

Article

Hierarchical Movement-Pattern Deficits During Drop Jump Predict Injury Risk in Football Players: A LESS-Based Prospective Cohort Study

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Abstract

Purpose: To determine whether specific movement-pattern deficits and their hierarchical interaction during drop jump (DJ) tasks can predict injury occurrence in football players using a LESS-based observational screening approach. **Methods:** Seventy-two male football players (age: 21.4 ± 3.2 years; height: 178.2 ± 6.4 cm; body mass: 73.5 ± 7.1 kg) completed a standardised DJ assessment during the pre-season period. Movement quality was evaluated using a modified Landing Error Scoring System (LESS)-based observational protocol including six biomechanical domains related to lower-limb and trunk control. The occurrence of non-contact lower-limb injuries resulting in time loss was prospectively monitored throughout the competitive season. Multivariate logistic regression and receiver operating characteristic (ROC) curve analyses were performed to identify independent predictors of injury and evaluate model discrimination. Additionally, a Classification and Regression Tree (CART) model was implemented to identify hierarchical movement-based injury-risk profiles. **Results:** Eighteen players (25%) sustained at least one time-loss injury during the observation period. Injured players demonstrated significantly higher composite movement-error scores compared with non-injured players (6.1 ± 1.8 vs. 4.3 ± 1.5 ; $p = 0.01$). Dynamic knee valgus (OR = 2.84; 95% CI: 1.32–6.12; $p = 0.008$) and trunk control deficits (OR = 2.17; 95% CI: 1.08–4.36; $p = 0.030$) emerged as independent predictors of injury risk. The logistic regression model demonstrated acceptable discriminative capacity (AUC = 0.74; sensitivity = 0.72; specificity = 0.67). CART analysis identified three hierarchical movement-risk profiles: low risk (predicted probability < 0.15), moderate risk (0.15–0.40), and high risk (>0.40). Players exhibiting combined dynamic knee valgus and trunk control deficits demonstrated the highest injury probability. **Conclusions:** The present findings support the use of movement-pattern profiling during DJ tasks as a practical and clinically interpretable strategy for injury-risk stratification in football players. Rather than relying exclusively on composite movement-error scores, the interaction between dynamic knee valgus and trunk control deficits appears to represent a distinct neuromuscular risk phenotype associated with elevated injury probability. Integrating observational movement screening with hierarchical risk modelling may contribute to the development of more individualised injury-prevention strategies in football.

Keywords: drop jump; injury risk; movement screening; Landing Error Scoring System; football; neuromuscular control; movement-pattern profiling; injury prevention



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1. Introduction

Injury prevention remains one of the most important and challenging areas within contemporary football performance and sports medicine. Despite substantial advances in monitoring technologies, medical support, and load-management strategies, musculoskeletal injuries continue to impose considerable physiological, economic, and competitive burdens on athletes and teams [1]. Time-loss injuries negatively affect player availability, disrupt training continuity, reduce team performance, and may compromise long-term athletic development [2–4]. Consequently, the identification of athletes at increased injury risk remains a major priority in applied sport science.

Current models of sports injury aetiology conceptualise injury risk as a dynamic and multifactorial process emerging from the interaction of intrinsic and extrinsic factors rather than from isolated biomechanical deficits alone [3,5]. Within this framework, neuromuscular control has emerged as a particularly relevant component due to its direct influence on force absorption, segmental coordination, joint stability, and movement adaptability during high-demand sporting actions [6,7]. Deficits in neuromuscular function may alter lower-limb mechanics, compromise force distribution throughout the kinetic chain, and increase tissue loading during tasks involving landing, deceleration, and rapid changes in direction [8,9].

Among functional assessment tasks, the drop jump (DJ) has become one of the most widely used tools for evaluating lower-limb neuromuscular performance in athletic populations [10–12]. Beyond its utility for assessing explosive performance characteristics, the DJ also provides valuable information regarding movement quality, intersegmental coordination, and dynamic postural control under conditions of rapid eccentric-concentric transition [6,13]. Altered movement strategies during landing have been associated with increased mechanical stress at the knee and hip joints and may contribute to the development of lower-limb injuries, particularly non-contact injuries involving the anterior cruciate ligament (ACL) and surrounding structures [14].

To evaluate movement quality during jump-landing tasks, observational screening tools such as the Landing Error Scoring System (LESS) have been widely implemented due to their practical applicability and low operational cost [15]. The LESS provides a standardised framework for identifying biomechanical movement deficits associated with potentially increased injury risk. Previous studies have demonstrated acceptable reliability and validity for LESS-based assessments, with good inter-rater agreement and moderate predictive utility for identifying high-risk movement strategies [16,17].

However, much of the existing literature has primarily focused on composite LESS scores as the principal outcome variable. Although global movement-error scores may provide a general estimation of movement quality, this reductionist approach may obscure the specific contribution and interaction of individual movement deficits. Athletes presenting similar total scores may exhibit substantially different neuromuscular strategies and biomechanical organisations, potentially limiting the sensitivity and clinical interpretability of traditional screening approaches [17].

Recent perspectives in movement science and injury-risk modelling suggest that injury susceptibility may emerge not from isolated movement errors, but from the hierarchical interaction and functional integration of multiple neuromuscular deficits within the movement pattern [6,18]. In this context, movement-pattern profiling may provide greater mechanistic insight than global scoring systems alone. Specifically, the interaction between distal movement deficits, such as dynamic knee valgus, and proximal control impairments, such as deficient trunk stability, may represent distinct neuromuscular risk phenotypes associated with increased injury probability [7,19].

Moreover, conventional linear statistical approaches may be insufficient to fully capture the hierarchical and non-linear structure of movement-related injury risk. Decision-tree

methodologies, such as Classification and Regression Tree (CART) analysis, offer an interpretable framework for identifying clinically meaningful thresholds and interaction patterns between movement variables [20]. Such approaches may enhance the ecological validity and translational applicability of injury-risk screening in football environments.

Previous biomechanical research has identified several movement characteristics during landing tasks that may contribute to lower-limb injury risk. Among these, dynamic knee valgus has consistently been associated with altered frontal-plane knee loading and increased ACL injury risk, whereas impaired trunk control may compromise proximal stability and influence lower-limb alignment during landing and deceleration tasks [5,21–23]. Nevertheless, it remains unclear whether these movement deficits represent the most relevant discriminative factors when movement quality is analysed as an integrated pattern rather than as isolated variables.

Therefore, the purpose of the present study was to investigate the association between DJ movement-pattern deficits and injury risk in football players using a LESS-based observational screening approach. Specifically, the aims were to: (1) determine which individual movement deficits are associated with injury occurrence; (2) identify independent movement-based predictors of injury through multivariate logistic regression; and (3) examine hierarchical movement-risk profiles using CART analysis. We hypothesized that specific movement deficits assessed during the DJ would be independently associated with injury occurrence and that hierarchical CART analysis would identify clinically meaningful movement-risk profiles based on combinations of these deficits.

2. Methods

2.1. Study Design

A prospective observational cohort study was conducted across one full competitive football season to investigate the association between movement-pattern deficits during drop jump (DJ) tasks and subsequent injury occurrence. The study design and reporting procedures followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines [24]. Ethical approval was obtained from the institutional ethics committee (approval no. 4248/CEIH/2024), and all procedures were performed in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants prior to study enrolment.

2.2. Participants

Seventy-two male football players competing at professional levels voluntarily participated in the study. Participants were recruited from two competitive football clubs during the pre-season period. All participants were professional football players belonging to teams competing in the Spanish First Division (LaLiga), Second Division (LaLiga Hypermotion), and Primera Federación (third tier of Spanish football). Inclusion criteria required players to be actively involved in regular training and competition and free from musculoskeletal injury at the time of baseline assessment. Exclusion criteria included: (1) any lower-limb injury within the previous six months; (2) surgical intervention during the preceding year; (3) neurological or vestibular disorders affecting movement execution; and (4) inability to perform maximal DJ testing.

Participant characteristics are presented in Table 1. An a priori power analysis was performed using G*Power software (version 3.1, Heinrich-Heine University, Düsseldorf, Germany). Based on an expected moderate effect size (odds ratio = 2.0), statistical power of 0.80, and alpha level of 0.05, a minimum sample size of 66 participants was required for logistic regression analysis. The final sample exceeded this threshold.

Table 1. Baseline participant characteristics stratified by injury group (mean $\pm$ SD).

Variable	Total (n = 72)	Injured (n = 18)	Non-Injured (n = 54)
Age (years)	21.4 $\pm$ 3.2	21.8 $\pm$ 3.0	21.3 $\pm$ 3.3
Height (cm)	178.2 $\pm$ 6.4	179.1 $\pm$ 5.9	177.9 $\pm$ 6.6
Body mass (kg)	73.5 $\pm$ 7.1	74.2 $\pm$ 6.8	73.3 $\pm$ 7.3
LESS_TOTAL	4.8 $\pm$ 1.7	6.1 $\pm$ 1.8 *	4.3 $\pm$ 1.5

Note. LESS_TOTAL = composite Landing Error Scoring System score. * $p < 0.05$ between injured and non-injured groups. No significant between-group differences were observed for anthropometric variables (all $p > 0.05$).

2.3. Experimental Procedures

Baseline testing was conducted during the pre-season period under standardised indoor environmental conditions. Participants were instructed to avoid intense physical activity for at least 24 h prior to testing. All assessments were completed within a single testing session.

Following anthropometric measurements, participants completed a standardised warm-up consisting of five minutes of low-intensity running followed by dynamic lower-extremity mobility exercises and submaximal jumping actions. All participants had previous experience performing movement tasks such as the drop jump. Furthermore, in the weeks preceding data collection, players were instructed in the drop jump technique as part of a familiarisation process to ensure consistent execution of the movement during testing. Subsequently, each participant performed three maximal DJs from a 30 cm platform with hands positioned on the hips throughout the movement. Participants were instructed to step forward from the box, land bilaterally, and immediately perform a maximal vertical jump while minimising ground contact time.

A passive recovery period of 60 s was provided between trials. The trial demonstrating the highest technical consistency, as independently determined by both evaluators, was selected for subsequent movement analysis.

2.4. Motion Capture and Video Analysis

All DJ trials were simultaneously recorded in the frontal and sagittal planes using two high-speed digital cameras (acA1920-155um; Basler AG, Ahrensburg, Germany) operating at 120 frames $\cdot$ s⁻¹. The frontal-plane camera was positioned perpendicular to the participant at hip height and approximately 3 m from the landing area. The sagittal-plane camera was positioned laterally at a distance of 3–4 m. Camera placement and environmental conditions were standardised across all testing sessions.

Video recordings were analysed frame-by-frame using motion-analysis software (Kinovea, version 0.9.5, Bordeaux, France). Temporal synchronisation between frontal and sagittal recordings was verified before analysis.

2.5. Movement-Pattern Assessment

Movement quality during the DJ task was evaluated using a modified observational protocol derived from the Landing Error Scoring System (LESS) [15]. Six biomechanical movement domains associated with lower-limb and trunk neuromuscular control were analysed:

1. Dynamic knee valgus;
2. Knee flexion strategy at initial contact and peak loading;
3. Trunk lateral and anterior control;
4. Hip alignment;
5. Landing stiffness;
6. Bilateral asymmetry.

Each domain was scored using a three-point ordinal scale:

- 0 = Optimal execution;
- 1 = Minor movement deviation;
- 2 = Major movement deviation.

Dynamic knee valgus was operationally defined as medial displacement of the knee joint relative to the foot during landing. Trunk control deficits were identified based on excessive lateral trunk lean or anterior trunk displacement during the deceleration phase. Landing stiffness was characterised by limited hip and knee flexion during force absorption, whereas bilateral asymmetry referred to observable asymmetrical lower-limb loading or movement execution during landing.

A composite movement-error score (LESS_TOTAL; range = 0–12) was calculated as the sum of all domain scores, with higher scores representing poorer movement quality.

All evaluations were independently performed by two experienced evaluators blinded to injury outcomes and to each other's scores. Prior to data collection, evaluators completed a familiarisation and standardisation process using pilot recordings.

2.6. Reliability Analysis

Inter-rater reliability was assessed using intraclass correlation coefficients (ICC) calculated from a two-way random-effects model with absolute agreement. Reliability interpretation followed previously established guidelines [25]: poor (<0.50), moderate (0.50–0.75), good (0.75–0.90), and excellent (>0.90). Standard error of measurement (SEM) and minimal detectable change (MDC95) were additionally calculated to quantify measurement precision.

2.7. Injury Surveillance

Injury incidence was prospectively monitored throughout the competitive season by club medical staff. A time-loss injury was defined according to the consensus statement for football injury surveillance as any musculoskeletal complaint resulting from football participation that caused absence from at least one subsequent training session or match [26].

Only non-contact injuries were included in the present analyses. Contact injuries (e.g., those resulting from tackles, collisions, or direct external impacts) were excluded because the purpose of this study was to investigate whether movement quality assessed through the LESS could predict injuries associated with intrinsic neuromuscular and biomechanical factors rather than traumatic contact events.

Injuries were classified according to:

- Anatomical location;
- Tissue type;
- Contact or non-contact mechanism;
- Acute or overuse onset.

Training and match exposure hours were recorded throughout the season to calculate injury incidence density expressed as injuries per 1000 h of football exposure.

2.8. Statistical Analysis

All statistical analyses were performed using R statistical software (version 4.3.0; R Foundation for Statistical Computing, Vienna, Austria). Data normality and homogeneity were assessed using the Shapiro–Wilk and Levene tests, respectively. Descriptive statistics are presented as mean $\pm$ standard deviation (SD).

Between-group comparisons were performed using independent-samples *t*-tests or Mann–Whitney U tests when appropriate. Chi-square tests were used for categorical variables. Effect sizes were calculated using Cohen's *d* and interpreted as small (≥ 0.20), medium (≥ 0.50), and large (≥ 0.80).

Multivariate binary logistic regression analysis was performed to identify independent predictors of injury occurrence. Variables demonstrating $p < 0.05$ during bivariate analysis were entered into the regression model. Multicollinearity was assessed using variance inflation factors (VIF), with values < 5 considered acceptable.

Model performance was evaluated using:

- Odds ratios (OR) and 95% confidence intervals (CI);
- Nagelkerke R^2 ;
- Hosmer–Lemeshow goodness-of-fit test;
- Receiver operating characteristic (ROC) curve analysis.

Discriminative ability was quantified using the area under the ROC curve (AUC) and interpreted according to established criteria: acceptable (0.70–0.79), good (0.80–0.89), and excellent (≥ 0.90) [27]. The optimal classification threshold was determined using the Youden Index. Sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) were subsequently calculated.

To explore hierarchical interactions between movement variables, a Classification and Regression Tree (CART) model was additionally implemented. Recursive partitioning was performed using Gini impurity criteria with ten-fold cross-validation to minimise overfitting and improve model stability. Statistical significance was established at $p < 0.05$.

3. Results

3.1. Participant Characteristics and Injury Incidence

All seventy-two players completed baseline testing and were included in the final analysis. During the competitive season, 18 players (25.0%) sustained at least one time-loss injury. No significant differences were observed between groups for age, height, or body mass (all $p > 0.05$), confirming baseline comparability (Table 1).

3.2. Inter-Rater Reliability

Inter-rater reliability was high across all movement domains (ICC: 0.81–0.91; 95% CI: 0.74–0.95), indicating good to excellent agreement between evaluators [25].

3.3. Descriptive and Bivariate Analysis

Injured players demonstrated significantly higher LESS_TOTAL scores (6.1 ± 1.8 vs. 4.3 ± 1.5 ; mean difference = 1.8, 95% CI: 0.9–2.7; $p = 0.01$; Cohen's $d = 1.07$). Dynamic knee valgus ($p = 0.010$) and trunk control deficits ($p = 0.020$) were significantly greater in injured players. No significant differences were identified for knee flexion angle, hip alignment, landing stiffness, or bilateral asymmetry (all $p > 0.05$). Full bivariate results are presented in Table 2.

Table 2. Bivariate comparisons of individual movement error domain scores between injured and non-injured players.

Movement Error Domain	Injured (M $\pm$ SD)	Non-Injured (M $\pm$ SD)	p -Value	Cohen's d
Dynamic knee valgus	1.61 $\pm$ 0.49	0.89 $\pm$ 0.62	0.010 *	0.97
Trunk lateral/ anterior control	1.44 $\pm$ 0.51	0.93 $\pm$ 0.58	0.020 *	0.76
Knee flexion angle	1.22 $\pm$ 0.55	0.98 $\pm$ 0.61	0.180	0.32
Hip alignment	0.83 $\pm$ 0.50	0.72 $\pm$ 0.54	0.410	0.18
Landing stiffness	0.78 $\pm$ 0.43	0.68 $\pm$ 0.48	0.380	0.18
Bilateral asymmetry	0.22 $\pm$ 0.43	0.17 $\pm$ 0.38	0.630	0.10

Note. Data expressed as mean $\pm$ SD. Cohen's d : small ≥ 0.20 , medium ≥ 0.50 , large ≥ 0.80 . * $p < 0.05$.

3.4. Logistic Regression Analysis

Multivariate logistic regression identified dynamic knee valgus (OR = 2.84; 95% CI: 1.32–6.12; $p = 0.008$) and trunk control deficit (OR = 2.17; 95% CI: 1.08–4.36; $p = 0.030$) as independent predictors of injury. The composite LESS_TOTAL score also remained significant (OR = 1.31; 95% CI: 1.05–1.72; $p = 0.010$), indicating a 31% increase in injury odds per unit increase. VIF values were below 1.40 for all predictors, confirming the absence of problematic multicollinearity. Model fit was acceptable (Nagelkerke $R^2 = 0.31$; Hosmer–Lemeshow $p > 0.05$). Results are presented in Table 3.

Table 3. Binary logistic regression: independent predictors of injury risk.

Variable	β	OR (95% CI)	p -Value	VIF
Dynamic knee valgus	1.04	2.84 (1.32–6.12)	0.008	1.21
Trunk control deficit	0.77	2.17 (1.08–4.36)	0.030	1.18
LESS_TOTAL (composite)	0.27	1.31 (1.05–1.72)	0.010	1.34

Note. β = unstandardised regression coefficient; OR = odds ratio; CI = confidence interval; VIF = variance inflation factor. Reference: score = 0 (optimal execution).

3.5. Model Discrimination and ROC Analysis

ROC curve analysis indicated acceptable discriminative ability (AUC = 0.74; 95% CI: 0.62–0.86). At the optimal Youden Index threshold, sensitivity was 0.72 and specificity 0.67. The NPV of 0.85 indicates that a low-risk classification correctly excluded injury in approximately 85% of cases. Full model performance statistics are presented in Table 4 (see also Figure 1).

Table 4. Logistic regression model performance statistics from ROC curve analysis.

Performance Metric	Value (95% CI)
AUC	0.74 (0.62–0.86)
Sensitivity	0.72
Specificity	0.67
Positive Predictive Value (PPV)	0.48
Negative Predictive Value (NPV)	0.85
Nagelkerke R^2	0.31
Hosmer–Lemeshow test (p)	>0.05

Note. AUC = area under the curve; PPV = positive predictive value; NPV = negative predictive value. Optimal threshold determined using the Youden Index.

3.6. Decision Tree Analysis

The CART model identified a hierarchical structure of movement-based injury risk. Dynamic knee valgus emerged as the primary discriminating node, followed by trunk control as the secondary node. Three functionally distinct movement profiles were identified:

1. Low risk: absence of dynamic knee valgus (predicted injury probability < 0.15);
2. Moderate risk: presence of knee valgus without concurrent trunk control deficit (predicted injury probability: 0.15–0.40);
3. High risk: combined presence of dynamic knee valgus and trunk control deficit (predicted injury probability > 0.40).

The distribution of injury cases across these three profiles was consistent with the multivariate logistic regression findings, with the proportion of injured players progressively increasing from the low-risk to the high-risk group (Figure 2).

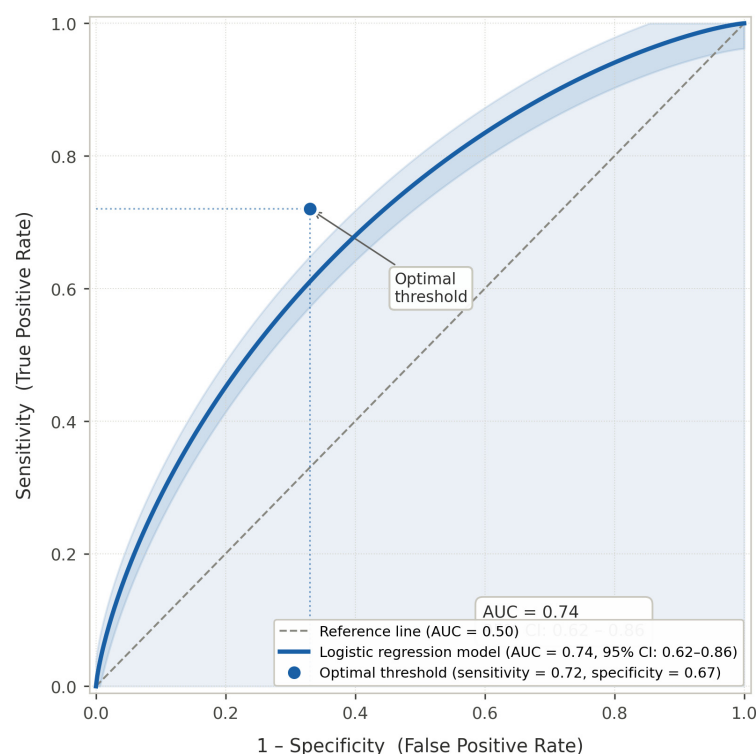


Figure 1. Receiver operating characteristic (ROC) curve for the logistic regression model. AUC = 0.74 (95% CI: 0.62–0.86). The dashed diagonal line represents chance-level discrimination (AUC = 0.50). The filled circle indicates the optimal threshold determined by the Youden Index (sensitivity = 0.72; specificity = 0.67).

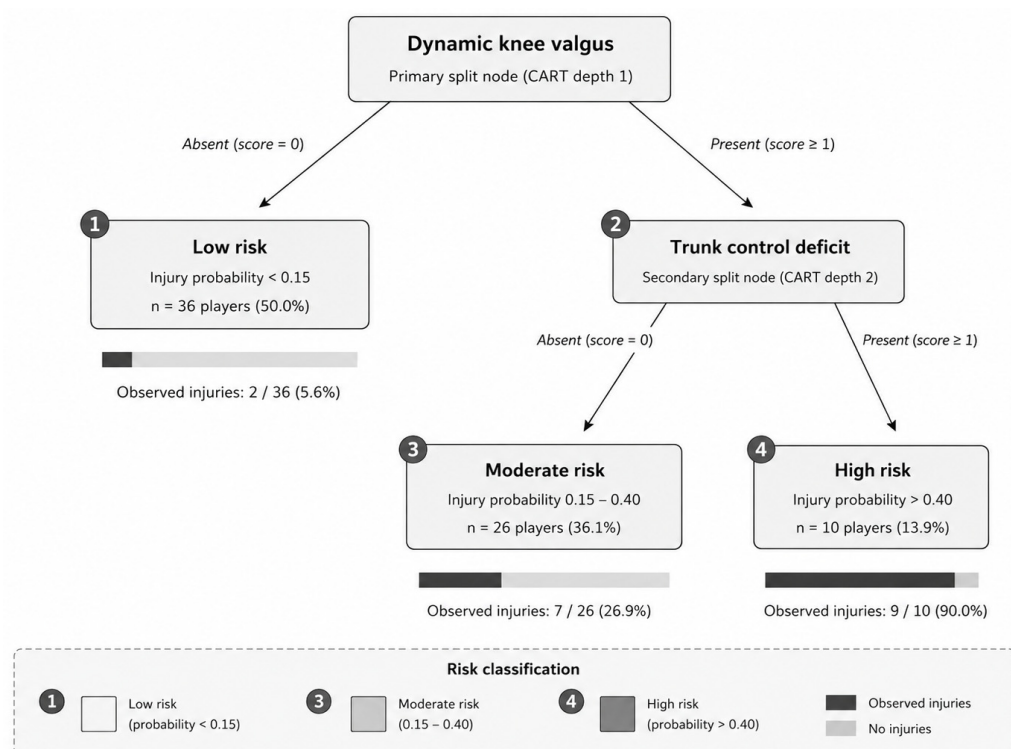


Figure 2. Decision tree (CART model) illustrating the hierarchical classification of injury risk based on DJ movement pattern deficits. Dynamic knee valgus functions as the primary discriminating node, with trunk control deficit as the secondary node. Three risk profiles are identified: low risk (predicted probability < 0.15), moderate risk (0.15–0.40), and high risk (>0.40). Numbers within terminal nodes indicate observed injury rates.

As illustrated in Figure 2, the CART analysis identified a hierarchical structure of movement-related injury risk. Dynamic knee valgus emerged as the primary discriminating factor, while trunk control deficits further stratified players presenting knee valgus into moderate- and high-risk profiles. Notably, the subgroup exhibiting both dynamic knee valgus and impaired trunk control represented only 13.9% of the cohort but accounted for 50% of all injuries recorded during the follow-up period (9 of 18 injuries). These findings suggest that injury risk is better explained by the hierarchical interaction of movement deficits than by isolated movement abnormalities, highlighting a distinct neuromuscular risk profile associated with non-contact lower-limb injury.

4. Discussion

4.1. Principal Findings

The present study investigated the association between movement-pattern deficits during drop jump (DJ) tasks and injury risk in football players using a LESS-based observational screening approach. The principal findings indicate that dynamic knee valgus and trunk control deficits emerged as the primary independent predictors of injury occurrence. Furthermore, the interaction between these movement deficits identified distinct hierarchical movement-risk profiles, suggesting that injury susceptibility may be more accurately characterised through movement-pattern profiling rather than through global movement-error scores alone.

Importantly, although the composite LESS_TOTAL score demonstrated significant associations with injury risk, individual movement variables provided greater explanatory and clinical value [28,29]. These findings support the concept that injury risk is not exclusively determined by the accumulation of movement errors, but rather by the functional interaction and neuromuscular organisation of specific movement deficits within the kinetic chain [16].

4.2. Dynamic Knee Valgus as a Primary Neuromuscular Risk Factor

Dynamic knee valgus emerged as the strongest movement-related predictor of injury in the present cohort. This finding is consistent with previous research identifying altered frontal-plane knee mechanics as a key biomechanical factor associated with increased lower-limb injury risk, particularly in relation to non-contact anterior cruciate ligament (ACL) injuries [8,14].

From a biomechanical perspective, dynamic knee valgus represents a multi-segmental movement dysfunction involving altered hip control, excessive femoral internal rotation, knee abduction, and impaired force attenuation strategies during landing and deceleration tasks [29,30]. Such movement behaviour may increase medial knee loading and compromise the ability to efficiently dissipate ground reaction forces during high-demand sporting actions [22,31].

Beyond local knee mechanics, valgus-related movement patterns likely reflect broader neuromuscular deficits involving sensorimotor control, intermuscular coordination, and force-transfer efficiency throughout the lower-extremity kinetic chain. Consequently, the presence of dynamic knee valgus may represent an externally observable manifestation of underlying neuromuscular dysfunction rather than an isolated biomechanical error.

4.3. Trunk Control and Proximal Stability

Trunk control deficits also demonstrated independent associations with injury occurrence, reinforcing the importance of proximal neuromuscular stability in the regulation of lower-limb mechanics. Previous investigations have shown that impaired trunk con-

trol may alter centre-of-mass positioning, increase frontal-plane loading, and amplify mechanical stress at distal joints during dynamic tasks [19,32].

The findings of the present study suggest that trunk control should not be interpreted solely as a postural variable, but rather as a central component of dynamic movement regulation. Deficient trunk stability may impair force transmission between the trunk and lower extremities, alter landing coordination strategies, and reduce the capacity to maintain optimal alignment under rapid eccentric loading conditions [33].

Importantly, the interaction observed between trunk control deficits and dynamic knee valgus supports the concept of proximal-to-distal neuromuscular coupling within the kinetic chain. Athletes exhibiting combined deficits demonstrated substantially greater injury probability than those presenting isolated movement alterations, indicating that movement dysfunction may emerge through synergistic interactions between proximal and distal control mechanisms [34,35].

4.4. From Composite Scores to Movement-Pattern Profiling

A major contribution of the present study lies in the transition from traditional score-based movement screening toward movement-pattern profiling. Although composite scoring systems such as the LESS provide practical information regarding overall movement quality, global scores may obscure important biomechanical interactions and neuromuscular strategies underlying injury susceptibility.

Athletes presenting similar composite scores may demonstrate markedly different movement organisations, resulting in substantially different risk profiles despite comparable total values [36]. In this context, movement-pattern profiling may offer superior ecological validity and greater mechanistic interpretability compared with reductionist scoring approaches.

The present findings support the idea that injury risk may be better conceptualised as a neuromuscular phenotype emerging from the interaction of multiple movement deficits rather than from isolated biomechanical variables. Specifically, the combined presence of dynamic knee valgus and trunk control impairment appears to represent a distinct high-risk movement phenotype associated with elevated injury probability.

4.5. Hierarchical Modelling and Clinical Interpretability

The Classification and Regression Tree (CART) analysis provided additional insight into the hierarchical structure of movement-related injury risk. Dynamic knee valgus emerged as the primary discriminating variable, whereas trunk control deficits functioned as a secondary modifier of injury probability. This hierarchical organisation suggests that certain movement deficits may possess greater discriminative importance within the overall movement system.

Unlike traditional linear models, decision-tree methodologies provide clinically interpretable threshold-based classifications that may facilitate implementation in applied environments. The identification of low-, moderate-, and high-risk movement profiles may assist practitioners in prioritising athletes for targeted neuromuscular interventions and individualised preventive strategies [28].

Furthermore, the CART-derived profiles reinforce the concept that injury risk emerges through non-linear interactions between movement variables. Such findings are consistent with contemporary complex-systems models of sports injury, which propose that injury occurrence results from the dynamic interaction of multiple biomechanical and neuromuscular constraints rather than from single isolated factors [5].

4.6. Neuromuscular Function and Force-Transmission Perspective

The present findings may also be interpreted from a force-transmission and neuromuscular function perspective. Efficient landing mechanics require coordinated modulation of eccentric force absorption, segmental stiffness regulation, and rapid neuromuscular adaptation during high-impact tasks. Altered movement patterns may therefore reflect deficiencies in force-time characteristics and neuromuscular control strategies rather than purely kinematic abnormalities [37,38].

In this regard, movement deficits such as dynamic knee valgus and impaired trunk control may represent observable indicators of altered neuromuscular force regulation, reduced eccentric control capacity, or impaired reactive stabilisation mechanisms [32,39]. This interpretation aligns with emerging approaches integrating movement screening with kinetic and neuromuscular assessment frameworks to better characterise athlete-specific injury-risk profiles.

The integration of observational movement analysis with force-based technologies, including functional electromechanical dynamometry and wearable sensor systems, may provide a more comprehensive understanding of the relationship between movement quality, force-production capabilities, and injury susceptibility [8].

Although the present findings support the relevance of movement-pattern deficits identified during the DJ task, injury risk should continue to be interpreted as a multifactorial phenomenon. It is plausible that the predictive capacity of the proposed model could be enhanced through the inclusion of additional neuromuscular and functional variables that were not assessed in the current investigation. In particular, measures of muscular strength, inter-limb force asymmetries, eccentric force-production capacity, rate of force development, and joint mobility or range of motion may provide complementary information regarding an athlete's ability to tolerate mechanical loads and maintain movement efficiency during high-demand sporting actions. As demonstrated in previous research, deficits in strength capacity and mobility can influence movement mechanics, alter force-transmission strategies, and contribute to increased injury susceptibility in athletic populations [33,35,40]. Consequently, although movement-pattern profiling appears to offer valuable insight into injury risk, integrating these movement-based observations with physical-performance and musculoskeletal-function assessments may provide a more comprehensive and reliable framework for estimating injury vulnerability in football players.

Furthermore, it is imperative to recognize that the risk of injury is not a static characteristic, but rather a dynamic process that may evolve throughout the competitive season as a consequence of changes in training load, competitive exposure, accumulated fatigue, physical adaptations, recovery status, and previous injury occurrence [5,41]. Consequently, movement patterns assessed during the pre-season may also be subject to modification over time. Although repeated biomechanical evaluations during the season could potentially improve understanding of temporal changes in injury-risk profiles, the methodological approach adopted in the present study is consistent with numerous prospective investigations in sports injury research. Several authors have successfully employed baseline assessments conducted during the pre-season to investigate subsequent injury occurrence over the course of an entire competitive season [42–45]. This includes studies based on functional movement screening, strength-related risk factors, and multivariable injury prediction models in football players. Nevertheless, the absence of repeated in-season assessments should be recognised as a limitation of the present investigation, as it may have restricted the researchers' ability to identify potential changes in movement quality and neuromuscular control throughout the season. It is suggested that future longitudinal studies incorporating periodic biomechanical monitoring may assist in determining

whether alterations in movement-pattern characteristics offer additional predictive value beyond baseline screening assessments.

4.7. Model Performance and Applied Relevance

The logistic regression model demonstrated acceptable discriminative capacity ($AUC = 0.74$), which is consistent with the expected predictive performance of multifactorial injury-screening tools in applied sport settings. Although injury prediction in complex sporting environments remains inherently challenging, the relatively high negative predictive value observed in the present study suggests that the proposed model may be particularly useful for identifying low-risk athletes.

From an applied perspective, the observational approach utilised in this investigation offers several practical advantages. The methodology is low-cost, scalable, time-efficient, and feasible within routine football-performance environments without requiring advanced laboratory equipment. Consequently, movement-pattern screening during DJ tasks may represent a valuable addition to multidisciplinary injury-prevention frameworks in football.

The present findings further support the prioritisation of dynamic knee valgus and trunk control assessment during routine screening procedures. Athletes demonstrating combined deficits may benefit from targeted neuromuscular interventions focused on proximal stability, frontal-plane control, landing mechanics, and eccentric force-management strategies.

5. Limitations

Several limitations should be acknowledged when interpreting the present findings. First, the observational nature of the movement assessment introduces a degree of subjectivity despite the use of standardised protocols and high inter-rater reliability. Second, although the sample size met the requirements established by the a priori power analysis, a larger cohort may have further increased the statistical power of the analyses and enhanced the generalizability of the findings. Nevertheless, the present study was conducted exclusively in professional football players competing in the Spanish First and Second Divisions, a population that is inherently difficult to access for prospective research. Therefore, we consider that the present sample represents a substantial cohort within this highly specific context and provides valuable prospective evidence from an elite football population. Third, the absence of three-dimensional biomechanical, kinetic, electromyographic, or force-platform data limits the ability to fully characterise the neuromuscular mechanisms underlying the observed movement deficits. Fourth, injury surveillance was conducted across a single competitive season, potentially limiting the assessment of long-term injury-risk dynamics.

Furthermore, the quality of movement was evaluated on a single occasion only during the pre-season period. Given that neuromuscular characteristics and movement strategies may change throughout the competitive season, the absence of repeated assessments prevented the evaluation of temporal fluctuations in movement-pattern deficits and their potential influence on injury risk.

Additionally, the CART model may remain partially susceptible to overfitting despite the use of cross-validation procedures. Finally, as with all observational cohort studies, causality cannot be inferred, and injury occurrence should continue to be interpreted within a multifactorial framework involving biomechanical, physiological, psychological, and contextual determinants.

6. Future Research Directions

Future research should aim to validate these findings in larger and more diverse cohorts across multiple competitive levels and over extended observation periods. A key

direction involves the integration of kinematic and kinetic data to enhance the understanding of neuromuscular deficits associated with injury risk.

While the present study focused on observational movement assessment, future work should incorporate force-related variables obtained through dynamometry-based systems. The combination of kinematic variables, such as joint alignment and segmental control, with kinetic parameters, including force production, rate of force development, and asymmetries, may provide deeper insight into the mechanisms underlying movement dysfunction. The use of functional electromechanical dynamometry represents a particularly promising avenue for capturing real-time force-time characteristics and linking kinetic outputs with movement pattern analysis.

In addition, it is recommended that subsequent research endeavours involve the incorporation of movement-pattern analysis with concomitant variables pertaining to musculoskeletal function and physical performance. These variables should encompass strength characteristics, inter-limb asymmetries, eccentric force capabilities, and mobility assessments. The rationale for this approach is rooted in the growing recognition that isolated movement screening may not fully capture the complexity of injury risk. In contrast, multidimensional models incorporating both movement quality and physical-function indicators have the potential to enhance risk classification and athlete profiling. Indeed, motivated by the limitations identified in the current study and the absence of a definitive solution within the extant literature, our research group has recently initiated a longitudinal investigation aimed at integrating movement-pattern variables with strength- and mobility-related measures. It is anticipated that this research will contribute to the development of more robust and clinically meaningful models for injury-risk assessment and prevention in football players.

Furthermore, the integration of movement screening with wearable technologies, such as inertial measurement units (IMUs), may allow continuous monitoring of movement quality in ecologically valid settings, supporting a transition from single-point screening toward longitudinal profiling. Combining these data within multivariate and machine learning frameworks may enhance predictive accuracy and contribute to the development of advanced decision-support systems for injury prevention.

7. Conclusions

The present study demonstrates that movement-pattern deficits during DJ tasks are associated with injury risk in football players and supports the use of movement-pattern profiling as a clinically interpretable approach for injury-risk stratification. Dynamic knee valgus and trunk control deficits emerged as the primary independent predictors of injury occurrence, highlighting the importance of both distal joint mechanics and proximal neuromuscular stability within the kinetic chain.

Importantly, the findings indicate that injury susceptibility may not be adequately explained through global movement-error scores alone, but rather through the hierarchical interaction and functional integration of specific neuromuscular deficits. The identification of distinct movement-risk phenotypes through CART analysis reinforces the relevance of non-linear and systems-based approaches to injury-risk assessment.

From an applied perspective, DJ-based observational screening provides a scalable and low-cost strategy for identifying athletes potentially at increased injury risk, thereby supporting the implementation of more targeted and individualised preventive interventions. Collectively, these findings contribute to the evolving paradigm shift from isolated movement-error identification toward integrated neuromuscular movement-pattern profiling in football injury prevention.

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