> 28 days recovery time) was registered. In case of an ACL injury, an MRI and a clinical examination were carried out to confirm the presence of the ACL tear. Additional information, e.g., the nature of the injury mechanism (non-contact, indirect contact, contact) and the context (training, match), were retrieved.

STATISTICAL ANALYSIS

Based on the occurrence of an ACL injury during the follow-up period, the players were divided into two groups: "*No injury*" and "*ACL injury*". Kinematic data were retrieved for the injured and dominant leg for the latter and former group, respectively.[17] The normal distribution of the data was verified through the Shapiro-Wilk test. The categorical variables were presented as a percentage over the total, while the continuous variables were presented as mean ± standard deviation (95% Confidence Interval – CI).

For the 3D kinematics waveforms, the two-tailed Student's t-test with Statistical Parametric Mapping (SPM) was used to investigate the difference between the two groups.[18]

For the 2D analysis, the two-tailed Student's t-test was used to compare continuous 2D kinematics variables, and Cohen's d effect size was reported. Effect size was considered small, medium, and large for Cohen's d value of 0.2, 0.5, and 0.8, respectively. Furthermore, the Chi-square test for 3x2 (3 scores x 2 groups) contingency tables was computed to investigate the differences in the 2D scoring system percentage between the two groups for each of the five criteria. The Mann-Whitney U test was used to investigate the differences in the total score and in non-normally distributed variables, and Rank Biserial Correlation was reported as effect size measure. Differences were considered statistically significant for $p < 0.05$. The statistical analyses were conducted in Matlab (The MathWorks, Natick, MA, US) and SPSS (IBM, Armonk, NY, US).

Given the pilot nature of the present study, no a-priori power-analysis was performed. However, the present cohort of 16 participants is consistent with previous pilot studies with similar purpose and methodological accuracy showing a minimum power of 0.80 for the analysis of frontal and sagittal plane knee and hip kinematics.[19,20]

RESULTS

Overall, four players out of 16 (25% of the cohort) experienced an ACL injury during the two football seasons following the data collection. All injuries occurred during football matches with a non-contact mechanism. A complete ACL rupture in all injured athletes was confirmed through MRI examination. No other severe joint/muscle injuries were reported. Age at the time of data collection was significantly lower (p=0.009) in the ACL-injured group, while no differences (p<0.05) were found in demographics and approaching COD speed between ACL-injured and non-injured players (Table 1).

3D MOTION CAPTURE

The ACL-injured players showed greater knee valgus (p=0.029) and internal rotation (p=0.017) during the early stance phase and lower knee flexion (p=0.023) during the late stance phase (Figure 1, first row). Less hip flexion (p=0.042) coupled with greater external rotation (p=0.003) were also noted in the ACL-injured group (Figure 1, second

Table 1. Demographic data of the subjects enrolled in the study according to the occurrence of ACL injury during the following two football seasons.

	All (n=16)	No ACL injury (n=12)	ACL injury (n=4)	p-value
Age	21.4 ± 4.3 [19.3 – 23.5]	22.4 ± 4.5 [19.8 – 24.9]	18.3 ± 0.5 [17.8 – 18.8]	0.009
Height (cm)	166.8 ± 6.7 [163.5 – 170.1]	167.7 ± 6.3 [157.4 – 164.6]	164.0 ± 8.1 [156.1 – 171.9]	n.s.
Weight (kg)	58.1 ± 4.4 [55.9 – 60.3]	58.3 ± 4.7 [55.6 – 61.0]	57.5 ± 4.2 [53.4 – 61.6]	n.s.
BMI	20.9 ± 1.7 [20.1 – 21.7]	20.8 ± 1.9 [19.7 – 21.9]	21.4 ± 1.3 [20.1 – 22.7]	n.s.
Dominant limb (r/l)	14/2	11/1	3/1	n.s.
COD Approaching speed (m/s)	2.7 ± 0.6 [2.4 – 3.0]	2.6 ± 0.6 [2.3 – 2.9]	2.8 ± 0.5 [2.3 – 3.3]	n.s.

Notes: Data were expressed as mean ± standard deviation [95% confidence intervals]. COD=Change of Direction; n.s.=non-statistically significant difference (p>0.05). Dominant limb is meant as the preferred one used to kick a ball.

row). Furthermore, ACL-injured players showed greater ankle eversion tendency and contralateral pelvic drop (p<0.001, Figure 1, third and fourth row).

2D VIDEO ANALYSIS

ACL-injured players showed greater internal foot rotation, pelvic contralateral drop, lower knee flexion (moderate effect size), and contralateral trunk tilt (large effect size, Table 2, Figure 2). Pelvis stability and trunk stability scores showed the highest predictive value towards ACL injury (significantly more 0/2 scores in ACL-injured players, Table 3, Figure 3). Total score was significantly lower in ACL-injured players (moderate effect size), that never scored greater than 7/10 (Table 3, Figure 4).

DISCUSSION

The main finding of the present study was that both the 3D motion capture and 2D analysis of the COD technique offered predictive insights towards the ACL injury risk in female football players. Significant differences between players experiencing an ACL injury in the two seasons after testing and non-injured players were consistent with the current literature on non-contact ACL injury biomechanics.[21-24] Moreover, the 2D scoring system successfully identified the ACL-injured players, that showed a lower total score (Figure 4). Thus, such a scoring system has the potential to identify female footballers at high risk for ACL injury in a cost-effective fashion.

A video-analysis study by Lucarno et al. recently described the ACL situational patterns and injury mechanism of professional female footballers, highlighting the frequent occurrence of non-contact or indirect contact injuries with multiplanar biomechanics.[23] Injury biomechanics included knee dynamic valgus, limited lower limb flexion, pelvis and trunk tilt and rotation, and ankle rotation, consistently with the one of male counterparts.[25] In the present study, all the differences found between ACL-inured and non-injured players agreed with the typical biomechanical profile for non-contact ACL injury described by Lucarno et al. and Della Villa et al.[23,25]

The ACL-injured players exhibited greater knee valgus and internal rotation and hip external rotation (Figure 1). These patterns have been shown to increase the KAM and the load on knee ligaments.[24,26,27] In LS score, none of the ACL-injured players' tasks was rated as 2/2. However, no differences in FPKPA were found and the overall rating was shifted towards the 0/2 score (Figure 2). These findings suggest a good sensitivity but a lower specificity of the LS score and the FPKPA for the ACL injury risk, in line with previous literature on other functional tests.[28,29]

Lower hip and knee flexion angles were also observed in the ACL-injured players in both 3D and 2D joint angles. Though not happening in the early stance phase, these results suggest a stiffer kinematic strategy adopted by the ACL-injured players.[23,30,31]

Pelvic drop was detected during the whole stance phase in the players that sustained an ACL injury (Figure 1). Pelvic drop and trunk lean in the ACL-injured players were also detected through the PA and TA 2D angles with a moderate-to-large effect. The PS and TS criteria strongly were the best predictors of ACL injury in the 2D scoring system: the percentage of trials rated 0/2 in the ACL-injured players was double than the non-injured players in the PS, and triple in the TS. Moreover, ACL-injured players were never rated 2/2 in PS. The association between poor core stability and the risk of knee overloading has been proposed in literature.[12,13] The video-analysis studies on professional athletes clearly identified that ACL injuries happen with pelvis and trunk in non-neutral position.[23,25] Donelon et al. recently listed the maintenance of an upright pelvis and trunk position among the actions aimed to modify the COD technique and mitigate the ACL injury risk.[22] The results of the present study suggest that the analysis of pelvis and trunk frontal plane kinematics in 2D could effectively detect core imbalance during the COD task and that the scoring system described could have a strong predictive power towards the risk of ACL injury.

Greater ankle eversion was noted in the players that sustained an ACL injury in the second half of the stance phase (Figure 1). The 2D analysis revealed a more internal foot progression angle at peak knee flexion. Both aspects of the foot position indicate that ACL-injured players landed on the force platform adopting a more anticipatory strategy
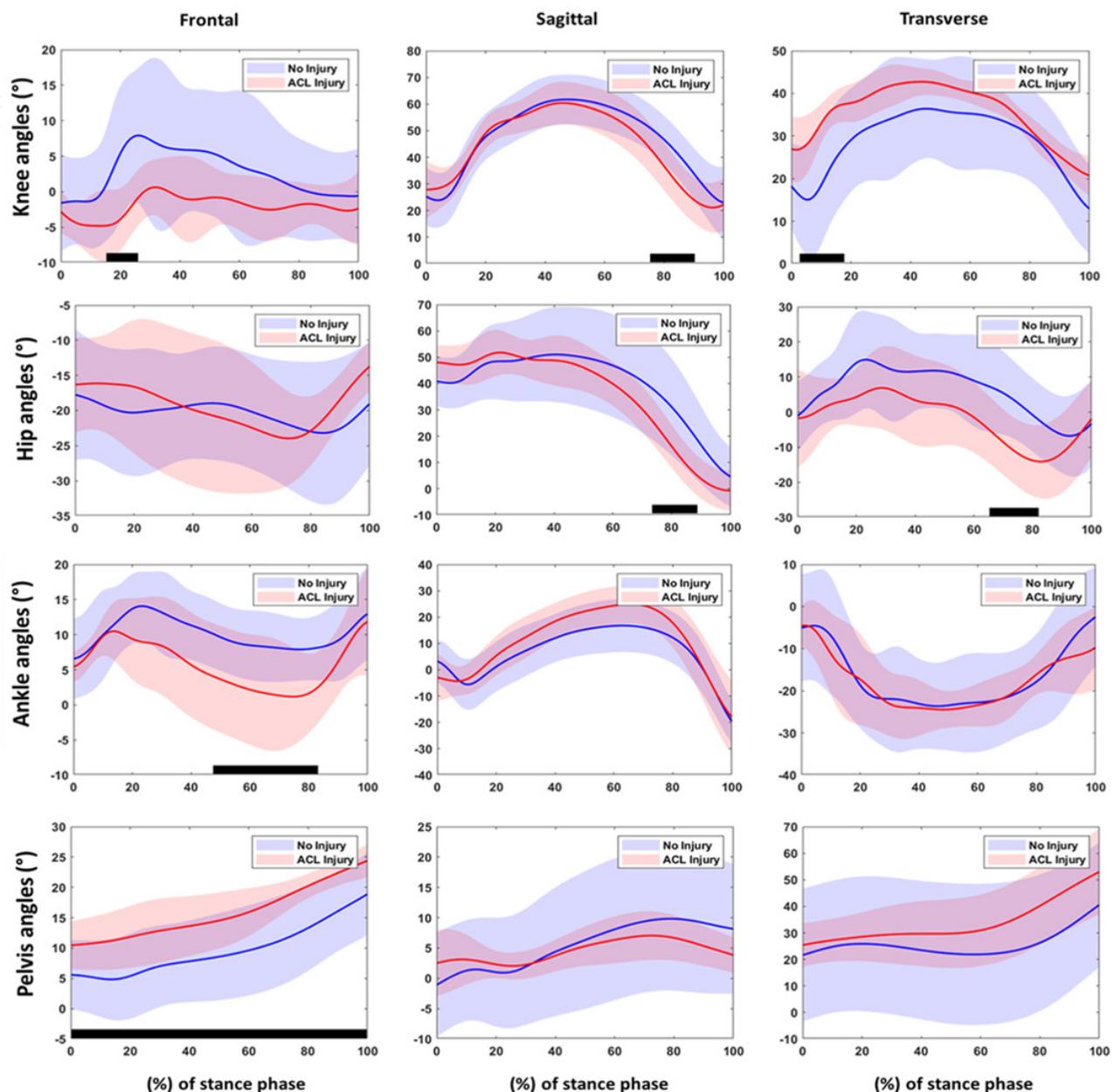
Figure 1. Joint kinematics in frontal, transverse, and sagittal plane from 3D motion capture for knee (first row), hip (second row), ankle (third row), and pelvis (fourth row) joints.

Notes: Data were normalized over the last stance phase before the 90° change of direction and reported as mean (solid lines) and standard deviation (dashed bars) for non-injured (blue) and ACL-injured (red) players. Student's t-test in SPM was reported with statistically significant differences represented by black lines (p<0.05). Positive rotations: varus (knee), adduction (hip), inversion (ankle), contralateral drop (pelvis); internal rotation (knee, hip, ankle), contralateral rotation (pelvis); flexion (knee, hip, pelvis), dorsiflexion (ankle).

than the non-injured players. An anticipatory strategy with a greater internal foot progression angle has been associated with faster cutting but in conflict with a safe mechanism.[32] Foot eversion and rotation are also common in the professional football players that sustain an ACL injury.[23,25] The analysis of foot progression angle could give valuable insights on the attitude of players COD technique and strongly influence joint loading propagation on the kinetic chain.

The 2D total score proposed in the present study distinguished the players that sustained an ACL injury from the non-injured ones. Average total score was lower in the ACL-injured players (4.6 vs 2.4, moderate effect, Table 3) and none of the ACL-injured players' trials were rated more than 7/10 (Figure 4). The total score is an intuitive measure that can be used by the professionals to track a player's overall movement quality during the COD task and her progression over a prevention (or rehabilitation) program. From the results of the present pilot study, a total score of 4/10 or lower could be indicative or higher risk for ACL injury, while a score higher than 7/10 could be indicative of a protective COD technique.

Table 2. Joint kinematics (°) extracted from 2D video-analysis according to the occurrence of ACL injury during the following two football seasons.

2D angle	No ACL injury (n=12)	ACL injury (n=4)	p-value	Cohen's d
Foot Progression Angle	-15.2 ± 19.4 [-26.2 – -4.2]	-25.2 ± 19.9 [-44.7 – -5.7]	0.041	0.51
Frontal Plane Knee Projection Angle	36.8 ± 17.2 [27.1 – 46.5]	41.8 ± 8.1 [33.9 – 49.7]	n.s.	0.23
Pelvic Drop Angle	-9.9 ± 7.7 [-14.3 – -5.5]	-12.9 ± 9.1 [-21.8 – -3.9]	0.022	0.38
Trunk Tilt Angle	4.2 ± 7.4 [0.1 – 8.4]	-5.7 ± 11.7 [-17.2 – 5.8]	<0.001	1.11
α (180°-Knee Flexion Angle)	118.7 ± 10.7 [112.6 – 124.8]	124.3 ± 10.5 [114.0 – 134.6]	0.026	0.53

Notes: Data were expressed as mean ± standard deviation [95% confidence intervals]. n.s.=non-statistically significant difference (p>0.05). Positive rotations: foot external rotation, knee valgus, pelvic contralateral hike, trunk ipsilateral tilt.
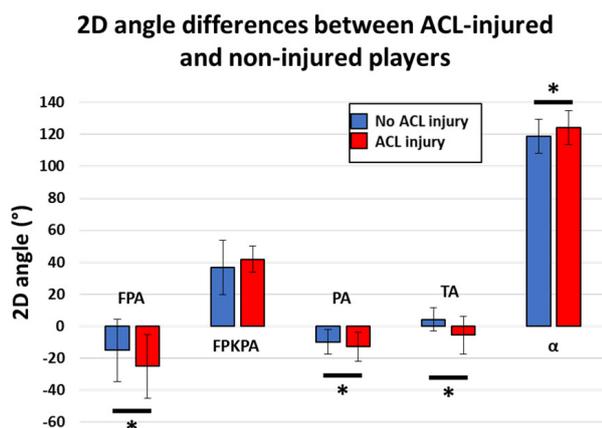

Figure 2. Joint kinematics from 2D video-analysis. Data are presented as mean and standard deviation for the non-injured (blue) and ACL-injured (red) players.

Notes: Asterisks represent statistically significant differences between the two groups (p<0.05). FPA (Foot Progression Angle), FPKPA (Frontal Plane Knee Projection Angle), PA (Pelvic Drop Angle), TA (Trunk Tilt Angle), α (180°-Knee Flexion Angle). Positive rotations: foot external rotation, knee valgus, pelvic contralateral hike, trunk ipsilateral tilt.

The multiplanar risk factors detected in the players that sustained an ACL after testing were extremely congruent with the injury mechanism proposed in video-analysis studies on professional female footballers ([Figure 5]).[23] Both the 3D motion capture and 2D video-analysis detected and agreed on most of the clinically-relevant differences. In the 2D video-analysis, frontal plane was indicative of a higher injury risk, but both frontal and sagittal view would be required to obtain a comprehensive measure of COD movement quality. Knee abduction angle, frequently used in multiple 2D assessments for this and other tasks (e.g., drop vertical jump, squats, and single-leg landings), might be not sufficient to explain the movement complexity and the relation with the ACL injury risk.[28,29,33] Furthermore, approaching and landing strategies such as penultimate foot contact deceleration, anticipatory cut, flatfoot or heel strike, should be taken into account to finetune the assessment.[11,12,22,34]

In the present study, 25% of the cohort experienced an ACL injury. Previous larger prospective studies reported an injury rate of 7-11%.[29,35,36] In the present study, the tests were performed in late February, thus close to one of the two peaks of injury occurrence identified in professional football players.[23] All injuries occurred during matches and without a direct contact with an opponent. This is again in line with the predominance of non-contact/indirect contact mechanisms found in professional female footballers (88%[23]). The fact that ACL-injured players were younger (p=0.009) than the rest of the cohort is consistent with the data reporting earlier occurrence (younger age) of the first ACL injury in female football.[37] All these aspects deserve awareness from the football medicine community and highlight the urgent need for dedicated tools to counteract such a high injury risk since more and more female players turn professional earlier.

The present study has some limitations. First, the present pilot investigation involved a small cohort; thus, inferences should be interpreted with caution and are far from

Table 3. Frequencies (%) of single sub-scores for the qualitative scoring system from 2D video-analysis according to the occurrence of ACL injury during the following two football seasons.

Score	No ACL injury (n=12)			ACL injury (n=4)			p-value	Cohen's d
	0	1	2	0	1	2		
Limb Stability	87.0	7.4	5.6	95.8	4.2	0.0	n.s.	1.8
Pelvis Stability	48.1	27.8	24.1	87.5	12.5	0.0	0.003	11.7
Trunk Stability	18.5	46.3	35.2	58.3	20.8	20.8	0.002	12.5
Shock Absorption	16.7	59.3	24.1	25.0	66.7	8.3	n.s.	2.9
Motor Strategy	16.7	29.6	53.7	29.2	29.2	41.7	n.s.	1.8
Total Score	4.6 ± 2.8 [3.0 – 6.2]			2.4 ± 1.8 [0.6 – 4.2]			0.001	0.45

Notes: Total score data were as mean ± standard deviation [95% confidence intervals]. n.s.=non-statistically significant difference (p>0.05).

## 2D score differences between ACL-injured and non-injured players
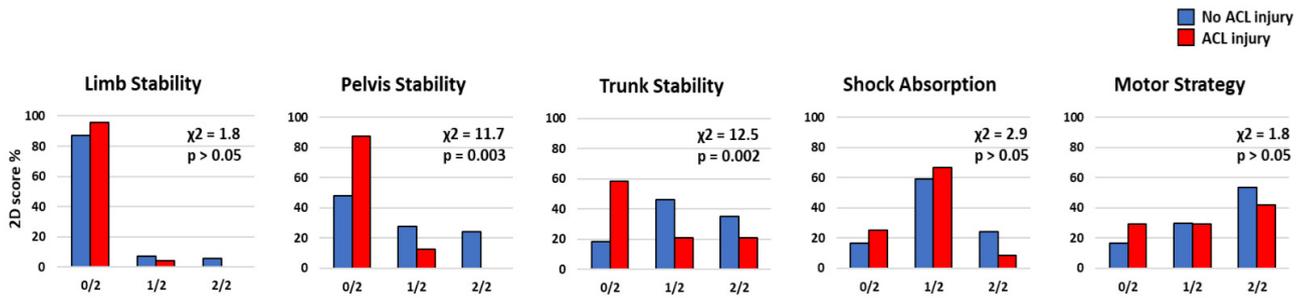
Figure 3. 2D score assigned through video-analysis.

Notes: Frequency distribution (%) are presented for the non-injured (blue) and ACL-injured (red) players for each of the 5 sub-criteria. P-value and Chi-square for each contingency table is shown.
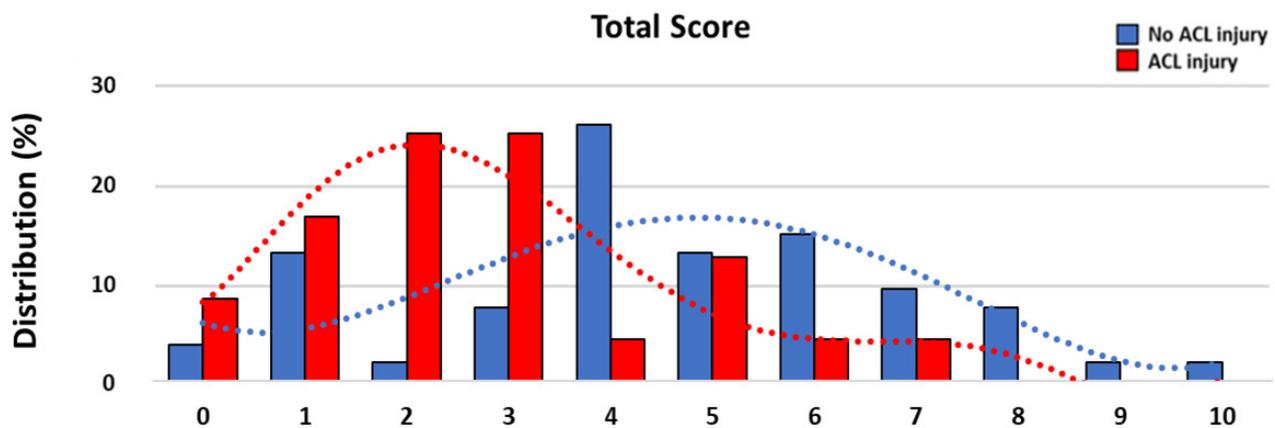

Figure 4. 2D Total score frequency distribution (%) for the non-injured (blue) and ACL-injured (red) players.

Notes: The score ranges from 0/10 (worst) to 10/10 (best).

being conclusive. Despite the sample size, the results of both the 2D and 3D analyses were consistent with current literature on ACL injury risk biomechanics.[21-24] Prospective studies with larger cohorts are necessary to set a benchmark for objective measurements in ACL injury prevention in football. Second, the 90° COD task assessed in the present study was pre-planned. Recent studies suggest that unanticipated sidestepping tasks could offer important insights on ACL injury risk.[38] Preventative testing should consider the use of both pre-planned and unplanned tasks to get a wider understanding of players' injury risk. No muscular strength data were collected. Such data could have increased the level of detail of the players' comparison. The data collection was performed in a single session and no post-operative investigation was performed on those who were injured. The longitudinal analysis of the ACL-injured players could be used to quantitatively inform the ACL rehabilitation programs.

The clinical relevance of the present work is that the adoption of a 2D video-analysis scoring system based on quantitative measurements has the potential to identify female football players at higher risk for ACL injury in a cost-effective fashion. The players could therefore benefit from additional preventative neuromuscular training. Given the rapid growth of female football and their greater predisposition to the ACL injury,[4,39] dedicated methodologies assessing players' movement quality and injury risk are fundamental to mitigate the injury rates in early football careers.

CONCLUSION

Significant kinematic differences during a planned COD task were identified between ACL injured and non-injured players with both the 3D and 2D methodologies. The biomechanical pattern of the ACL-injured players was strongly consistent with the video-analysis of ACL injured elite players.[23] Both the 3D and 2D methodologies offered precious predictive insights to assess and mitigate the ACL injury risk in women's football.

Limb stability	Pelvis stability	Trunk stability	Shock absorption	Movement strategy	TOTAL SCORE
0	0	0	1	1	2
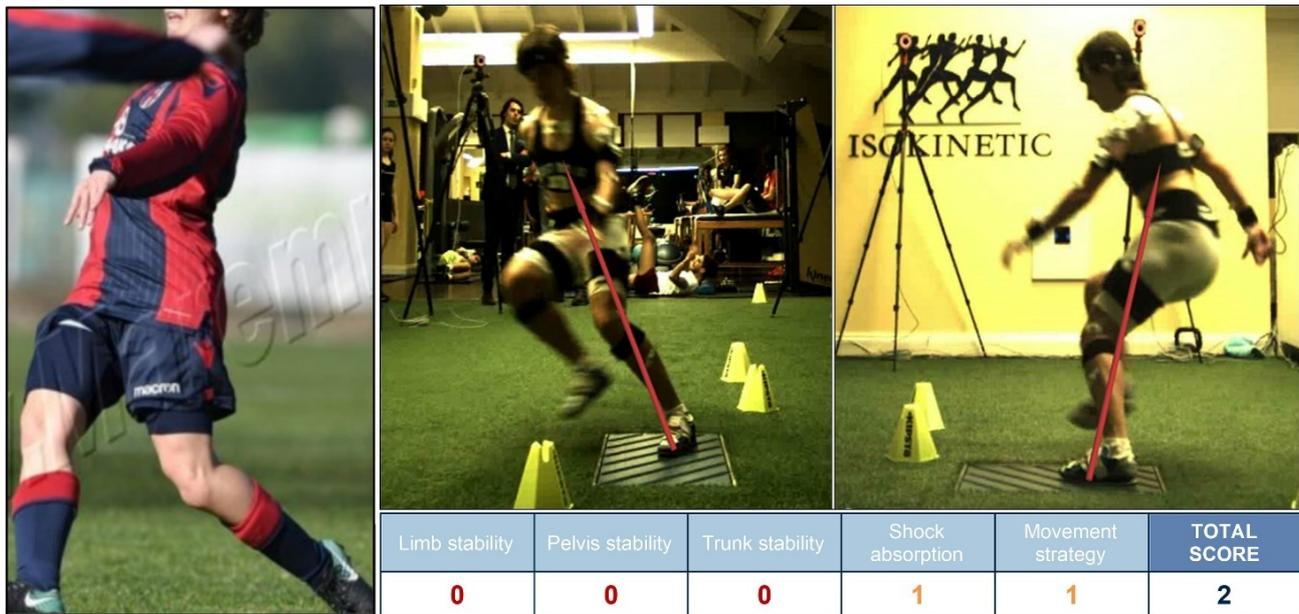
Figure 5. ACL injury frame (left) of one of the players involved in the prospective cohort. The frontal (middle, up) and sagittal (right, up) view of the 90° change of direction test performed with the involved limb is reported.

Notes: The associated 2D total score was 2/10 (bottom).

LIST OF ABBREVIATIONS

Anterior cruciate ligament (ACL)
Body Mass Index (BMI)
Body Weight (BW)
Change of Direction (COD)
Confidence intervals (CI)
Foot Projection Angle (FPA)
Frontal Plane Knee Projection Angle (FPKPA)
Ground Reaction Force (GRF)
Knee Abduction Moment (KAM)
Limb Stability (LS)
Movement strategy (MS)
Pelvis tilt angle (PA)
Pelvis stability (PS)
Shock absorption (SA)
Statistical Parametric Mapping (SPM)
Trunk tilt angle (TA)
Trunk stability (TS)

CONFLICT OF INTEREST

REFERENCES

1. Geertsema C, Geertsema L, Farooq A, et al. Injury prevention knowledge, beliefs and strategies in elite female footballers at the FIFA Women's World Cup France 2019. *Br J Sports Med*. 2021;55(14):801-806. doi:10.1136/bjsports-2020-103131

2. Peters CM, Hendry DT, Hodges NJ. A scoping review on developmental activities of girls' and women's sports. *Front Sports Act Living*. 2022;4:903886. doi:10.3389/fspor.2022.903886

3. Allen MM, Pareek A, Krych AJ, et al. Are female soccer players at an increased risk of second anterior cruciate ligament injury compared with their athletic peers? *Am J Sports Med*. 2016;44(10):2492-2498. doi:10.1177/0363546516648439

4. Xiao M, Lemos JL, Hwang CE, Sherman SL, Safran MR, Abrams GD. Increased risk of ACL injury for female but not male soccer players on artificial turf versus natural grass: a systematic review and meta-analysis. *Orthop J Sports Med*. 2022;10(8):23259671221114350. doi:10.1177/23259671221114353

5. Akbari H, Sahebozamani M, Daneshjoo A, Amiri-Khorasani M, Shimokochi Y. Effect of the FIFA 11+ on landing patterns and baseline movement errors in elite male youth soccer players. *J Sport Rehabil*. 2020;29(6):730-737. doi:10.1123/jsr.2018-0374

6. Silvers-Granelli HJ, Bizzini M, Arundale A, Mandelbaum BR, Snyder-Mackler L. Does the FIFA 11+ injury prevention program reduce the incidence of ACL injury in male soccer players? *Clin Orthop Relat Res*. 2017;475(10):2447-2455. doi:10.1007/s11999-017-5342-5

7. Hewett TE, Bates NA. Preventive biomechanics: a paradigm shift with a translational approach to injury prevention. *Am J Sports Med*. 2017;45(11):2654-2664. doi:10.1177/0363546516686080

8. Jones PA, Herrington LC, Graham-Smith P. Technique determinants of knee abduction moments during pivoting in female soccer players. *Clin Biomech*. 2016;31:107-112. doi:10.1016/j.clinbiomech.2015.09.012

9. Bates NA, Myer GD, Hale RF, Schilaty ND, Hewett TE. Prospective frontal plane angles used to predict ACL strain and identify those at high risk for sports-related ACL injury. *Orthop J Sports Med*. 2020;8(10):2325967120957646. doi:10.1177/2325967120957646

10. Della Villa F, Di Paolo S, Santagati D, et al. A 2D video-analysis scoring system of 90° change of direction technique identifies football players with high knee abduction moment. *Knee Surg Sports Traumatol Arthrosc*. 2021;30(11):3616-3625. doi:10.1007/s00167-021-06571-2

11. Di Paolo S, Zaffagnini S, Tosarelli F, et al. A 2D qualitative movement assessment of a deceleration task detects football players with high knee joint loading. *Knee Surg Sports Traumatol Arthrosc*. 2021;29(12):4032-4040. doi:10.1007/s00167-021-06709-2

12. Dos'Santos T, McBurnie A, Donelon T, Thomas C, Comfort P, Jones PA. A qualitative screening tool to identify athletes with 'high-risk' movement mechanics during cutting: The cutting movement assessment score (CMAS). *Phys Ther Sport*. 2019;38:152-161. doi:10.1016/j.ptsp.2019.05.004

13. Straub RK, Powers CM. Utility of 2D video analysis for assessing frontal plane trunk and pelvis motion during stepping, landing, and change in direction tasks: a validity study. *Int J Sports Phys Ther*. 2022;17(2):139-147. doi:10.26603/001c.30994

14. Weir G, Alderson J, Smailes N, Elliott B, Donnelly C. A reliable video-based ACL injury screening tool for female team sport athletes. *Int J Sports Med*. 2019;40(3):191-199. doi:10.1055/a-0756-9659

15. Di Paolo S, Lopomo NF, Della Villa F, et al. Rehabilitation and return to sport assessment after anterior cruciate ligament injury: quantifying joint kinematics during complex high-speed tasks through wearable sensors. *Sensors*. 2021;21(7):2331. doi:10.3390/s21072331

16. Buckthorpe M, Della Villa F, Della Villa S, Roi GS. On-field rehabilitation part 1: 4 pillars of high-quality on-field rehabilitation are restoring movement quality, physical conditioning, restoring sport-specific skills, and progressively developing chronic training load. *J Orthop Sports Phys Ther*. 2019;49(8):565-569. doi:10.2519/jospt.2019.8954

17. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med*. 2005;33(4):492-501. doi:10.1177/0363546504269591

18. Pataky TC, Vanrenterghem J, Robinson MA. Zero- vs. one-dimensional, parametric vs. non-parametric, and confidence interval vs. hypothesis testing procedures in one-dimensional biomechanical trajectory analysis. *J Biomech*. 2015;48(7):1277-1285. doi:10.1016/j.jbiomech.2015.02.051

19. Ameer MA, Muaidi QI. Relation between peak knee flexion angle and knee ankle kinetics in single-leg jump landing from running: a pilot study on male handball players to prevent ACL injury. *Phys Sportsmed*. 2017;45(3):337-343. doi:10.1080/00913847.2017.1344514

20. Nguyen AD, Zuk EF, Baellow AL, Pfile KR, DiStefano LJ, Boling MC. Longitudinal Changes in hip strength and range of motion in female youth soccer players: implications for ACL injury, a pilot study. *J Sport Rehabil*. 2017;26(5):358-364. doi:10.1123/jsr.2015-0197

21. Dix C, Arundale A, Silvers-Granelli H, Marmon A, Zarzycki R, Snyder-Mackler L. Biomechanical changes during a 90o cut in collegiate female soccer players with participation in the 11. *Int J Sports Phys Ther*. 2021;16(3):671-680. doi:10.26603/001c.22146

22. Donelon TA, Dos'Santos T, Pitchers G, Brown M, Jones PA. Biomechanical Determinants of knee joint loads associated with increased anterior cruciate ligament loading during cutting: a systematic review and technical framework. *Sports Med Open*. 2020;6(1):53. doi:10.1186/s40798-020-00276-5

23. Lucarno S, Zago M, Buckthorpe M, et al. Systematic Video analysis of anterior cruciate ligament injuries in professional female soccer players. *Am J Sports Med*. 2021;49(7):1794-1802. doi:10.1177/03635465211008169

24. Sigurðsson HB, Karlsson J, Snyder-Mackler L, Briem K. Kinematics observed during ACL injury are associated with large early peak knee abduction moments during a change of direction task in healthy adolescents. *J Orthop Res*. 2020;39(10):2281-2290. doi:10.1002/jor.24942

25. Della Villa F, Buckthorpe M, Grassi A, et al. Systematic video analysis of ACL injuries in professional male football (soccer): injury mechanisms, situational patterns and biomechanics study on 134 consecutive cases. *Br J Sports Med*. 2020;54(23):1423-1432. doi:10.1136/bjsports-2019-101247

26. Hewett TE, Myer GD, Kiefer AW, Ford KR. Longitudinal Increases in knee abduction moments in females during adolescent growth. *Med Sci Sports Exerc*. 2015;47(12):2579-2585. doi:10.1249/mss.0000000000000700

27. Navacchia A, Bates NA, Schilaty ND, Krych AJ, Hewett TE. Knee Abduction and internal rotation moments increase ACL force during landing through the posterior slope of the tibia. *J Orthop Res*. 2019;37(8):1730-1742. doi:10.1002/jor.24313

28. Krosshaug T, Steffen K, Kristianslund E, et al. The Vertical drop jump is a poor screening test for ACL injuries in female elite soccer and handball players: a prospective cohort study of 710 athletes. *Am J Sports Med*. 2016;44(4):874-883. doi:10.1177/0363546515625048

29. Petushek E, Nilstad A, Bahr R, Krosshaug T. Drop jump? Single-leg squat? Not if you aim to predict anterior cruciate ligament injury from real-time clinical assessment: a prospective cohort study involving 880 elite female athletes. *J Orthop Sports Phys Ther*. 2021;51(7):372-378. doi:10.2519/jospt.2021.10170

30. Leppänen M, Pasanen K, Kujala UM, et al. Stiff Landings are associated with increased ACL injury risk in young female basketball and floorball players. *Am J Sports Med*. 2017;45(2):386-393. doi:10.1177/0363546516665810

31. Pollard CD, Sigward SM, Powers CM. Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. *Clinical Biomechanics*. 2010;25(2):142-146. doi:10.1016/j.clinbiomech.2009.10.005

32. Dos'Santos T, Thomas C, McBurnie A, Comfort P, Jones PA. Biomechanical determinants of performance and injury risk during cutting: a performance-injury conflict? *Sports Med*. 2021;51(9):1983-1998. doi:10.1007/s40279-021-01448-3

33. Dingenen B, Malfait B, Vanrenterghem J, Robinson MA, Verschueren SMP, Staes FF. Can two-dimensional measured peak sagittal plane excursions during drop vertical jumps help identify three-dimensional measured joint moments? *Knee*. 2015;22(2):73-79. doi:10.1016/j.knee.2014.12.006

34. Di Paolo S, Bragonzoni L, Della Villa F, Grassi A, Zaffagnini S. Do healthy athletes exhibit at-risk biomechanics for anterior cruciate ligament injury during pivoting movements? *Sports Biomechanics*. Published online June 2, 2022:1-14. doi:10.1080/14763141.2022.2080105

35. Dix C, Arundale A, Silvers-Granelli H, Marmon A, Zarzycki R, Snyder-Mackler L. Biomechanical measures during two sport-specific tasks differentiate between soccer players who go on to anterior cruciate ligament injury and those who do not: a prospective cohort analysis. *Int J Sports Phys Ther*. 2020;15(6):928-935. doi:10.26603/ijspt20200928

36. Fältström A, Hägglund M, Hedevik H, Kvist J. Poor validity of functional performance tests to predict knee injury in female soccer players with or without anterior cruciate ligament reconstruction. *Am J Sports Med*. 2021;49(6):1441-1450. doi:10.1177/0363546521 1002541

37. Beck NA, Lawrence JTR, Nordin JD, DeFor TA, Tompkins M. ACL Tears in school-aged children and adolescents over 20 years. *Pediatrics*. 2017;139(3). doi:10.1542/peds.2016-1877

38. Weir G, van Emmerik R, Jewell C, Hamill J. Coordination and variability during anticipated and unanticipated sidestepping. *Gait Posture*. 2019;67:1-8. doi:10.1016/j.gaitpost.2018.09.007

39. Silvers-Granelli H. Why do female athletes injure their ACLs more frequently? What can we do to mitigate their risk? *Int J Sports Phys Ther*. 2021;16(4):971-977. doi:10.26603/001c.25467