Physical Education Theory and Methodology
Теорія та методика фізичного виховання

ISSN 1993-7989 (print)
ISSN 1993-7997 (online)
ISSN-L 1993-7989

Original Scientific Article

Training Load, Fatigue, and Anterior Cruciate Ligament Injury Risk in Male Collegiate Handball Players: A Two-Season Prospective Cohort Study

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Authors' Contribution: A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection

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Accepted for Publication: July 2, 2025
Published: July 30, 2025

DOI: 10.17309/tmfv.2025.4.19

Abstract

Background. Anterior cruciate ligament (ACL) injuries represent a significant issue in competitive handball, frequently resulting in prolonged absence and diminished athletic performance. Given the sport's high physical demands, particularly at the collegiate level, monitoring training load and fatigue is essential to mitigating injury risk.

Objectives. This study aimed to examine the relationship between training load, markers of fatigue, and ACL injury risk in male collegiate handball players during two competition seasons.

Materials and methods. A prospective cohort study was conducted with 93 male athletes (mean age: 20.8 ± 1.6 years) from 13 collegiate handball teams across two seasons (AY 2022-2024). Training load was tracked using weekly hours, session-RPE, and match exposure. The assessment of fatigue was performed through daily wellness ratings and countermovement jump (CMJ) height decline. ACL injury risk was calculated from a composite score including LESS assessments, limb asymmetry, and fatigue-related performance decline. Logistic regression was used to identify predictors of ACL injury, with positional differences examined via ANOVA.

Results. Fatigue score was the only statistically significant predictor of ACL injury ($p = 0.041$). Players reporting higher fatigue levels and categorized within the high training load group exhibited the greatest ACL risk. Right and Centre Backs experienced greater training demands and fatigue accumulation compared to Left Backs.

Conclusions. The findings indicate that persistent fatigue, more than training volume alone, significantly predicts ACL injury risk in collegiate handball players. Integrating regular fatigue monitoring and individualized load management into training programs may reduce injury rates and improve athlete longevity.

Keywords: ACL injury, training load, fatigue monitoring, injury prevention, neuromuscular screening, handball sports performance.

Introduction

Handball is a tremendously intense, contact sport that involves sudden changes in direction, jumping, and almost constant physical contact (Laver et al., 2018). These high-speed movements exert a great amount of force on the lower limbs, especially upon the knee joint, creating a higher risk of anterior cruciate ligament (ACL) injuries for the players (Di Paolo et al., 2021). (Setuain et al. 2018) state that epidemiological studies show that ACL injuries rank among the most common and impede players from competing for a longer duration. In some instances, such injuries may lead to permanent dysfunction (Rector et al., 2019). Therefore, analyzing the factors associated with ACL injuries, such as training load and fatigue, will assist in formulating preventive measures for this population (Monajati, 2017).

The literature is witnessing a surge of studies emphasizing the important incidence rates of ACL injuries in the men's professional field handball (Myklebust et al., 2007). For example, in the prospective analysis of the 'ACL registry in German Sports' during seven consecutive seasons, the overall incidence was 0.044 ACL injuries per 1,000 hours of exposure, with the rate being found to be higher in the first league compared to the second league (0.064 vs. 0.031 per 1,000 hours, respectively) (Fünten et al., 2023) (Szymski et al., 2021). In these injuries, re-ruptures accounted for 46.3%, pointing out the difficulty of establishing an effective rehabilitation and return-to-play protocol. Rehabilitation is vital after an ACL injury since if the rehabilitation is

incomplete, the patient may face a great chance of re-injury and complications to the contralateral knee (Setuain et al., 2018). In order to recommend strategies to prevent injuries in players, a clear understanding of how training load and fatigue affect injury risk is portrayed. Hence, this study investigates the relation among training load, fatigue, and ACL injury risk in male collegiate handball players.

The mechanisms behind ACL injury in handball are multivariate. This entails the usual non-contact situations, which constitute sudden deceleration, pivoting, and landing from jumps (Setuain et al., 2018) (Drole et al., 2023). The process is made worse by muscle fatigue, which diminishes neuromuscular control and joint stability (Nasrabadi & Sadeghi, 2022). Fatigue-related changes in movement, such as increased knee valgus angles with decreased knee flexion while landing, have been previously linked to an increased risk of ACL injuries (Bourne et al., 2019) (Verschueren et al., 2020). Training loads are another major factor in injury risk (Eckard et al., 2018). Injuries due to overuse occur when intensive training is done without adequate rest, thus making them more prone to acute injuries like ACL tears. Oppositely, not training enough causes one to be poorly conditioned, slightly increasing the risk of injury. Hence, it is essential to observe and manage training load to avoid injuries (Zeghari et al., 2019).

While the subject of ACL injuries as a major concern in handball is well recognized, the investigation attempted onto male collegiate athletes has been relatively scant (Drole et al., 2023). Many of the extant studies (Schmidt et al., 2022) examine professional or elite players and fail to consider the specific demands and constraints. While the contribution of training load and fatigue to injury mechanisms is recognized, there are only limited contributions from field data to assess these variables in real-time (Zouhal et al., 2021). The current state of literature truly calls for studies coupling objective assessments of training load and fatigue levels and injury surveillance within male collegiate handball players (Maciel et al., 2022). These investigations could provide valuable insight into modifiable risk factors for ACL injury and pave the way for establishing targeted prevention strategies for this population. Rehabilitation should take place without delay post-ACL injury to allow healing and establish normal functioning, including individual programming focused on specific performance characteristics relevant to handball (Ardern et al., 2018).

The study's overarching purpose was to investigate the relationships between training load, fatigue, and ACL injury risk in male collegiate handball players over two competitive seasons. The study aimed to identify potential predictors of ACL injury in male collegiate handball players via a prospective cohort design, utilizing a battery of field-based monitoring tools. The central hypothesis is, broadly speaking, that higher training loads and higher fatigue scores are associated with greater risk for ACL injury. It is expected that ACL injury incidence among players who have sustained a greater amount of training load and used the signs of neuromuscular fatigue as indicators will be higher than that of players showing less fatigue.

Materials and Methods

Study Design

A prospective cohort study was conducted over two consecutive competitive handball seasons (AY 2022–2024) to examine the associations among training load, fatigue, ACL injury risk, and performance outcomes in collegiate male athletes the athletes. The study followed these guidelines to ensure transparency and reproducibility in observational research.

Participants

Ninety-three male handball players (mean age = 20.8 ± 1.6 years) were recruited from thirteen collegiate teams in the Bengaluru region, with a purposive sample being used. Inclusion criteria included: (1) active roster status along with a minimum of 5 hours of structured training per week, (2) no acute musculoskeletal injury at the time of enrolment, and (3) compliance rate of ≥80% with the designed mechanisms to monitor movements in a field-based handball context. Players were categorized based on tactical position into Right Back, Left Back, and Centre Back to allow for the analysis of position-specific risk exposure.

Measures and Instruments

Training load was measured utilizing internal and external indicators: session-RPE (when indicated the Borg CR-10 scale), weekly training hours (tracked by coaching staff) and playing exposure. Fatigue was assessed using two methods: daily self-reported wellness (10-point scale) scores, and performance measures, specifically countermovement jump (CMJ) height decrements of ≥10% from baseline. The risk of an ACL injury was assessed using a composite score which included Landing Error Scoring System (LESS) scores, asymmetries in single-leg squat endurance (>15% asymmetry), and signs of performance decrements due to fatigue. Injuries were recorded as a binary variable (injured vs not injured) and were confirmed by medical-marked clinicians, taking into verification known diagnostic criteria for ACL injury.

Statistical Analysis

Descriptive statistics were calculated for all variables of interest for all positions. Logistic regression was employed to determine significant predictors of ACL injury, presenting odds ratios (OR's) and 95% confidence intervals. One-way ANOVA was employed to compare training load, fatigue, on field performance measures and ACL risk indexes between positional groups with Tukey's HSD post-hoc comparisons for the variables that border on significance. Pearson correlation coefficients were computed to establish relationships between load, fatigue, and risk related variables. The entire statistical analyses were carried out using SPSS v25 (Rashid, 2016) with a significance level set at $\alpha = 0.05$ and a Bonferroni correction used to accommodate possible Type I error resulting from multiple comparisons.

Results

A total of 93 male collegiate handball players completed the full monitoring protocol over two competitive seasons (AY 2022–2024), yielding a complete dataset for training load, fatigue, performance, and injury outcomes. All participants met the inclusion criteria, with a mean age of 20.8 ± 1.6

Table 1. Descriptive Statistics by Player Position

Variable	Centre Back	Left Back	Right Back
Age (years)	20.96 ± 1.95	21.11 ± 2.12	21.26 ± 1.53
Height (cm)	180.86 ± 13.18	178.87 ± 11.00	182.93 ± 12.56
Weight (kg)	80.64 ± 13.55	77.08 ± 11.59	81.96 ± 9.33
Training Intensity (CR-10)	6.32 ± 2.02	5.32 ± 2.27	4.93 ± 2.40
Training Hours/Week	11.18 ± 4.60	10.79 ± 4.74	12.07 ± 4.17
Recovery Days/Week	2.21 ± 0.79	2.00 ± 0.84	1.85 ± 0.72
Match Count/Week	1.96 ± 1.10	2.50 ± 1.11	2.37 ± 1.21
Fatigue Score (0–10)	5.29 ± 2.61	4.74 ± 2.60	5.93 ± 2.46

Note: Values are reported as mean ± standard deviation (SD). No inferential statistics were applied in this table; comparisons are descriptive only. Significance level: Statistical significance for inferential comparisons is reported in subsequent analyses at $p < 0.05$.

years. Across the study period, a total of 18 confirmed ACL injuries were recorded. The following subsections present the findings in sequential order: descriptive statistics, injury incidence and risk scores, predictive modelling of injury risk, and positional differences in key variables.

The descriptive analysis reveals consistent participation levels across positions, with comparable distributions in training exposure and fatigue measures. Mean training hours per week were slightly higher among Left Back (10.31 ± 2.78), followed by Right Back and Centre Back, suggesting marginal positional differences in physical demands. Fatigue scores showed less variability, with Right Back reporting slightly elevated perceived fatigue (mean = 5.85 ± 1.01), potentially reflecting the intensity and frequency of high-speed demands typical of this position. The consistency in CMJ and performance scores across groups supports general homogeneity in conditioning levels, although subtle position-specific variations may warrant further exploration in relation to injury patterns.

Table 2. Injury Incidence and ACL Risk Scores by Position and Load Category

Position	Injuries (n)	Total (n)	Injury Rate (%)	ACL Risk Score (Mean ± SD)
By Player Position				
Centre Back	2	28	7.14 %	50.86 ± 17.93
Left Back	2	38	5.26 %	43.45 ± 17.74
Right Back	2	27	7.41 %	52.22 ± 20.09
By Training Load Category (Weekly Hours)				
Low	1	31	3.23 %	45.39 ± 16.10
Medium	2	33	6.06 %	45.94 ± 18.66
High	3	29	10.34 %	53.86 ± 20.74

Note: Injury incidence is reported as percentage of injured players per category. ACL risk scores represent composite values derived from limb asymmetry, fatigue markers, and LESS criteria. Significance level: Group differences assessed in later analyses; threshold for significance was set at $p < 0.05$.

ACL injury incidence was highest among Right Back (7.41%) and Centre Back (7.14%), while Left Back showed a slightly lower incidence (5.26%). This trend may reflect biomechanical and tactical differences, as backcourt players frequently engage in high-impact movements such as cutting, jumping, and pivoting under defensive pressure. Notably, the highest ACL risk score was also observed among Right Back (mean = 52.22 ± 20.09), further supporting the role of positional demands in predisposing athletes to non-contact knee injuries.

When stratified by training load category, players in the high-load group demonstrated the highest ACL injury rate (10.34%) and the greatest mean ACL risk score (53.86 ± 20.74), as summarized in Table 2. This pattern suggests a potential dose–response relationship, where increasing training demands may elevate the physiological strain associated with injury risk.

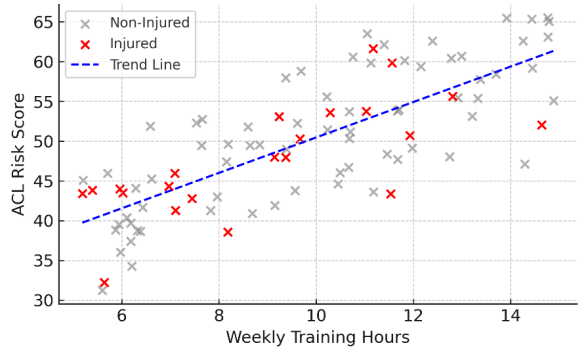

Fig. 1. Training Load Vs. ACL Risk

To further explore this relationship, Figure 1 presents a scatterplot depicting individual weekly training hours in relation to ACL risk scores. The scatterplot reveals a clear positive trend, indicating that athletes with higher training loads tend to exhibit elevated ACL risk scores. Notably, players who sustained injuries (highlighted in red) are more concentrated in the upper range of both training hours and risk scores, suggesting that cumulative external load may play a critical role in injury susceptibility.

Multivariate logistic regression identified fatigue score as the only statistically significant predictor of ACL injury ($\beta = 0.884$, $p = 0.041$). The odds ratio of 2.42 suggests that for each one-unit increase in fatigue score, the likelihood of sustaining an ACL injury more than doubles. This reinforces the importance of subjective fatigue monitoring in injury prevention models and supports fatigue as a critical modifiable risk factor in load management protocols.

Table 3. Logistic Regression Predicting ACL Injury Occurrence

Variable	β Coefficient	Std. Error	p	Odds Ratio (OR)
Intercept (const)	-9.000	4.328	0.038	0.00
Training Intensity	0.182	0.234	0.438	1.20
Training Hours/Week	0.141	0.120	0.238	1.15
Fatigue Score	0.884	0.433	0.041	2.42
Recovery Days/Week	-1.539	0.831	0.064	0.21

Note: Odds ratios (OR) with 95% confidence intervals (CI) are reported for each predictor variable. Model fit assessed using Nagelkerke R^2 and Hosmer–Lemeshow goodness-of-fit test. Significance level: $p < 0.05$ considered statistically significant

Although not statistically significant, recovery days per week demonstrated a protective trend (OR = 0.21, p = 0.064), indicating that structured recovery may mitigate injury risk. Neither training intensity nor weekly training hours were significant predictors, although both showed small positive associations with injury likelihood. These findings suggest that injury risk is more closely tied to recovery adequacy and accumulated fatigue than to training volume alone.

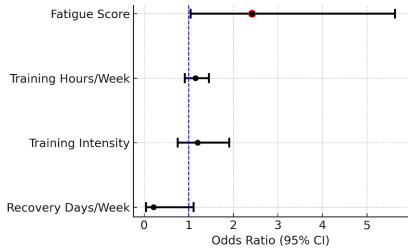

Fig. 2. logistic regression predictors of ACL injury

To visually summarize the predictive strength of each variable, a forest plot was constructed (Figure 2), displaying odds ratios and corresponding 95% confidence intervals. The figure highlights fatigue score as the most prominent risk factor, while illustrating the nonsignificant but directionally relevant roles of other load-related variables.

Table 4. ANOVA Results for Positional Differences

Variable	F	p
Training Hours/Week	0.642	0.529
Training Intensity	2.907	0.060
Fatigue Score	1.704	0.188
Performance Score	1.778	0.175
ACL Risk Score	2.180	0.119

Note: One-way ANOVA used to test differences among player positions. Variables with $p < 0.05$ were subjected to post hoc analysis using Tukey's HSD test. Significance level: $p < 0.05$. Bonferroni correction applied where multiple comparisons were performed.

ANOVA revealed no statistically significant differences among positions across the five variables examined. However, training intensity approached significance (F = 2.91, p = 0.060), suggesting a trend toward positional variation in internal load. This preliminary signal was further explored through post hoc testing (Table 4), which identified a near-significant difference between Centre Back and Right Back (mean difference = -1.40, p = 0.059). Such a trend may reflect distinct tactical roles and physiological profiles associated with each position, wherein Centre Back are typically involved in both playmaking and defensive transitions.

Fatigue score, performance metrics, and ACL risk scores did not differ significantly by position, which may reflect uniformity in training programs or small sample variation. Nevertheless, the positional trends observed warrant continued investigation using larger samples and multilevel modelling approaches to capture the complexity of positional demands in collegiate handball.

Discussion

The study followed a two-season prospective cohort and revealed significant associations between perceived fatigue and ACL injury incidence in collegiate male handball players. Among all factors analyzed, fatigue score was the only statistically significant variable for ACL injury (OR = 2.42, p = 0.041), meaning that athletes who considered themselves more fatigued were twice-and-a-half times more likely to sustain an ACL injury. This is in line with several proposals stating that neuromuscular fatigue lessens the ability of the muscle system to assure dynamic stability and sensorimotor control, thereby heightening injury risk during high-load activities, such as deceleration, cutting, and landing (Méjane et al., 2019) (Larson et al., 2018).

On the other hand, cases in high training load situations registered injury rates higher than 10.34% and ACL risk scores (Bowen et al., 2017), hence strengthening the relevance of insufficient recovery from an increased external load. Injuries showed no statistically significant difference in relation to training intensity and total hours within the regression models, yet the directional association with injury susceptibility has been reported elsewhere (Ertel et al., 2020) (Batterson et al., 2020), thereby confirming load and recovery-based interaction as the principal factors determining injury risk (Yung et al., 2023). The tendency for greater risks in Right Back and Centre Back may relate to position-specific movement demands involving lateral movements and high-frequency contacts stressing the knee joint complex.

In agreement with the literature complaint fatigue and poor load management as primary risk factors for lower extremity injuries within team sports (Payne et al., 2023), these findings are observed. Past studies have also stated that fa-

Table 5. Post Hoc Analysis: Training Intensity by Position (Tukey HSD)

Comparison	Mean Difference	p	95% CI (Lower – Upper)	Significant
Centre Back vs Left Back	-1.01	0.174	[-2.33, 0.32]	No
Centre Back vs Right Back	-1.40	0.059	[-2.83, 0.04]	No (borderline)
Left Back vs Right Back	-0.39	0.768	[-1.73, 0.95]	No

Note: Pairwise comparisons conducted using Tukey's Honestly Significant Difference (HSD) test. Results indicate which positional differences in training intensity reached statistical significance. Significance level: Post hoc results were interpreted at $p < 0.05$ following a significant ANOVA main effect.

tigue disturbs the joint stabilization and alters the lower limb kinematics upon landing and pivoting in elite and youth-handball populations (Payne et al., 2023; Rostami et al., 2018). Relevant associations have also been evinced in fellow pivot-dominant sports like basketball and soccer wherein neuromuscular fatigue has been suggested to increase lesser knee flexion angles and greater valgus moments, both implicated in ACL injury mechanisms (Bourne et al., 2019; Parker et al., 2022). These results further emphasize the development of training and recovery programs to prevent ACL injuries, especially in sports of high intensity, such as handball.

Our results add to the evidence produced in Favor of the short-ACWR model, in those abrupt increments in training load, especially when paired with insufficient recovery time, tend to increase injury risk (Andrade et al., 2020). However, our study extends the body of literature on this matter by considering subjective fatigue measures alongside field-based ACL risk screening (LESS scores, limb asymmetry), thereby allowing for a more integrated evaluation of injury susceptibility than studies that rely solely on biomechanical or performance variables.

Hence, monitoring fatigue and individualized load management are essential in collegiate handball settings. Subjective tools, such as a daily wellness questionnaire, could be a cheap, sensitive indicator of the accumulated neuromuscular strain. Suppose after crossing a certain critical fatigue threshold, either modified training protocols or extra recovery days or even neuromuscular reconditioning are given to athletes. In that case, the incidence of injuries could drastically be lowered (Sampson et al., 2019). Next, we suggest position-specific interventions. Because of the heightened risk among right-Back and Centre Back, neuromuscular training (perturbation training, single-leg stability exercises) that specifically addresses these players should be added into their weekly training schedule (Yamchi et al., 2022).

At the same time, internal loads should be monitored (session-RPE) along with the external (mean training hours, sprint volume) to avoid overuse and decreases in abrupt increments of ACWR (Andrade et al., 2020). When possible, to alleviate accumulated joint stress, performance staff may wish to consider rotating higher risk players or staggering their heavy sessions.

A very strong aspect of this study by Zemková et al. (2020) is its prospective nature over two competitive seasons, thus making greater temporal inference about causality possible than with retrospective analyses. Furthermore, in the load monitoring procedure, a wide spectrum of parameters was measured, ranging from subjective ones (fatigue, wellness scores) to objective ones (training duration, performance outcomes), thus increasing its ecological validity and real-world applicability.

A few limitations, however, need to be acknowledged. First, the sample was limited to male collegiate handball athletes, which limits generalization to female athletes or other levels of play. Previous research has shown sex-specific biomechanical and hormonal differences in ACL injury mechanisms, which were not considered by this study. Second, although field-based fatigue markers such as CMJ decline are practical, they may not be as sensitive as laboratory-grade measures (e.g., electromyography, isokinetics) at detecting subclinical neuromuscular deficits. Third, even if using self-reported training data and coach logs may introduce recall or reporting bias, the use of standardized monitoring procedures probably limits this possibility.

Conclusions

The present study is the first to provide prospective evidence concerning the association between training load, fatigue, and the risk of ACL injury in collegiate male handball players. Fatigue was found to be the strongest predictor for ACL injury, with injury risk more than doubling for high subjective fatigue scores. Those players experiencing high records of training load without sufficient recovery were again found to have high risk profiles for ACLs, whereas such players were concurrently prone to experiencing far greater injury incidence levels, stressing the role of proper load management on injury prevention.

This, consequently, demands the coaching staff and sports scientists to monitor fatigue systematically by using simple tools such as well-being questionnaires and jump performance as part of their routine training oversight. Doing so, while monitoring the internal and external loads regularly, especially for positional groups deemed at risk such as the Right and Centre Back, will allow for the identification of at-risk athletes before injuries occur.

These findings provide valuable insights for educators, coaches, and sports scientists working with collegiate athletes. By incorporating simple monitoring tools into physical education programs, institutions can better manage athlete workload, reduce injury risk, and improve performance sustainability.

Acknowledgment

The author sincerely appreciates the handball players for their valuable cooperation, support, and the positive energy they brought to this study.

Conflict of Interest

The authors declare that they have no conflicts of interest.

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Тренувальне навантаження, втома та ризик травмування передньої хрестоподібної зв'язки у студентів-гандболістів чоловічої статі: Двосезонне проспективне когортне дослідження

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

Реферат. Стаття: 7 с., 3 табл., 2 рис., 32 джерела.

Історія питання. Травмування передньої хрестоподібної зв'язки (ПХЗ) становить суттєву проблему в змагальному гандболі, що часто призводить до тривалої відсутності гравця та зниження спортивної результативності. З огляду на високі фізичні вимоги до цього виду спорту, особливо на студентському рівні, моніторинг тренувального навантаження та втоми є надзвичайно важливим для зменшення ризику травмування.

Мета дослідження. Мета цього дослідження полягала у вивченні взаємозв'язку між тренувальним навантаженням, маркерами втоми та ризиком травмування передньої хрестоподібної зв'язки у студентів-гандболістів чоловічої статі впродовж двох змагальних сезонів.

Матеріали та методи. Проведено проспективне когортне дослідження за участю 93 спортсменів-чоловіків (середній вік: 20.8 ± 1.6 року) з 13 студентських гандбольних команд протягом двох сезонів (2022-2024 навчальні роки). Тренувальне навантаження відстежувалося за допомогою щотижневих годин, тренувальних сесій, в яких інтенсивність вправ регулювалася на основі індивідуального сприйняття навантаження та рівня ризику отримання травмування під час матчів. Оцінка рівня втоми проводилася через щоденні показники самопочуття та зниження висоти стрибка з контррухом (СКР). Ризик травмування ПХЗ розраховувався на основі комбінованого балу, що включав показники LESS (система оцінювання помилок під час приземлення), асиметрію кінцівок та зниження результативності, пов'язане з втомою. З метою визначення предикторів травми ПХЗ використовувалася логістична регресія, а позиційні відмінності досліджувалися за методом дисперсійного аналізу.

Результати. Показник втоми був єдиним статистично значущим предиктором травми передньої хрестоподібної зв'язки ($p = 0.041$). Гравці, які повідомляли про вищий рівень втоми і належали до групи з високим тренувальним навантаженням, мали найбільший ризик травмування передньої хрестоподібної зв'язки. Праві та центральні захисники стикалися з більшими тренувальними навантаженнями та накопиченням втоми порівняно з лівими захисниками.

Висновки. Результати дослідження свідчать, що постійна втома, як чинник, що має більший вплив, ніж обсяг тренувань, є значущим предиктором ризику травмування передньої хрестоподібної зв'язки у студентів-гандболістів. Інтеграція регулярного моніторингу втоми та індивідуального контролю навантажень до тренувальних програм може сприяти зниженню рівня травматизму та покращенню спортивного довголіття.

Ключові слова: травма передньої хрестоподібної зв'язки, тренувальне навантаження, моніторинг втоми, профілактика травмування, нервово-м'язовий скринінг, спортивна результативність у гандболі.

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Cite this article as: Syed, A. A. S., & James, J. D. M. (2025). Training Load, Fatigue, and Anterior Cruciate Ligament Injury Risk in Male Collegiate Handball Players: A Two-Season Prospective Cohort Study. Physical Education Theory and Methodology, 25(4), 905-911. https://doi.org/10.17309/tmfv.2025.4.19

Received: 05.06.2025. Accepted: 02.07.2025. Published: 30.07.2025