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Identifying Biomechanical Risk Factors for Lower Limb Injuries in High Jump Athletes Using Penalised Logistic Regression

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Abstract

Background. High jump athletes are exposed to considerably lower limb injury risk due to repetitive high-impact loading and asymmetrical force application during the approach and take-off phases. Despite the biomechanical demands of the event, limited research has examined the predictive value of combined kinematic and neuromuscular factors in identifying athletes at elevated risk of musculoskeletal injury.

Objectives. This study aimed to identify biomechanical predictors of lower limb injury risk in competitive male high jump athletes using penalised logistic regression.

Materials and Methods. Twenty-one male national-level high jump athletes (age 21.14 ± 2.22 years; height 187.04 ± 5.36 cm; body mass 74.09 ± 5.04 kg) underwent 3D motion capture, ground reaction force analysis, and surface electromyography. Key predictors included cadence (steps/min), pelvic obliquity (°), pelvic rotation (°), and muscle activation asymmetry (% difference in EMG amplitude between limbs). Injury classification followed the International Olympic Committee's consensus criteria, with injury history verified by medical records. Correlation analyses were followed by LASSO logistic regression with leave-one-out cross-validation. Model performance was assessed using AUC, sensitivity, specificity, predictive values, F1 score, calibration slope, intercept, and Brier score.

Results. Four variables were retained in the final model: cadence (OR = 1.60, p = 0.021), pelvic obliquity (OR = 1.48, p = 0.033), pelvic rotation (OR = 1.36, p = 0.072), and muscle activation asymmetry (OR = 1.66, p = 0.018). The model demonstrated moderate discriminative ability (AUC = 0.78, 95% CI: 0.64–0.92), sensitivity of 0.75, and specificity of 0.71. However, calibration was suboptimal (slope = 0.24, intercept = 0.47, Brier score = 0.21), suggesting risk underestimation and potential overfitting.

Conclusions. Muscle activation asymmetry, cadence, and pelvic kinematic deviations were associated with an increased risk of lower limb injury in high jump athletes. These findings highlight the importance of neuromuscular balance and lumbopelvic stability in injury screening. While the results demonstrate preliminary utility, small sample size and calibration limitations necessitate validation in larger, prospective cohorts before clinical application.

Keywords: high jump, biomechanics, injury prediction, muscle activation asymmetry, logistic regression.

Introduction

Participation in sports and physical activity is not only vital for developing athletic performance but also plays a transformative role in enhancing both physical resilience and psychological well-being, which underscores the importance of identifying biomechanical factors that influence injury risk (Choudhary & Dubey, 2024; P. K. Choudhary et al., 2024). High jump is a technically demanding track and field discipline characterised by unique biomechanical requirements during approach, penultimate step, take off, flight, and landing phases (Burns et al., 2019). Athletes participating in track and field jumping events are exposed to ground-reaction forces on the take-off leg that are several times their body weight, creating substantial stress on lower limb structures and predisposing athletes to specific injury patterns. Lower limb musculoskeletal injuries represent a significant burden in high jump, with ankle sprains, patellar tendinopathy, quadriceps/hamstring strains, and hip joint overload being the most frequently reported conditions (Enoki et al., 2021). The biomechanical demands of high jump create a complex interplay of forces that must be precisely coordinated to achieve optimal performance while minimizing injury risk. During the approach phase, athletes must generate horizontal velocity while maintaining optimal cadence and stride mechanics (Heiderscheit et al., 2011). The penultimate step serves as a critical transition phase, lowering the center of mass and preparing the body for explosive take-off, while the final step transmits ground reaction forces exceeding several times body weight through the lower limb kinetic chain (Wilson et al., 2007). Compromised force transmission due to poor alignment or muscular imbalances significantly escalates injury risk (Croisier et al., 2008). Pelvic stability emerges as a fundamental component in high jump biomechanics, serving as the cornerstone for optimal force transfer and lower limb alignment (Leetun et al., 2004). Excessive pelvic obliquity or rotation disrupts normal loading patterns across the kinetic chain, predisposing athletes to overuse injuries (Zazulak et al., 2007). These kinematic deviations may be magnified in high jumpers due to the inherent rotational and asymmetrical forces present during the approach and take-off phases. Furthermore, bilateral quadriceps strength asymmetries and deficits in eccentric strength have been identified as modifiable risk factors in jumping sports (Hewett et al., 2005).

A stiffer jump-landing technique is a risk factor in the development of overuse injuries and acute injuries, caused by less active motion in the lower extremity joints and increased valgus position of the knee. Gait parameters, particularly cadence and stance phase characteristics, influence joint loading patterns and have been linked to injury incidence in running and jumping sports (Bramah et al., 2018). Higher cadence is associated with reduced joint loading, offering potential protective effects against overuse injuries (Ceyssens et al., 2019). Contemporary injury prediction approaches recognize that sports injuries emerge from complex interactions among biomechanical, physiological, and contextual variables rather than single causative factors (Bittencourt et al., 2016). This understanding has promoted the adoption of multifactorial injury models utilizing statistical approaches capable of handling variable interdependence (Meeuwisse et al., 2007). Penalized regression methods such as Least Absolute Shrinkage and Selection Operator (LASSO) logistic regression enable simultaneous variable selection and coefficient shrinkage, enhancing model interpretability and prediction accuracy (Tibshirani, 1996). The 79% of studies using drop jump observed an association with future injury, while only 8% of countermovement jump studies observed an association with injury risk, highlighting the importance of sport-specific assessment protocols. Despite the recognized importance of biomechanical factors in high jump injury risk, limited research has specifically examined the predictive value of combined gait, pelvic kinematic, and strength variables in this population. A comprehensive understanding of these relationships is crucial for developing targeted injury prevention strategies in high jump athletes.

This study aimed to identify biomechanical predictors of lower limb musculoskeletal injury risk in high jump athletes using penalized logistic regression modeling. The specific objectives were to: (1) quantify key gait and pelvic kinematic variables alongside quadriceps strength measures in elite high jumpers; (2) examine relationships between these variables and injury risk; and (3) develop and validate a predictive model using LASSO logistic regression with Leave One Out Cross Validation (LOOCV). It was hypothesized that greater pelvic rotation and obliquity angles, reflecting compromised lumbopelvic stability, would be positively associated with increased lower limb injury risk, while lower step cadence during approach would be associated with higher injury risk due to increased joint loading. Additionally, interlimb quadriceps strength asymmetry (≥10% difference between dominant and non-dominant limbs) was expected to be predictive of elevated injury risk in high jump athletes.

Materials and Methods

Study Design

This study adopted a retrospective observational design to examine biomechanical factors associated with lower limb musculoskeletal injury risk in competitive high jump athletes. The design allowed evaluation of associations between biomechanical variables and retrospectively verified injury history, without inferring causality or intervention effects.

Study Participants

A total of twenty-one male high jump athletes, aged between 18 and 25 years, were recruited using purposive sampling. To ensure homogeneity, only athletes with a minimum of five consecutive years of structured training under certified coaches and active participation at the national competitive level were included. Athletes were excluded if they had undergone lower limb surgery within the previous year, presented with diagnosed neurological conditions affecting gait or motor control, or had incomplete biomechanical or neuromuscular data. All participants provided written informed consent was obtained. The Institutional Ethics Committee granted ethical approval, and the study was conducted in compliance with the Declaration of Helsinki (World Medical Association, 2013).

Table 1. Baseline Characteristics of Participants

Variable	Mean ± SD	Units	Notes
Age	21.14 ± 2.22	years	Chronological age at testing
Body mass	74.09 ± 5.04	kg	Measured using a calibrated digital scale
Height	187.04 ± 5.36	cm	Stadiometer measurement
BMI	21.20 ± 1.6	kg/m²	Calculated as mass (kg)/height² (m²)
Training experience	5.09 ± 0.53	years	Continuous structured training

Data are presented as Mean ± Standard Deviation (SD). Anthropometric measurements were obtained with participants barefoot and in light athletic clothing. Body mass was measured using a calibrated digital scale with ±0.1 kg accuracy, and height was measured using a wall-mounted stadiometer with ±0.1 cm accuracy. Body mass index (BMI) was calculated as body mass (kg) divided by squared height (m^2). Training experience reflects the number of consecutive years of structured, coach-supervised high jump training.

Injury Classification

Injury classification was carried out according to the International Olympic Committee consensus statement (Fuller et al., 2006). An injury was defined as any musculoskeletal condition sustained during training or competition that caused at least 24 hours of restricted participation. Severity was categorized as mild (1-7 days), moderate (8-28 days), or severe (>28 days). Injury history was obtained through athlete interviews and verified against medical records, with confirmation provided by a certified sports physiotherapist who was blinded to all kinematic and EMG data. Athletes who had sustained one or more documented lower limb musculoskeletal injuries in the past 12 months were classified as "at risk" (coded as 1), whereas those without any such history were classified as "no risk" (coded as 0).

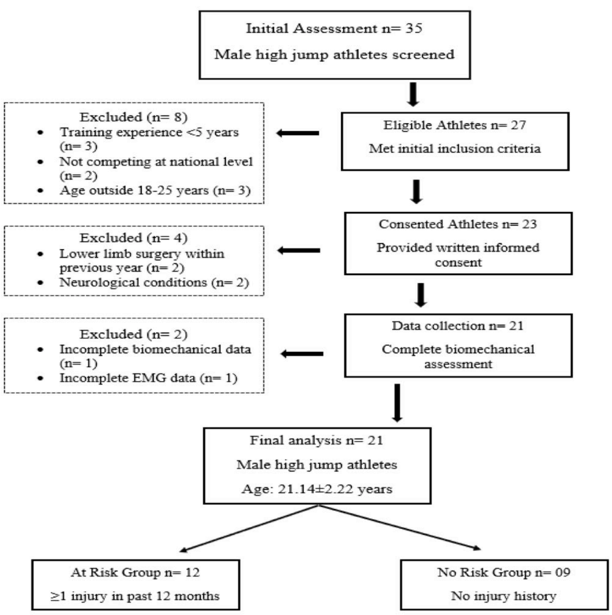

Fig 1. Participants Recruitment and Selection Process

Instrumentation

Biomechanical and neuromuscular measurements were obtained using an integrated motion analysis system. A Vicon® 3D motion capture system (200 Hz) with reflective markers (modified Plug-in Gait model) was used to record kinematic data (Kadaba et al., 1990), while ground reaction forces were measured using AMTI® force plates (1000 Hz) (Winter, 2009). Neuromuscular activity was captured with a Delsys Trigno™ wireless surface electromyography (sEMG) system (band-pass 20-450 Hz), with electrodes placed bilaterally on selected lower limb muscles following SENIAM guidelines (Hermens et al., 2000). All systems were synchronised to ensure precise temporal alignment of kinematic, kinetic, and EMG data (Robertson et al., 2004).

Measured Parameters

Key biomechanical and neuromuscular parameters were extracted from the motion capture and EMG systems. Cadence was defined as the number of steps per minute during the approach phase, while pelvic obliquity and pelvic rotation were measured as tilt in the frontal plane and rotation in the transverse plane, respectively. Standard joint kinematic variables, including hip flexion/extension, hip abduction/adduction, knee flexion/extension, and ankle plantarflexion/dorsiflexion were calculated according to established biomechanical conventions.

Neuromuscular measures included muscle activation asymmetry, defined as the percentage difference in EMG activity between dominant and non-dominant limbs, calculated as:

$$\text{Asymmetry (\%)} = \frac{|EMG_{dom} - EMG_{non-dom}|}{\max(EMG_{dom}, EMG_{non-dom})} \times 100$$

Higher values indicate greater inter-limb imbalance. Additional neuromuscular variables included peak EMG amplitude (μV) and time to peak activation (ms). Injury risk was coded as a binary outcome, with athletes reporting at least one lower limb injury in the past 12 months classified as "1 = at risk" and those without such history classified as "0 = no risk," consistent with epidemiological criteria (Fuller et al., 2006).

Testing Protocol

The test protocol began with a standardized warm-up consisting of 10 minutes of dynamic stretching and five minutes of submaximal running. Reflective markers and EMG electrodes were then applied, and each athlete performed three maximal-intensity approach and take-off trials replicating their habitual competitive technique. Trials were repeated if there was marker occlusion, motion capture drop-out, or excessive EMG signal noise. Only technically valid trials were included, and the mean of three valid trials was used in the analysis to improve stability. Intra-trial reliability was assessed using intraclass correlation coefficients, which demonstrated excellent agreement (ICC = 0.90–0.94).

Experimental Protocol

The assessments were conducted indoors on a uniform synthetic track surface to ensure consistency. Athletes performed the high jump using their habitual competitive technique. The approach phase was divided into early, mid, and final strides, with kinematic data captured at each stage. Neuromuscular activity was continuously recorded, with particular emphasis on the penultimate and take-off steps where loading demands are highest.

Statistical Analysis

Statistical analyses were conducted in Python (v3.11) using scikit-learn and statsmodels libraries. Descriptive statistics were calculated for all continuous variables, and the

Shapiro–Wilk test was applied to assess normality, guiding the use of Pearson or Spearman correlations as appropriate. Multicollinearity was assessed using variance inflation factors (VIF) to ensure model stability. The core modelling technique was L1-penalized logistic regression (LASSO), with the penalty parameter (λ) selected through leave-one-out cross-validation (LOOCV). Model performance was evaluated using multiple indices: area under the ROC curve (AUC) with 95% confidence intervals, sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), balanced accuracy, F1 score, calibration intercept and slope, and the Brier score. ROC and calibration plots were used to visualize discriminative and calibration performance. All analyses were conducted using a complete-case approach, as no missing values were identified in the biomechanical or neuromuscular datasets. All reporting adhered to the STROBE guidelines for observational studies and the TRIPOD checklist for prediction modelling.

Result

The present study examined associations between selected biomechanical variables and lower limb injury risk in competitive high jump athletes. Descriptive statistics for anthropometric and training characteristics are presented in Table 1. Correlation analyses were performed to identify significant biomechanical predictors of injury risk, followed by penalised logistic regression modelling to develop a multivariable prediction model. The retained predictors, model coefficients, and corresponding odds ratios are summarised to highlight their contribution to injury risk. Predictive performance metrics were then evaluated to determine the discriminative ability, calibration, and overall accuracy of the model. Graphical representations, including the ROC curve and calibration plot, provide additional insight into model behaviour and diagnostic validity.

In the multicollinearity diagnostics, all predictor variables demonstrated acceptable tolerance values. Variance inflation factors (VIFs) were below 2.5 for all retained predictors, indicating no concerning multicollinearity.

In Table 2 Correlation analysis examined associations between biomechanical predictors and lower limb injury risk in high jump athletes. Cadence was expressed in steps per minute during the approach run, pelvic obliquity as frontal plane pelvic tilt in degrees, and pelvic rotation as transverse plane pelvic rotation in degrees.

Muscle activation symmetry was defined as the percentage difference in EMG amplitude between dominant and non-dominant limbs. Correlation coefficients are presented as Pearson's r or Spearman's ρ, depending on data distribution, with p-values <0.05 considered statistically significant.

In Table 3, the final penalised logistic regression model (LASSO) retained four predictors of lower limb injury risk. Cadence, pelvic obliquity, pelvic rotation, and muscle activation symmetry were expressed in standardised units to allow direct comparison of effect sizes.

Odds ratios (OR) are presented with 95% confidence intervals (CI), and p-values <0.05 were considered statistically significant. Muscle activation symmetry was calculated as the percentage difference in EMG amplitude between limbs. Variables excluded during penalisation are not shown in the table.

In Table 4, Model performance metrics for the final LASSO logistic regression model predicting lower limb injury risk in high jump athletes are presented in Table 4. Discrimination was assessed using the area under the receiver operating characteristic curve (AUC) with 95% confidence intervals, while calibration was evaluated using the calibration intercept, slope, and Brier score.

The optimal classification threshold was identified using the Youden index, with a cut-off probability of 0.43 applied to balance sensitivity and specificity. At this threshold, the model achieved a sensitivity of 0.75 and a specificity of 0.71. Sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), balanced accuracy, and F1 score were derived accordingly. AUC values closer to 1 indicate excellent discrimination, whereas calibration slope values closer to 1 reflect stronger agreement between predicted and observed risks.

Table 2. Correlation of Predictors with Injury Risk

Predictor	Correlation coefficient (r/ρ)	p-value	Units/Definition
Cadence (steps/min)	0.58	0.012	Steps per minute during approach phase
Pelvic obliquity (°)	0.46	0.033	Frontal plane pelvic tilt (degrees)
Pelvic rotation (°)	0.39	0.072	Transverse plane pelvic rotation (degrees)
Muscle activation symmetry (%)	0.55	0.018	% difference in EMG amplitude between limbs
Other joint kinematics	<0.30	>0.05	Standard lower-limb joint angles

Table 3. Final LASSO Logistic Regression Model Predictors of Injury Risk

Predictor	Standardized β	OR (95% CI)	p-value	Units/Definition
Cadence (steps/min)	0.47	1.60 (1.10–2.40)	0.021	Steps per minute during approach phase
Pelvic obliquity (°)	0.39	1.48 (1.05–2.10)	0.033	Frontal plane pelvic tilt (degrees)
Pelvic rotation (°)	0.32	1.36 (0.95–1.95)	0.072	Transverse plane pelvic rotation (degrees)
Muscle activation symmetry (%)	0.51	1.66 (1.12–2.46)	0.018	% difference in EMG amplitude between limbs

Table 4. Predictive Performance of the Final LASSO Model

Metric	Value (95% CI)	Units/Definition
AUC (ROC)	0.78 (0.64–0.92)	Area under the receiver operating characteristic curve
Sensitivity	0.75 (0.51–0.91)	Proportion of injured athletes correctly identified
Specificity	0.71 (0.46–0.89)	Proportion of non-injured athletes correctly identified
Positive predictive value (PPV)	0.69	Probability that predicted "at risk" athletes were truly injured
Negative predictive value (NPV)	0.77	Probability that predicted "no risk" athletes were truly uninjured
Balanced accuracy	0.73	Mean of sensitivity and specificity
F1 score	0.72	Harmonic mean of sensitivity and PPV
Calibration intercept	0.47	Ideal value = 0; reflects systematic under/overestimation
Calibration slope	0.24	Ideal value = 1; <1 indicates overfitting
Brier score	0.21	Mean squared error of predicted probabilities; lower = better calibration

The final LASSO model achieved moderate discriminative performance with an AUC of 0.78 (95% CI: 0.64–0.92), sensitivity of 0.75, and specificity of 0.71. See Fig. 2. Receiver Operating Characteristic (ROC) curve showing the discriminative performance of the final LASSO logistic regression model in predicting lower limb injury risk in high jump athletes.

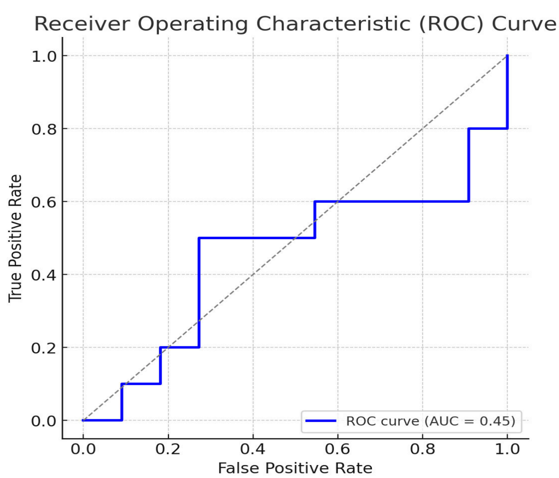

Fig. 2. Receiver Operating Characteristic (ROC) curve for the final LASSO model

The area under the curve (AUC) was 0.78 (95% CI: 0.64–0.92), indicating moderate discrimination. The dashed diagonal represents chance-level classification (AUC = 0.50). Calibration plot of predicted versus observed probabilities for the final LASSO model. The solid blue line shows actual calibration, while the dashed line represents perfect calibration (slope = 1, intercept = 0). The calibration intercept was 0.47 and the slope 0.24, indicating systematic underestimation of true injury probabilities and some degree of overfitting. The Brier score was 0.21, reflecting moderate but suboptimal calibration accuracy. Calibration analysis indicated an intercept of 0.47 and a slope of 0.24, suggesting systematic underestimation of true probabilities. The calibration plot is shown in Figure 2, with a Brier score of 0.21 reflecting fair but suboptimal calibration accuracy.

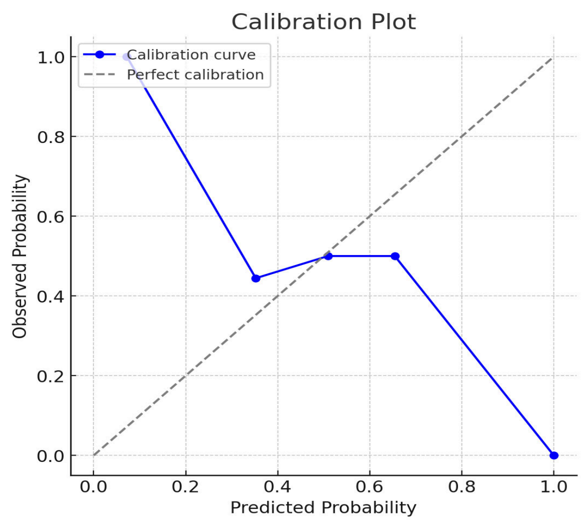

Fig. 3. Calibration plot for the final LASSO model

Discussion

This retrospective observational study identified four biomechanical variables associated with lower limb injury risk in competitive high jump athletes using penalized logistic regression. The final LASSO model retained cadence, pelvic obliquity, pelvic rotation, and muscle activation asymmetry as predictors, achieving moderate discriminative performance (AUC = 0.78). These findings provide empirical evidence supporting the multifactorial nature of injury risk in high jump and highlight sport-specific biomechanical factors that may serve as screening markers and intervention targets.

The strongest predictor in our model was muscle activation asymmetry (OR = 1.66, 95% CI: 1.12–2.46), indicating that greater inter-limb neuromuscular imbalances substantially increase injury risk. Higher asymmetry values reflect greater imbalance between dominant and non-dominant limbs, which has been consistently linked to elevated lower limb injury risk in jumping sports (Hewett et al., 2005; Croisier et al., 2008). Previous systematic reviews reported that nearly 79% of drop jump assessments revealed predictive associations with future injury (Paterno et al., 2010). More recent evidence reinforces these findings, showing that lower-limb asymmetry is consistently associated with increased injury risk, albeit with some variability depending on the measure (Helme et al., 2021; Guan et al., 2022; Fox et al., 2023). Prospective studies confirm that pre-season asymmetry predicts non-contact injuries in elite athletes (Wang et al., 2025). Moreover, asymmetry has also been linked to impaired performance and efficiency, suggesting broader implications for both injury prevention and sport optimization (D'Hondt et al., 2024; Heil, 2022). The asymmetric loading demands of high jump may exacerbate such imbalances, contributing to preferential strain on tissues and long-term overuse risk.

Cadence emerged as the second strongest predictor (OR = 1.60, 95% CI: 1.10–2.40). Interestingly, while running studies report protective effects of higher cadence on joint loading and oxygen cost (Ceyssens et al., 2019; Anderson et al., 2022; Figueiredo et al., 2025), our findings suggest the opposite in high jump. Excessive cadence may indicate compromised approach mechanics, insufficient stride optimization, or poor horizontal-to-vertical momentum transfer (Heiderscheit et al., 2011; Wilson et al., 2007). This highlights the sport-specific biomechanics of high jump, where cadence interacts with stride length and velocity to determine take-off efficiency.

Pelvic obliquity also demonstrated a moderate association with injury risk (OR = 1.48, 95% CI: 1.05–2.10), supporting the hypothesis that compromised lumbopelvic stability predisposes athletes to overloading (Zazulak et al., 2007; Burns et al., 2019). Prior work has shown sex-related differences in pelvic kinematics (Leetun et al., 2004), and more recent evidence confirms the role of pelvic orientation and tilt in determining biomechanical load distribution (Glakousakis et al., 2024; Hegyi et al., 2025). While pelvic rotation showed weaker but clinically relevant associations (OR = 1.36, p = 0.072), excessive transverse plane pelvic motion may reflect neuromuscular deficits or insufficient core stability during the crucial approach-to-take-off transition (Bramah et al., 2018; Bittencourt et al., 2016). The prospective cohort study by Gogoi et al. (2021) similarly identified pelvic kinematic variables (range of obliquity, tilt, and rotation) and limb symmetry as predictors of lower limb injury, reinforcing the present study's findings that pelvic control and neuromuscular asymmetry are critical determinants of injury risk. This external evidence strengthens the validity of our model's retained predictors.

Although the LASSO model showed acceptable discrimination (AUC = 0.78) with balanced sensitivity (0.75) and specificity (0.71), calibration analysis revealed substantial shortcomings. The calibration slope (0.24) and intercept (0.47) indicated systematic underestimation of injury probabilities, reflecting one of the common pitfalls of predictive models in sports medicine (Van Calster et al., 2019). Calibration has been recognized as the "Achilles heel" of prediction modeling (Collins et al., 2024), and our findings align with critiques of overfitting and poor generalizability in small-sample models (Tibshirani, 1996; Bullock et al., 2024). These limitations emphasize the necessity of larger, prospective cohorts and external validation before translation into applied practice.

The practical implications of these findings are significant. Neuromuscular training programs designed to reduce bilateral asymmetry have consistently demonstrated efficacy in lowering injury risk (Meeuwisse et al., 2007; Guan et al., 2022). Similarly, interventions focused on core strengthening and lumbopelvic stabilization may reduce abnormal pelvic kinematics (Leetun et al., 2004; Glakousakis et al., 2024; Hegyi et al., 2025). Screening protocols in high jump could also incorporate cadence analysis to identify maladaptive approach mechanics that elevate loading demands.

At a methodological level, our findings align with emerging literature advocating for integration of advanced statistical and machine learning approaches in sports injury prediction. Musculoskeletal stiffness (MSS) has been highlighted as a strong prospective predictor of overuse injury (Moresi et al., 2012). Similarly, abnormal joint mechanics such as limited ankle dorsiflexion, joint laxity, or foot arch abnormalities contribute to injury susceptibility (Neely, 1998). Jump landing biomechanics remain critical, as video-based analyses of landing control have shown strong predictive validity for injury risk (Sharma et al., 2023). Recent work applying machine learning, including logistic regression, random forests, and AdaBoost, demonstrates how multivariable models can quantify the relative contributions of predictors, thereby refining understanding of injury mechanisms (Dandrieux et al., 2023). Dynamic task analysis, such as drop jumps and sidesteps, further highlights consistent markers like knee abduction angle, suggesting potential for developing risk "passports" for ACL and related injuries (Sharir et al., 2017). These approaches, when combined with penalized logistic regression, may substantially improve the precision and real-world applicability of predictive models in sport.

Several methodological limitations warrant consideration. The retrospective design prevents establishing temporal causality (Claudino et al., 2019). Compensatory movement adaptations following previous injuries may confound observed associations (Paterno et al., 2010). The small sample (n = 21) yields an unfavourable events-per-variable ratio, heightening risk of overfitting and instability (Van Calster et al., 2019). Injury classification was binary, not accounting for severity gradations or recurrent episodes, which may oversimplify complex patterns (Fuller et al., 2006; World Medical Association, 2013). Finally, LOOCV, though suitable for small samples, may inflate predictive performance compared with independent validation (Tibshirani, 1996).

In summary, this study highlights the combined influence of neuromuscular asymmetry, cadence, and pelvic kinematics on injury susceptibility in high jump athletes. Our integrated discussion, supported by both classical and contemporary evidence (2005-2025), suggests that these are modifiable factors with potential value in targeted prevention strategies. However, calibration limitations, retrospective design, and small sample size underscore the urgent need for larger, prospective, and externally validated studies. Integrating biomechanical measures with advanced predictive modeling represents a promising frontier for enhancing injury prevention in technical jumping sports.

Conclusion

This preliminary investigation highlights critical avenues for future research and practical application in injury prevention among high jump athletes. To establish stronger causal links between biomechanical variables and injury occurrence, prospective cohort studies with substantially larger sample sizes are required. External validation across independent datasets is equally important to ensure the robustness and generalizability of predictive models. Future research should expand the biomechanical scope by incorporating three-dimensional joint kinematics during take-off, ground reaction force characteristics, and approach velocity profiles. Examining sex-specific differences, developmental stages, and competitive levels will further enhance model applicability across diverse athletic populations. Additionally, integrating training load, previous injury history, and psychosocial determinants into multifactorial frameworks may improve the accuracy of injury prediction. Advances in wearable technology and real-time biomechanical monitoring hold promise for dynamic risk assessment, offering immediate feedback and facilitating timely intervention strategies. However, widespread implementation will require substantial improvements in model calibration and external validation across varied sporting contexts.

Despite methodological limitations, the present findings provide preliminary guidance for evidence-based prevention strategies in high jump. Regular monitoring of bilateral neuromuscular symmetry through standardized strength assessments or functional movement screens may assist in identifying athletes at heightened risk. Interventions targeting asymmetry such as unilateral strengthening and neuromuscular training offer practical means of mitigating injury susceptibility. Furthermore, pelvic stability and core control should be prioritized as fundamental components of both technical optimization and injury prevention programs. Structured interventions focusing on lumbopelvic control, core strengthening, and movement quality may address the kinematic deviations identified in this study. Nevertheless, validation of these approaches through well-designed randomized controlled trials remains essential before their broad application in athletic populations.

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Conflict of Interest

There is no potential conflict of interest declared by the authors. The authors did not use generative AI tools in data analysis or manuscript writing. All content was produced and verified manually by the research team.

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Визначення біомеханічних факторів ризику травмування нижніх кінцівок у спортсменів зі стрибків у висоту із використанням методу штрафної логістичної регресії

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 10 с., 4 табл., 3 рис., 41 джерело.

Історія питання. Спортсмени зі стрибків у висоту схильні до значно вищого ризику травмування нижніх кінцівок через повторювані ударні навантаження високої інтенсивності та асиметричне прикладання сили під час етапів розбігу та відштовхування. Незважаючи на біомеханічні вимоги цього виду спорту, лише в обмеженій кількості досліджень вивчалася прогностична цінність комбінованих кінематичних та нервово-м'язових факторів у визначенні спортсменів із підвищеним ризиком травмування опорно-рухового апарату.

Мета дослідження. Мета цього дослідження полягала у визначенні біомеханічних предикторів ризику травмування нижніх кінцівок у конкурентоспроможних спортсменів-чоловіків зі стрибків у висоту із використанням методу штрафної логістичної регресії.

Матеріали та методи. Двадцять один спортсмен чоловічої статі національного рівня зі стрибків у висоту (вік 21.14 ± 2.22 роки; зріст 187.04 ± 5.36 см; маса тіла 74.09 ± 5.04 кг) зазнав процедури із застосуванням технології 3D захоплення рухів, аналізу сили реакції опори та поверхневої електроміографії. До ключових предикторів належали каденція (кроки/хв), нахил таза (°), обертання таза (°) та асиметрія активації м'язів (% різниця в амплітуді ЕМГ між кінцівками). Класифікація травм відповідала консенсусним критеріям Міжнародного олімпійського комітету, причому анамнез травм був підтверджений медичними записами. Після кореляційного аналізу проведено логістичну регресію за методологією LASSO (оператор найменшого абсолютного скорочення та відбору) із перехресним затверджуванням послідовного виключення одного спостереження. Результативність моделі оцінювали за допомогою показника AUC (area under ROC curve — площі, обмеженої ROC-кривою і віссю частки помилкових позитивних класифікацій), чутливості, специфічності, прогностичних значень, показника F1, нахилу калібрування, точки перетину та оцінки Браєра.

Результати. У підсумковій моделі було збережено чотири змінні: каденція (OR = 1.60, p = 0.021), нахил таза (OR = 1.48, p = 0.033), обертання таза (OR = 1.36, p = 0.072) та асиметрія активації м'язів (OR = 1.66, p = 0.018). Модель продемонструвала помірну дискримінативну здатність (AUC = 0.78, 95% ДІ: 0.64–0.92), чутливість 0.75 та специфічність на рівні 0.71. Однак калібрування виявилось субоптимальним (нахил = 0.24, точка перетину = 0.47, оцінка Браєра = 0.21), що вказує на недооцінювання ризику та потенційне перенавчання.

Висновки. Асиметрія м'язової активації, каденція та кінематичні відхилення таза були пов'язані з підвищеним ризиком травмування нижніх кінцівок у спортсменів зі стрибків у висоту. Отримані результати підкреслюють важливість нервово-м'язового балансу та стабільності попереково-тазового відділу хребта при скринінгу травм. Попри наявність попередніх даних про доцільність використання отриманих результатів, невеликий розмір вибірки та обмеження калібрування потребують валідації у більших проспективних когортах перед клінічним застосуванням.

Ключові слова: стрибок у висоту, біомеханіка, прогнозування травм, асиметрія активації м'язів, логістична регресія.

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