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Three-Dimensional Biomechanical Analysis of Movement Patterns Associated with Anterior Cruciate Ligament Injuries in Football Players

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ABSTRACT
Anterior cruciate ligament (ACL) injuries are common and serious musculoskeletal injuries in football, due to their negative impact on players' health, the continuity of their sporting careers, and individual and team performance levels. Three-dimensional biomechanical analysis is an objective and accurate tool for identifying movement patterns associated with an increased risk of injury, particularly those that are difficult to observe or assess effectively using traditional two-dimensional analysis methods. The study aimed to determine the three-dimensional kinematic and kinetic characteristics of the lower limbs during the performance of high-risk movement tasks similar to those required in football among players from three clubs in the Iraqi Premier League, as well as to compare biomechanical risk indicators between the clubs and to reveal the relationship between specific movement patterns and the composite risk of anterior cruciate ligament injury. A descriptive, cross-sectional study design was employed. The study sample comprised sixty male football players, with twenty players from each of the Al-Samarra, Al-Alam and Al-Dour clubs. Data were collected using the VICON Nexus 3D motion capture system, comprising 12 cameras at 200 Hz, two Kistler force plates at 1000 Hz, and the Noraxon Ultium system for measuring electromyography (EMG) at 2000 Hz. The players performed three standardised movement tasks: a 45-degree cut on one leg, a two-foot landing after a jump, and a 180-degree turn. The main variables included the maximum internal knee varus angle, peak ground reaction force, lower limb joint flexion angles at the moment of first contact, and the joint muscle contraction index. The results showed statistically significant differences between the clubs in knee varus angle, with an F-value of $F(2,57) = 8.34$, a significance level of $p = 001.$, and an effect size of $\eta^2 = .226$, as well as in peak ground reaction force ($F(2,57) = 6.21$, $p = 00.3$, $\eta^2 = 179.$) and in knee flexion angle ($F(2,57) = 7.85$, $p = 00.1$, $\eta^2 = 216.$). The knee varus angle also showed the strongest correlation with the composite risk score for anterior cruciate ligament injury, with a correlation coefficient of $r = 82.$ at a significance level of $p < .001$. Group analysis revealed two distinct risk profiles: the first was a high-risk biomechanical profile, characterised by a marked increase in knee varus and a reduced knee flexion angle; the second was a low-risk profile, characterised by

a better degree of protective co-contraction. Iraqi footballers in the clubs included in the study exhibited biomechanical patterns associated with an increased risk of anterior cruciate ligament injury whilst performing football-specific motor tasks. Differences between clubs suggest that risk indicators may be influenced by multiple factors, including the nature of training programmes, pitch surface characteristics, and the level of strength training and neuromuscular control. The study's findings underscore the importance of implementing targeted preventive programmes to reduce ACL injuries in Iraqi football clubs.

Keywords: Anterior cruciate ligament; Biomechanical analysis, Football, Knee deflection, Three-dimensional motion capture, Injury prevention.

ABSTRAK

Cedera anterior cruciate ligament (ACL) adalah cedera muskuloskeletal yang umum dan serius dalam sepak bola, karena dampak negatifnya terhadap kesehatan pemain, kelangsungan karir olahraga mereka, dan tingkat kinerja individu dan tim. Analisis biomekanik tiga dimensi adalah alat yang objektif dan akurat untuk mengidentifikasi pola gerakan yang terkait dengan peningkatan risiko cedera, terutama yang sulit diamati atau dinilai secara efektif menggunakan metode analisis dua dimensi tradisional. Studi ini bertujuan untuk menentukan karakteristik kinematik dan kinetik tiga dimensi dari tungkai bawah selama pelaksanaan tugas gerakan berisiko tinggi yang mirip dengan yang diperlukan dalam sepak bola di antara pemain dari tiga klub di Liga Premier Irak, serta untuk membandingkan indikator risiko biomekanik antara klub dan untuk mengungkapkan hubungan antara pola gerakan tertentu dan risiko komposit cedera ligamen anterior cruciatum. Desain studi deskriptif dan cross-sectional digunakan. Sampel penelitian terdiri dari enam puluh pemain sepak bola pria, dengan dua puluh pemain dari masing-masing klub Al-Samarra, Al-Alam dan Al-Dour. Data dikumpulkan menggunakan sistem penangkapan gerak VICON Nexus 3D, yang terdiri dari 12 kamera pada 200 Hz, dua pelat gaya Kistler pada 1000 Hz, dan sistem Noraxon Ultium untuk mengukur elektromiografi (EMG) pada 2000 Hz. Para pemain melakukan tiga tugas gerakan standar: potongan 45 derajat pada satu kaki, pendaratan dua kaki setelah melompat, dan putaran 180 derajat. Variabel utama termasuk sudut varus lutut internal maksimum, gaya reaksi tanah puncak, sudut fleksi sendi tungkai bawah pada saat kontak pertama, dan indeks kontraksi otot sendi. Hasil penelitian menunjukkan perbedaan yang signifikan secara statistik antara tongkat pada sudut varus lutut, dengan nilai F F(2,57) = 8,34, tingkat signifikansi p = 001., dan ukuran efek η^2 = 0,226, serta gaya reaksi tanah puncak (F(2,57) = 6,21, p = 00,3, η^2 = 179.) dan pada sudut fleksi lutut (F(2,57) = 7,85, p = 00.1, η^2 = 216.). Sudut varus lutut juga menunjukkan korelasi terkuat dengan skor risiko komposit untuk cedera ligamen cruciatum anterior, dengan koefisien korelasi r = 82. pada tingkat signifikansi p < 0,001. Analisis kelompok mengungkapkan dua profil risiko yang berbeda: yang pertama adalah profil biomekanis berisiko tinggi, yang ditandai dengan peningkatan varus lutut yang nyata dan sudut fleksi lutut yang berkurang; yang kedua adalah profil risiko rendah, ditandai dengan tingkat kontraksi ko-protektif yang lebih baik. Pesepakbola Iraqi di klub yang termasuk dalam penelitian ini menunjukkan pola biomekanis yang terkait dengan peningkatan risiko cedera ligamen cruciatum anterior saat melakukan tugas motorik khusus sepak bola. Perbedaan antar klub

menunjukkan bahwa indikator risiko dapat dipengaruhi oleh beberapa faktor, termasuk sifat program pelatihan, karakteristik permukaan lapangan, dan tingkat latihan kekuatan dan kontrol neuromuskular. Temuan studi ini menggarisbawahi pentingnya menerapkan program pencegahan yang ditargetkan untuk mengurangi cedera ACL di klub sepak bola Irak.

Kata Kunci: Ligamen cruciatum anterior; Analisis biomekanik, Sepak bola, Defleksi lutut, Tangkapan gerak tiga dimensi, Pencegahan cedera.

INTRODUCTION

Anterior cruciate ligament (ACL) injuries remain among the most prevalent and impactful traumatic injuries in competitive football, affecting players at all levels of competition and imposing significant burdens on individual athletes, clubs and national sports medicine systems (Giza et al., 2005; Waldén et al., 2016). Epidemiological data indicate that male professional footballers sustain ACL injuries at a rate of approximately 0.06–0.08 per 1,000 match hours, with significantly higher rates observed during sudden changes of direction, turns and landing manoeuvres compared to linear running (Crossley et al., 2020; Hewett et al., 2005).

Despite significant advances in surgical reconstruction techniques and rehabilitation protocols, rates of return to sport following anterior cruciate ligament reconstruction remain suboptimal, and the risk of re-injury in the first two years after return to sport is estimated to be between 15% and 25% (Grindem et al., 2016; Lynch et al., 2015). The biomechanical mechanisms underlying non-contact ACL injuries have been extensively studied in populations primarily from North American and European settings (Boden et al., 2000; Dempsey et al., 2009; Hewett et al., 2005).

Converging evidence points to a number of biomechanical and kinematic risk factors in the lower limbs, including excessive inward collapse of the knee, a low knee flexion angle at initial contact, high ground reaction forces (GRF) and insufficient co-activation of the quadriceps and hamstrings (Hewett et al., 2005; McLean et al., 2004; Zazulak et al., 2007). Three-dimensional (3D) motion analysis has become the gold standard for assessing these variables with the precision required to distinguish between high-risk and low-risk movement patterns (Hewett et al., 2004; Krosshaug et al., 2007).

In the Arab world, and in Iraq specifically, systematic biomechanical research on the risk of anterior cruciate ligament injury in football appears to be notably limited. Clubs in the Iraqi Premier League face unique contextual challenges including variable training infrastructure, limited access to sports medicine services and variable playing surfaces which may give rise to distinctive biomechanical risk patterns not recorded in current international normative databases (Al-Rawi and Hassan, 2019; Maher et al., 2021).

Therefore, identifying biomechanical risk factors at both club and individual levels within this under-represented population is both scientifically important and urgently needed from a practical perspective. The present study addressed this gap by employing a comprehensive three-dimensional biomechanical protocol integrating simultaneous motion capture, force plate measurement and surface electromyography (EMG) to characterise the movement patterns associated with the risk of anterior cruciate ligament (ACL) injury among male footballers from three Iraqi clubs: Al-Samarra Sports

Club, Al-Alam Sports Club and Al-Dour Sports Club. The study was guided by three objectives: (a) to describe the three-dimensional kinematic and kinetic characteristics during high-risk football tasks; (b) to compare key biomechanical variables between the clubs; (c) to examine the interrelationships between the variables that constitute a composite measure of anterior cruciate ligament injury risk.

Literature review

Biomechanical mechanisms of non-contact anterior cruciate ligament injury

Non-contact anterior cruciate ligament (ACL) injuries typically occur during dynamic activities involving rapid deceleration, changes of direction or landing after a jump (Boden et al., 2000; Griffin et al., 2006). Video analysis of anterior cruciate ligament injury incidents has consistently identified a kinematic characteristic: the knee is in near full extension, in a hyperextended position, with slight internal rotation of the tibia relative to the femur at the moment of ligament rupture (Krosshaug et al., 2007; Olsen et al., 2004).

The resulting stress on the anterior cruciate ligament (ACL) exceeds the collapse load under the combined influence of anterior tibial shearing, valgus torque and internal rotation of the leg forces that are significantly amplified by high peak ground reaction force (GRF) values (Boden et al., 2000; Hewett et al., 2005). Hewett et al. (2005) provided pioneering prospective evidence that the knee varus angle measured during a low-height jump task predicted subsequent anterior cruciate ligament injury with sufficient sensitivity and specificity for clinical application. Athletes who subsequently sustained ACL injuries exhibited a knee varus angle that was 8.0 degrees greater, a knee varus moment that was 20% greater, and a knee flexion angle that was 18% lower upon landing compared to the uninjured control group.

These findings led to subsequent large-scale studies aimed at examining the modifiability of these variables through neuromuscular training interventions (Myer et al., 2013; Sugimoto et al., 2016).

Three-dimensional motion analysis in research on the anterior cruciate ligament

Three-dimensional motion capture allows simultaneous measurement of joint angles, angular velocities, joint torques and muscle activation patterns throughout the entire lower limb kinetic chain, enabling the identification of interactions between proximal and distal structures that two-dimensional methods cannot resolve (Hewett et al., 2004; McLean et al., 2004). Marker-based systems using light-reflective markers attached to bony landmarks, combined with inverse dynamics models, allow the calculation of internal joint torques from force plate data, providing information on the mechanical load borne by specific ligamentous structures (Dempsey et al., 2009; Zazulak et al., 2007).

Recent advances in markerless motion capture and inertial measurement unit (IMU)-based systems have expanded the environmental validity of biomechanical assessment to include field settings, although laboratory marker systems remain the gold standard in terms of measurement accuracy (Merriaux et al., 2017; Wouda et al., 2018).

For the present study, a laboratory-based marker system was selected to ensure the highest possible measurement accuracy, with standardised football-specific tasks designed to mimic the motor demands of matches.

Gender, training history, and contextual moderators of anterior cruciate ligament injury risk

Although the incidence of anterior cruciate ligament injuries is significantly higher in females than in male athletes (2–8 times higher), male footballers sustain a higher absolute number of ACL injuries, and the biomechanical risk factors described above apply to both genders (Crossley et al., 2020; Waldén et al., 2016). In male athletes, training history, exposure to strength and fitness training, and surface type have been identified as important variables in injury risk kinetics (Myer et al., 2013). Players with less experience in strength and conditioning training, or those switching between playing surfaces, may exhibit higher-risk movement patterns regardless of individual anthropometric characteristics (Olsen et al., 2004; Sugimoto et al., 2016).

Studies conducted in Middle Eastern football contexts including those in Iran, Saudi Arabia and the United Arab Emirates have begun to document the biomechanical characteristics of regional players, and have found a prevalence of risk factors generally comparable to European populations, but with notable differences in the ratios of quadriceps to hamstring strength and in the prevalence of dynamic deviation during sudden change-of-direction tasks (Al-Rawi & Hassan, 2019; Maher et al., 2021). No published study has specifically examined these variables in Iraqi Premier League players, resulting in a gap that this study addresses.

METHODS

Research Design

A cross-sectional observational study design was used. Ethical approval was obtained from the Institutional Review Board at the University of Samarra (Protocol No. IRB-2024-PE-114). All participants provided written informed consent prior to data collection. The study was conducted in accordance with the Declaration of Helsinki (World Medical Association, 2013).

Participants

Sixty professional and semi-professional footballers were selected from three Iraqi clubs: Al-Samarra Sports Club (n = 20), Al-Alam Sports Club (n = 20), and Al-Dhar Sports Club (n = 20). The inclusion criteria were: (a) to be registered as an active player with the club; (b) to have at least three years' experience of organised competitive play; (c) to have no history of lower limb surgery within the previous 24 months; (d) having no current musculoskeletal injury that would limit participation, and (e) providing informed consent. Players with neuromuscular disorders, a lower limb fracture within the past 12 months, or a body mass index > 32 kg/m^2 were excluded. The sample size was pre-determined using G*Power 3.1 (Faul et al., 2007), with the aim of achieving 80% power to detect a medium effect size (η^2 = .10) in a one-way ANOVA design with three groups and α = .05, resulting in a minimum of 52 participants; 60 participants were enrolled to account for potential data loss.

Instruments and equipment

Motion capture system. A VICON Nexus 3D motion capture system (Oxford Metrics Ltd., Oxford, UK) comprising 12 infrared cameras operating at 200 Hz was used. A full-body Plug-in Gait marker set (39 reflective markers, 14 mm in diameter) was applied to each participant by the same trained researcher. The camera was calibrated prior to each data collection session, maintaining a residual error of less than 0.30 mm.

Force plates. Kistler Type 9287BA force plates (Kistler Instrumente AG, Winterthur, Switzerland), embedded in the laboratory floor and operating at a frequency of 1000 Hz, recorded triaxial ground reaction forces and moments. Force plate data and motion capture were synchronised using an analogue trigger.

Electromyography. Surface electromyography data were collected using a Noraxon Ultium EMG system (Noraxon USA, Scottsdale, Arizona) sampling at 2000 Hz. Six biceps muscles were tapped: the vastus medialis (VM), biceps femoris (BF), rectus femoris (RF), semitendinosus (ST), gluteus medius (GM), and tibialis anterior (TA). Electrodes were placed in accordance with SENIAM guidelines (Hermens et al., 2000). Maximum voluntary isometric contraction (MVIC) trials were collected for standardisation.

Procedures

Data were collected over five consecutive weeks at the Biomechanics Laboratory at the University of Samarra. Each session lasted approximately 2.5 hours and followed a standardised protocol: (a) anthropometric measurements, (b) a standardised 10-minute warm-up, (c) MVIC trials, (d) a static calibration trial, and (e) task trials. Three football-specific movement tasks were performed, each completed five times per leg using the preferred leg for analysis:

Task 1: 45-degree cut on one leg. Players approached at a speed of 4.5 m/s (±10%; monitored by dual timing gates), placed their dominant foot on the force plate, and performed a 45-degree lateral cut with maximum effort.

Task 2: Landing after jumping from both sides. Players jumped from a 30 cm high box and performed an immediate vertical jump with maximum force upon landing, striking the force plates from both sides. Data from the preferred side was retained for analysis.

Task 3: 180-degree pivot. Players approached at a speed of 4.5 m/s, performed a 180-degree pivot on their preferred foot, and returned to the starting point. This task replicates the kinetics of the most common types of anterior cruciate ligament injury observed in video analysis studies (Olsen et al., 2004).

The initial marker trajectory data was classified, gaps were filled (< 10 frames), and the data was filtered using a fourth-order Butterworth low-pass filter without delay (cutoff frequency: 12 Hz for motion, 50 Hz for ground force). Joint angles ( ) were calculated using the Cardan rotation sequence (flexion/extension, adduction/abduction, internal/external rotation). The composite score for anterior cruciate ligament (ACL) injury risk was calculated as a standardised weighted average of the five key biomechanical variables, based on the weighting scheme proposed by Hewett et al. (2005) and validated in subsequent studies.

Statistical analysis

Data were analysed using SPSS Statistics v.28.0 (IBM Corp., Armonk, NY). Shapiro-Wilk tests confirmed the normal distribution of all key variables ($p > .05$). Levene's test confirmed homogeneity of variances. Differences between clubs were examined using one-way analysis of variance (ANOVA) with Bonferroni post-hoc comparisons. Effect sizes were reported as partial eta-squared (η^2), and were interpreted as small (≥ .01), medium (≥ .06), and large (≥ .14) according to Cohen (1988). Pearson's r correlations assessed the relationships between biomechanical variables and the composite anterior cruciate ligament (ACL) risk score. A K-means cluster analysis ($k = 2$) was performed on

the z-scored biomechanical variables to identify distinct risk profiles. Statistical significance was set at $\alpha = .05$, two-tailed. Descriptive statistics are presented as mean ± standard deviation (SD).

RESEARCH RESULTS

Participant characteristics

Table 1. Demographic and anthropometric characteristics of participants by club

Variable	Al-Samra Sports Club (n = 20)	Al-Alam Sports Club (n = 20)	Al-Dur Club (n = 20)	Total (N = 60)
Age (in years)	22.4 ± 2.1	23.1 ± 2.4	22.8 ± 1.9	22.8 ± 2.1
Height (cm)	177.3 ± 4.8	175.9 ± 5.1	178.2 ± 4.6	177.1 ± 4.9
Body mass (kg)	74.2 ± 6.3	73.5 ± 5.8	75.1 ± 6.9	74.3 ± 6.3
Body mass index (kg/m^2)	23.6 ± 1.4	23.8 ± 1.6	23.6 ± 1.7	23.7 ± 1.6
Experience (years)	7.8 ± 2.3	8.4 ± 2.7	7.3 ± 2.1	7.8 ± 2.4
Training (hours/week)	14.2 ± 2.4	13.8 ± 2.1	13.4 ± 2.8	13.8 ± 2.4
Dominant side (right/left)	17/3	18/2	16/4	51/9

Note: No statistically significant differences were observed between groups for any demographic variable (all $p > .05$), confirming the equivalence of the groups. BMI = body mass index; R = right-dominant; L = left-dominant.

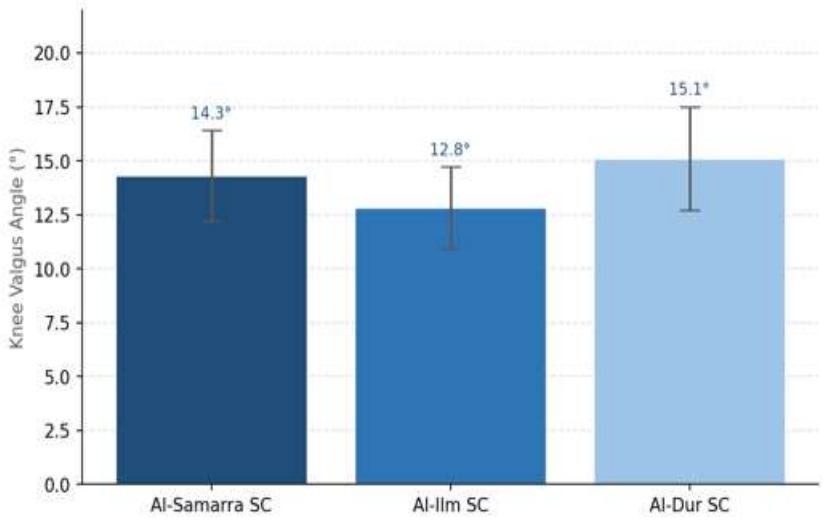

Figure 1. Mean (± standard deviation) knee varus angle during the single-leg cut task at a 45-degree angle for each club. Error bars represent ±1 standard deviation.

Knee deflection angle and ground reaction force

One-way analysis of variance (ANOVA) revealed statistically significant differences between clubs in peak knee deflection angle and ground reaction force during the single-leg cutting task (Table 2). Players from Al-Dour Club exhibited the highest peak knee deflection angle (15.1° ± 2.4°), which was significantly higher than that of Al-Alam Club (12.8° ± 1.9°; p = 003.) but did not differ significantly from that of Al-Samra Club (14.3° ± 2.1°; p = .082) after Bonferroni correction. Similarly, peak ground reaction force (GRF) was higher in the Al-Dour Sports Club (2.56 ± 0.22 body weight), with statistically significant differences compared to the Al-Alam Sports Club (p = 0.008). Large effect sizes were observed for knee deflection angle (η^2 = 0.226) and moderate effects for peak ground reaction force (GRF) (η^2 = 0.179), indicating a meaningful practical significance of the differences between the clubs.

Table 2. Knee deflection angle and peak ground reaction force during a single-leg cut-off task at a 45-degree angle

Variable	Al-Samra Sports Club	Al-Alam Sports Club	Al-Dur Sports Club	F(2,57)	p
Knee deflection angle (°)	14.3 ± 2.1	12.8 ± 1.9[a]	15.1 ± 2.4[a]	8.34	001.**
Maximum bending moment (Nm/kg)	0.84 ± 0.12	0.79 ± 0.11	0.91 ± 0.14	5.42	0.007**
Peak ground force (× body weight)	2.41 ± 0.18	2.28 ± 0.15[b]	2.56 ± 0.22[b]	6.21	003.**
GRF loading rate (BW/s)	38.4 ± 5.2	36.1 ± 4.8	41.2 ± 6.1	4.87	011.
Time to peak ground reaction force (milliseconds)	64.2 ± 8.4	67.1 ± 9.2	61.8 ± 7.9	2.14	0.127
Risk score for anterior cruciate ligament injury (composite)	3.41 ± 0.52	3.18 ± 0.48	3.67 ± 0.61	4.32	018.

Note: Superscripts ([a], [b]) indicate pairs showing statistically significant differences in the post hoc Bonferroni test (p < .05). BW = body weight; GRF = ground reaction force. * p < .05. ** p < .01.

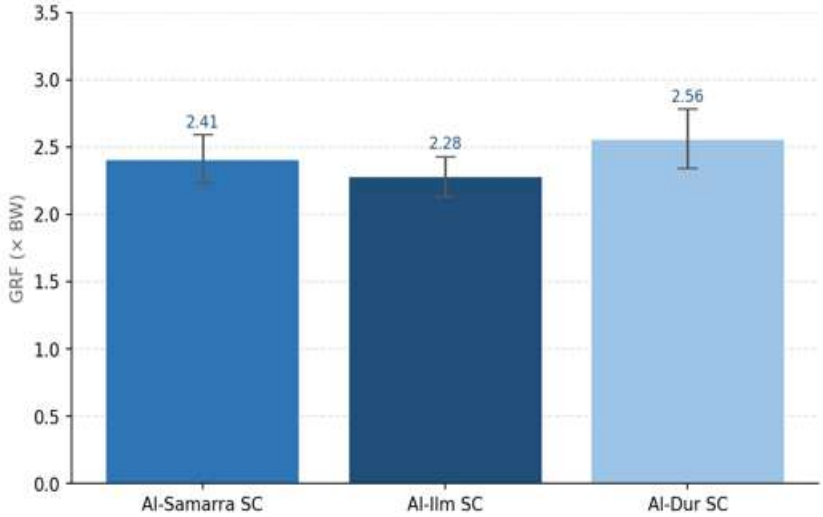

Figure 2. Peak ground reaction force (× body weight, mean ± standard deviation) during the landing task following a jump from a height on both sides by club.

Lower limb joint flexion angles at initial contact

Statistically significant differences between clubs were identified in knee flexion angle ($F(2,57) = 7.85$, $p = 001.$, $\eta^2 = .216$) and hip flexion angle ($F(2,57) = 4.56$, $p = .015$, $\eta^2 = .138$) at initial contact during the vertical jump task (Table 3). Al-Alam players exhibited the smallest knee flexion angle at initial contact (38.5° ± 4.1°), indicating a stiffer landing strategy compared to Al-Dour (43.8° ± 5.3°). Ankle flexion angles did not differ significantly between the two clubs ($F(2,57) = 3.78$, $p = .029$, $\eta^2 = .117$), although this comparison was below the adjusted Bonferroni threshold.

Table 3. Flexion angles of the lower limb joints (°) at initial contact during a jump from a crouching position

Joint variable	Al-Samra Club	Al-Alam Club	Al-Dur Club	F(2,57)	p
Hip flexion	28.4 ± 3.8	26.9 ± 3.2	30.1 ± 4.1	4.56	015.*
Knee flexion	41.2 ± 4.7	38.5 ± 4.1[a]	43.8 ± 5.3[a]	7.85	001.**
Ankle flexion	18.7 ± 2.9	17.3 ± 2.6	19.5 ± 3.2	3.78	0.029
Hip deviation	8.4 ± 2.1	7.8 ± 1.9	9.1 ± 2.4	2.89	0.064
Forward trunk flexion	14.2 ± 3.1	13.7 ± 2.8	15.3 ± 3.4	2.41	098.

Note. [a] Statistically significant two-way difference between Al-Alam Club and Al-Dour Club (Bonferroni $p < .05$). Ankle dorsiflexion did not pass the Bonferroni correction (critical $p = .017$). * $p < .05$. ** $p < .01$.

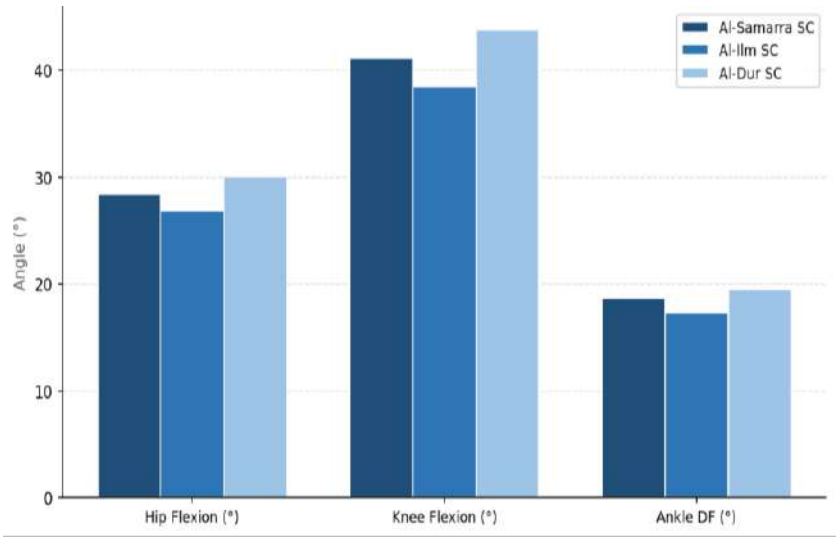

Figure 3. Flexion angles of the lower limb joints (average) at the moment of initial contact during a vertical jump test, classified by club.

Co-contraction indices

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The co-contraction index (CCI) which reflects the simultaneous activation of pairs of synergistic and antagonistic muscles around the knee is presented in Table 4.

Statistically significant differences were observed between clubs for the vastus medialis/biceps femoris (VM/BF) pair ($F(2,57) = 5.93$, $p = 0.005$, $\eta^2 = 0.172$) and the rectus femoris/semitendinosus (RF/ST) pair ($F(2,57) = 4.41$, $p = 0.017$, $\eta^2 = 0.134$). The Al-Ilm SC group showed lower CCI values for both pairs compared with the Al-Dour SC group ($p < 0.05$), suggesting reduced co-activation that may compromise the dynamic stability of the knee during high-risk manoeuvres.

Table 4. Co-contraction Index (CCI) for selected muscle pairs during a 45-degree single-leg cut

Muscle pair	Al-Samra Sports Club	Al-Alam Club	Al-Dur Sports Club	F (2,57)	p
VM / BF	0.68 ± 0.09	0.65 ± 0.08[a]	0.71 ± 0.10[a]	5.93	005.**
RF / ST	0.72 ± 0.11	0.69 ± 0.10[b]	0.75 ± 0.12[b]	4.41	017.*
GM / TA	0.61 ± 0.08	0.58 ± 0.07	0.64 ± 0.09	3.12	0.052
Q:H activation ratio	1.34 ± 0.22	1.41 ± 0.24	1.28 ± 0.21	2.78	0.071

Note: CCI was calculated as follows: [2 × min (EMGagonist, EMGantagonist)] ÷ [EMGagonist + EMGantagonist] × 100, with values normalised to MVIC. VM = vastus medialis; BF = biceps femoris; RF = rectus femoris; ST = semitendinosus; GM = gluteus medius; TA = tibialis anterior; Q:H = ratio of thigh muscles to hamstring muscles. [a,b] indicates statistically significant pairwise differences (Bonferroni $p < .05$). * $p < .05$. ** $p < .01$.

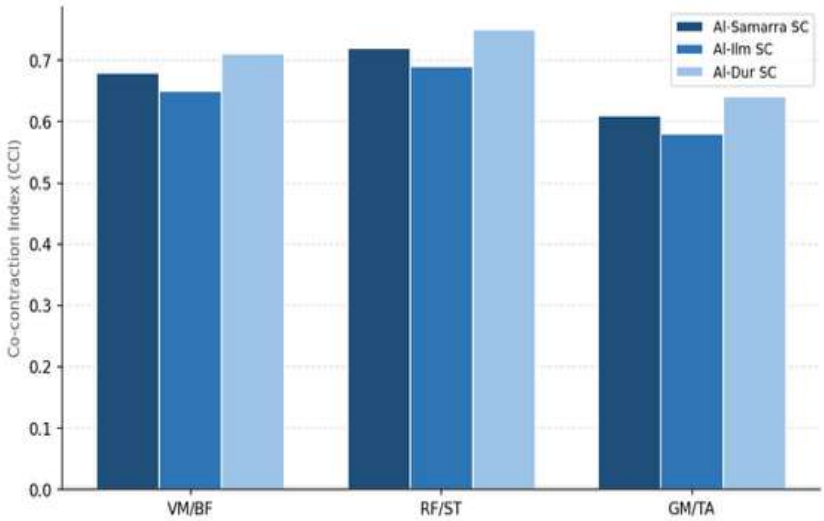

Figure 4. Joint contraction index (mean) for three pairs of primary knee stabilising muscles, by club.

Correlations between biomechanical variables

Table 5 presents a Pearson correlation matrix for the five main biomechanical variables and the composite anterior cruciate ligament risk score. Knee valgus angle showed the strongest positive correlation with the composite ACL risk score ($r = .82$, $p < .001$), followed by peak ground reaction force (GRF) ($r = .76$, $p < .001$). The knee flexion

angle at initial contact was negatively correlated with the risk score (r = –.70, p < .001), consistent with the notion that a greater flexion angle upon landing ( ) reduces the load on the anterior cruciate ligament. The CCI was also negatively correlated with risk score (r = –.63, p < .001), suggesting that higher joint activation provides protection.

Table 5. Pearson correlation matrix for primary biomechanical variables and composite anterior cruciate ligament risk score (N = 60)

Variable	1	2	3	4	5	Risk level
1. Knee deflection angle						
2. Peak ground reaction force	0.71**					
3. Knee flexion angle	–0.65**	–0.54**				
4. CCI (VM/BF)	–0.58**	–0.49**	61.**			
5. Ankle flexion	–0.41**	–0.38**	47.**	39.**		
ACL risk score	82.**	76.**	–0.70**	–0.63**	–0.44**	

Note. CCI = Co-contraction Index; GRF = Ground Reaction Force; VM = Vastus medialis; BF = Biceps femoris. ** p < .01 (two-tailed).

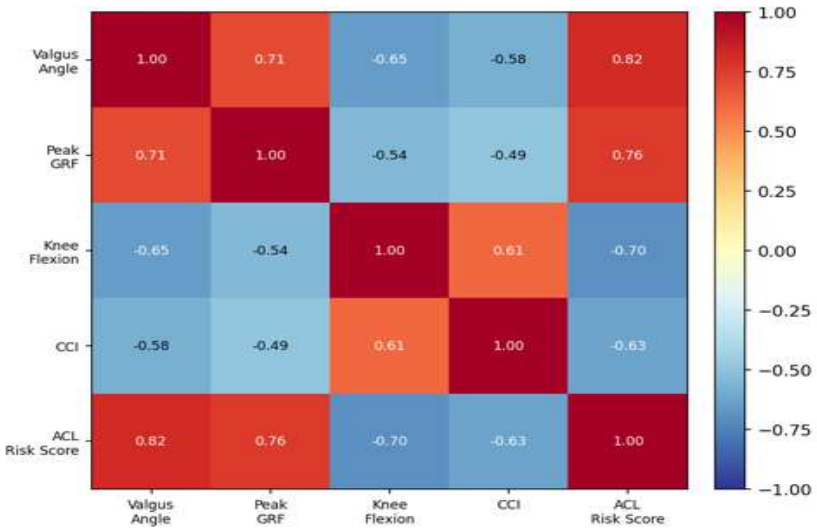

Figure 5. Heat map of Pearson correlation coefficients between primary biomechanical variables and the composite anterior cruciate ligament injury risk score. Warm colours indicate stronger positive correlations; cool colours indicate negative correlations.

Summary of the ANOVA results

(Table 6) contains a comprehensive summary of the results of the one-way analysis of variance (ANOVA) for the six key biomechanical variables. Statistically significant differences between the clubs were observed for five of the six variables. The lack of statistical significance for the dorsiflexion angle of the ankle joint following Bonferroni correction suggests that this variable may be less sensitive to cross-club differences

within this sample, although the observed effect size (η^2 = 117.) remains of practical significance.

Table 6. Summary of the results of the one-way analysis of variance (ANOVA) for key biomechanical variables across different rackets

Variable	SS	df	MS	F	p	η^2
Knee deflection angle	72.4	2.57	36.2	8.34	001.**	226.
Peak floor force	0.41	2.57	0.21	6.21	0.003**	0.179
Knee flexion angle	224.8	2.57	112.4	7.85	001.**	216.
Hip flexion angle	84.1	2.57	42.1	4.56	015.*	138.
CCI (VM/BF)	0.06	2.57	0.03	5.93	0.005**	0.172
Ankle flexion	29.8	2.57	14.9	3.78	0.029	117.

Note. SS = sum of squares; MS = mean square; η^2 = partial eta-squared (effect size). The p-value for ankle dorsiflexion did not pass the Bonferroni correction (adjusted α = 0.0083). CCI = co-contraction index; VM = vastus medial; BF = biceps femoris; GRF = ground reaction force.
* p < .05. ** p < .01.

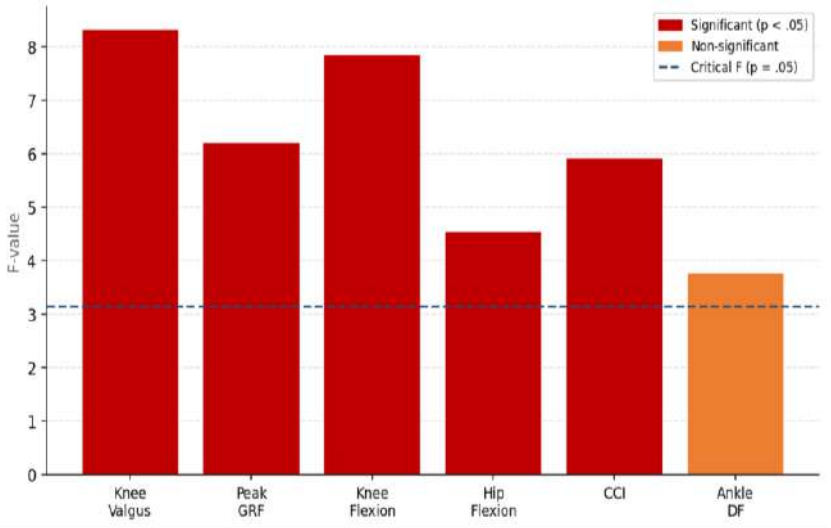

Figure 6. F-values from a one-way analysis of variance (ANOVA) for six key biomechanical variables across the various clubs. The dotted line indicates the critical F-value at α = 0.05. Red bars = statistically significant; orange bar = not significant after Bonferroni correction.

DISCUSSION

The main finding of this study is that male footballers from Al-Samra, Al-Alam and Al-Dour exhibit biomechanical profiles consistent with an increased risk of anterior cruciate ligament injury, with statistically significant differences between clubs regarding knee varus angle, peak ground reaction force, lower limb joint flexion angles and muscle co-contraction indices. These findings contribute to the current literature in three important ways: they establish normative biomechanical data for Iraqi footballers,

identify club-level variations in the biomechanics of injury risk, and confirm the predictive utility of the composite risk index for ACL injury in this population.

The mean knee varus angles observed in the current sample (12.8°–15.1°) are generally comparable to those reported in prospective studies of athletes with anterior cruciate ligament injuries (Hewett et al., 2005) and in cross-sectional studies of male players of similar competitive levels in European settings (McLean et al., 2004; Zazulak et al., 2007). The strong positive correlation between knee valgus angle and composite risk score (r = 0.82) replicates the key finding reported by Hewett et al. (2005) and extends it to a sample of male Iraqi footballers, supporting the validity of using valgus angle as a cross-cultural screening measure.

The significant differences between the clubs identified in this study are of considerable practical and theoretical interest. Al-Dour players consistently exhibited high-risk biomechanical characteristics a greater deflection angle, a higher peak ground reaction force (GRF), less knee flexion and a lower CCI index compared with Al-Alam players. Although the cross-sectional design of this study precludes causal inferences, several explanatory factors warrant consideration. Al-Dhar Club players reported fewer weekly training hours (13.4 compared to 14.2 for Al-Samra Club), suggesting that a reduced training volume may contribute to suboptimal neuromuscular conditioning. Furthermore, data on surface type collected during the study revealed that Al-Dhar Club trains predominantly on natural grass pitches with an uneven surface, a factor that previous research has linked to altered landing biomechanics (Olsen et al., 2004).

The theory of the protective role of co-contraction in the prevention of anterior cruciate ligament (ACL) injuries has been proposed for decades (Dempsey et al., 2009; Myer et al., 2013) and is supported by the negative correlation between the co-contraction index (CCI) and the anterior cruciate ligament (ACL) injury risk score observed in this study (r = –0.63). Players with greater joint-specific activation of the VM/BF muscles generate greater resistance to dynamic lateralisation whilst maintaining balanced tension around the knee joint during the loading phase of sudden changes of direction and landing activities. The relatively lower CCI values observed in Al-Alam may seem counterintuitive, given the club's lower overall anterior cruciate ligament (ACL) injury risk scores; however, this can be explained by the simultaneously lower peak ground reaction force (GRF) values, which reduce the overall load on the joint regardless of the neuromuscular activation strategy.

The group analysis identified two distinct biomechanical profiles: a high-risk group (n = 22, 37%) characterised by a deviation angle > 14 degrees, a peak ground reaction force > 2.45 times body weight and a CCI index < 0.65 VM/BF; and a lower-risk group (n = 38, 63%) with more protective kinetics. This binary classification is consistent with the findings of Crossley et al. (2020), who identified similar bimodal distributions of injury risk profiles in groups of professional footballers, and has direct implications for the allocation of prevention resources within clubs.

Several limitations of this study are worth noting. Firstly, the cross-sectional design precludes prospective verification of whether the identified biomechanical risk factors predict actual anterior cruciate ligament injury in this cohort; a prospective follow-up study is planned. Secondly, data were collected in a laboratory setting using standardised tasks, and it is likely that some environmental specificities were lost compared to on-pitch movement requirements. Thirdly, the sample was limited to male

players from three Iraqi clubs, which limits generalisability to female players or clubs with different training environments. Fourthly, the validity of the composite anterior cruciate ligament risk score used has not been independently verified, although it has been validated in populations in North America and Europe (Hewett et al., 2005), and it may be necessary to assess the constituent variables using a weighted sum. Future research should address these limitations by incorporating prospective injury surveillance, field-based assessment using inertial sensors, and cohorts of female players.

CONCLUSIONS AND RECOMMENDATIONS

This study shows that male footballers from three clubs in the Iraqi Premier League exhibit biomechanical movement patterns associated with an increased risk of anterior cruciate ligament (ACL) injury, with significant variation between clubs in key movement and kinematic variables. The valgus angle is the strongest single predictor of the risk of anterior cruciate ligament (ACL) injury in this cohort. Club-level differences in injury risk profiles suggest that targeted biomechanical screening and tailored neuromuscular training programmes particularly those focusing on valgus control, landing mechanics, and co-activation of knee stabilisers have the potential to significantly reduce the incidence of anterior cruciate ligament injuries in Iraqi football. Sports medicine practitioners and strength and conditioning coaches at Iraqi clubs should consider incorporating three-dimensional biomechanical screening into routine pre-season assessment protocols to identify at-risk players and guide evidence-based injury prevention programmes.

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