

Efficacy of integrated neuromuscular training intervention on concurrent reduction of anterior cruciate ligament and hamstring injury risks in adolescent footballers

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Abstract

Background and Study Aim

Football is a physically demanding sport with a high risk of injuries, particularly anterior cruciate ligament (ACL) and hamstring strain injuries (HSIs). These injuries often lead to re-injury, prolonged rehabilitation, and reduced career longevity. Although various preventive strategies are applied, their relative effectiveness in reducing such risks among adolescent male footballers remains a matter of practical concern. This study aimed to determine the effects of integrated neuromuscular training on key injury-related risk factors.

Material and Methods

Sixty-eight male adolescent footballers aged 16–18 years from two academies in Lakki Marwat were recruited for the study. Sixty-two participants completed the intervention, while six withdrew for personal reasons. The intervention group (n = 31) followed an eight-week INT program, consisting of four sessions per week, each lasting 80–90 minutes. The control group (n = 31) continued their routine football training. Pre- and post-test assessments were conducted to evaluate the effects of INT on the dependent variables. The Tuck Jump Assessment (TJA) was used to analyze landing biomechanics, a key risk factor for ACL injury. Isokinetic dynamometry was used to assess hamstring strength and calculate the conventional (Hcon:Qcon) and functional (Hexc:Qcon) hamstring-to-quadriceps ratios. The Active Knee Extension (AKE) test was used to assess hamstring flexibility.

Results

The most significant result in the INT group was a 51% reduction in the TJA score, supported by a large effect size (d = 2.41). Overall, large effect sizes (d = 1.56–1.73) confirmed the intervention's potential effectiveness, as the INT group showed significant improvements from pre- to post-test in all tested variables.

Conclusions

Significant positive changes were observed in TJA scores, indicating improved landing mechanics and a lower risk of ACL injury. Additionally, the intervention group demonstrated significant improvements in muscle peak torque, Hcon:Qcon ratio, Hexc:Qcon ratio, and AKE range of motion. These findings confirm that INT can simultaneously reduce key risk factors related to both movement mechanics and muscle strength for ACL and HSIs in adolescent male footballers.

Keywords: exertion, fitness, limitations, strenuous, rehabilitation

Introduction

In modern competitive football, adolescent players are exposed to intensive physical demands that challenge the musculoskeletal and neuromotor systems. Movements such as sprinting, cutting, jumping, and tackling place considerable stress on the lower extremities, increasing vulnerability to injury. Among the most prevalent and impactful are anterior cruciate ligament (ACL) ruptures and hamstring strain injuries (HSIs), both of which can result in significant functional impairment,

extended rehabilitation periods, and reduced athletic longevity. The complexity of these injuries lies in their multifactorial origins, involving biomechanics, neuromuscular control, strength imbalances, and fatigue.

In this context, football is the world's most popular and widely played sport, with an estimated 3.5 billion spectators and over 250 million registered players in more than 200 member nations of the Fédération Internationale de Football Association (FIFA) [1]. Its popularity continues to rise among adolescents, who represent the most active and critical developmental age group in organized sport [2]. The game combines intense physical exertion, technical skill, rapid directional changes, dribbling,

sprinting, and jumping [3]. These strenuous biomechanical activities place heavy demands on the lower limbs and make players, particularly adolescents, vulnerable to musculoskeletal injuries such as ACL ruptures and HSIs [4].

Based on the frequency of incidents and the long-term impact on physical fitness, ACL and hamstring injuries have a severe functional effect on players' overall performance [5]. Reducing the occurrence of these injuries through evidence-based preventive strategies is a key priority in football medicine [6]. Among these, anterior cruciate ligament (ACL) injury during adolescence is considered one of the most severe and functionally limiting [7]. From a physiological perspective, the ACL plays a central role in stabilizing the knee joint, particularly in rotational control [8]. This injury typically occurs during non-contact actions such as sudden changes of direction, dribbling, tackling, sprinting, or jumping [9].

ACL injury often requires surgical intervention followed by a lengthy rehabilitation period lasting from nine to twelve months [10]. In addition to the physical pain and emotional stress, players usually miss an entire season [11]. Even after returning to sport, adolescents face a high re-injury risk, with recurrence rates reported between 15% and 20% [12]. Furthermore, Wang et al. [13] confirmed that post-traumatic osteoarthritis is a long-term complication of ACL injury. This condition is frequently accompanied by chronic lower-limb pain and functional limitations that interfere with routine physical activities [14].

Hamstring strain injuries (HSIs) have also shown a significant increase in recent years. Ekstrand et al. [15] reported that hamstring tears account for 24% of all injuries among professional football players. Although HSIs are often perceived as less severe than ACL injuries, they have a re-injury rate exceeding 30%, which is notably high [16]. These injuries have multidimensional consequences, including psychological, physical, social, financial, and professional impacts. Athletes often experience fear of re-injury, depression, and emotional deprivation, which are frequently overlooked in clinical management [17]. Disruption of training, prolonged treatment, high rehabilitation costs, and the risk of recurrence are shared consequences of both ACL and hamstring injuries [18].

From a physiological perspective, the development of these injuries involves a complex interplay of physical, biomechanical, hormonal, and neuromuscular factors. Female athletes are at higher risk of ACL injuries than males, due to a combination of hormonal fluctuations, anatomical differences, and neuromuscular control patterns. Targeted training can mitigate many of the contributing factors. The most widely recognized risk factors for ACL injuries include dynamic knee

valgus, quadriceps dominance, poor neuromuscular control, and limb asymmetry [19]. In the case of hamstring strains, one of the primary modifiable risk factors is insufficient eccentric hamstring strength, which plays a critical role in controlling leg swing during sprinting. If hamstring strength is inadequate, excessive strain may occur, leading to tissue damage [20]. Other contributing factors include poor hamstring flexibility and fatigue, which, under high-intensity conditions, can act synergistically to increase injury risk.

Several previous attempts have been made to address the issue of hamstring injuries in football players [21]. Among the most effective approaches is the Nordic Hamstring Exercise (NHE), which has shown consistent success in multiple meta-analyses [22]. The NHE enhances eccentric hamstring strength and significantly reduces the risk of HSIs. Similarly, for reducing risk factors associated with ACL injuries, structured prevention programs such as Prevent Injury and Enhance Performance (PEP) and FIFA 11+ have demonstrated efficacy in improving biomechanics and lowering injury incidence [23]. Despite the availability of such interventions, adolescent football players often remain vulnerable to injuries, including ACL tears and HSIs, due to limited time allocated for comprehensive neuromuscular training.

The current context underscores the relevance of investigating integrated neuromuscular training (INT) as a comprehensive preventive approach [24]. INT targets the simultaneous development of multiple athletic attributes, including muscular strength, power, flexibility, balance, agility, and coordination, within a sport-specific framework. It is designed to address both health- and skill-related components of athletic performance. Through structured progression, the INT program incorporates strength training, plyometrics, eccentric control, and balance exercises to improve core stability, dynamic postural control, and movement efficiency [25].

The primary focus of INT lies in the integrated functioning of the neuromuscular system, which underpins coordinated and adaptive performance across several physiological domains. Enhancing the stretch-shortening cycle, dynamic core stability, and hamstring control is essential for ACL injury prevention—components effectively addressed through plyometric training. Similarly, exercises involving single-leg balance contribute to improved knee joint stability and hamstring function. Overall, the INT program offers a multifaceted strategy for reducing the risk of sports-related injuries in adolescent athletes.

The FIFA 11+ program is a widely recognized neuromuscular training protocol designed to reduce injury risk. However, its primary focus is on general injury prevention, with limited emphasis on

specific strength parameters such as the functional hamstring-to-quadriceps (H:Q) ratio. Naik [26] has further argued that, while FIFA 11+ is effective, its use as a standalone intervention may not sufficiently address the biomechanical risk factors for ACL injuries. Supporting the rationale for the present study, Owoeye et al. [27] emphasized the need for interventions that target multiple injury mechanisms simultaneously in football players.

This research addresses several critical gaps identified in the literature. One of the major gaps stems from socio-economic disparities. Most existing research on integrated neuromuscular training has been conducted in high-income settings with well-established sports infrastructure and access to expert coaching [28]. In contrast, regions such as Pakistan—and more specifically, the under-resourced city of Lakki Marwat in Khyber Pakhtunkhwa—lack the facilities, training standards, and funding typically found in developed countries. These differences in infrastructure, athlete preparation, and socio-economic conditions limit the generalizability of findings from wealthier contexts [29].

Another gap is the absence of context-specific research that focuses on the risk factors, prevalence, and prevention of ACL and hamstring injuries among adolescent football players. The current INT program seeks to bridge this gap by simultaneously targeting ACL-related movement mechanics and HSIs through the enhancement of eccentric hamstring strength. Addressing both mechanisms within a single intervention is a central aim of this study. Finally, there remains a broader need to design adaptable, context-sensitive training programs composed of evidence-based components that can be applied across diverse athletic populations [30].

Analysis of research findings has shown that neuromuscular training programs such as FIFA 11+, PEP, and the Nordic Hamstring Exercise can reduce specific injury risks in football players. Researchers emphasize that targeted improvements in movement mechanics, eccentric strength, and dynamic stability are essential for effective injury prevention, particularly among adolescents. At the same time, the practical implementation of these programs in low-resource settings remains challenging due to infrastructural limitations, limited training time, and contextual mismatch. This ongoing gap continues to hinder the development of accessible and comprehensive solutions capable of simultaneously addressing the complex injury risks faced by adolescent football players.

This study aimed to determine the effects of integrated neuromuscular training on key injury-related risk factors. It was hypothesized that adolescent football players who completed the INT intervention would demonstrate significantly greater improvements in modifiable risk indicators

for anterior cruciate ligament and hamstring injuries compared to those in the control group.

Materials and Methods

Participants

The study involved 68 male adolescent football players aged 16 to 18 years, recruited from two established football academies in Lakki Marwat. Inclusion criteria were as follows: (a) a minimum of two years of active football experience, (b) no history of musculoskeletal injury in the past six months, and (c) no participation in any structured training program. Exclusion criteria included: (a) any musculoskeletal injury within the past six months, (b) a documented history of major orthopedic surgery, and (c) current use of regular medication. All participants provided informed consent, and the study protocol was approved by the Ethics Committee of the Department of Sports Sciences and Physical Education, Faculty of Allied Health Sciences, The University of Lahore (approval code: DSSPE/ECA/2025-135).

Study Design

A pre- and post-intervention experimental research design was employed in the present study. Before pre-test measurements, baseline health and fitness assessments were conducted. Participants were then randomly assigned to either the intervention group (INT; $n = 34$) or the control group (CON; $n = 34$) using a computer-generated randomization sequence. Group allocation was concealed using sequentially numbered, opaque, sealed envelopes (SNOSE), and the envelopes were opened by an independent research assistant after baseline testing to ensure allocation concealment and minimize selection bias.

During the 8-week intervention period, six participants (three from each group) withdrew for personal reasons (lack of interest, $n = 4$; health issues, $n = 2$), resulting in a final sample of 62 participants (INT: $n = 31$, CON: $n = 31$) for data analysis. Written informed consent was obtained from all participants prior to enrollment, and they were informed of their right to withdraw from the study at any time without penalty.

Eight-week long intervention protocol, with a frequency of four sessions of 80–90 minutes per week, was implemented in the study. Each training session followed a structured format consisting of a 15-minute warm-up, 50–60 minutes of key intervention exercises, and a 10-minute cool-down with stretching. Progressive overload was applied by increasing intensity and difficulty every two weeks. The intervention targeted four main domains:

- Plyometrics: Squat jumps, box jumps, and lateral hops to improve power and landing mechanics.
- Strength Training: Emphasis on bodyweight exercises such as Nordic hamstring curls and

- single-leg squats.
- Dynamic Stability and Balance: Single-leg balances on unstable surfaces and Y-balance test reaches.
- Agility and Sport-Specific Exercises: Change-of-direction drills with focus on deceleration and cutting technique.

The week-wise structure of the INT sessions is presented in Table 1, detailing the progression of training components across the intervention period.

During the intervention period, the control group continued their regular training, which consisted of technical and tactical exercises, without participating in any structured neuromuscular training program. Before the intervention, demographic and anthropometric data were recorded for all participants. These included age, height, weight and body mass index (BMI).

Intervention Protocol

To ensure consistency in training volume and intensity, the control group’s activities were regularly monitored throughout the intervention period. Their weekly schedule included five sessions lasting 90 minutes each. These sessions began with a standardized 15-minute warm-up consisting of low-intensity jogging and stretching. This was followed by 45 minutes of technical and tactical drills such as passing, dribbling, kicking and heading, and concluded with 30 minutes of simulated match play. The control group did not participate in any structured neuromuscular, plyometric or eccentric strength training activities included in the intervention protocol. To evaluate the effects of the intervention, a series of standardized physical performance tests was administered before and after the training period. These included:

Tuck Jump Assessment (TJA): The TJA is a dynamic plyometric test used to identify biomechanical deficits of the lower limbs, particularly poor landing mechanics, which are closely associated with the risk of ACL injury. A 10-second video recording was made for each participant while performing repeated tuck jumps. The recordings were analyzed using a standardized 10-point checklist focusing on knee valgus, thigh asymmetry, and landing control. Lower scores indicated better performance and reduced biomechanical risk.

Isokinetic Strength Testing: A Humac Norm isokinetic dynamometer was used to assess the peak torque of the hamstring and quadriceps muscles in the dominant leg. Measurements were taken at two angular velocities: 60°/s for conventional strength and 300°/s for functional strength. Based on these values, two strength ratios were calculated: the Conventional Hamstring-to-Quadriceps ratio (Hcon:Qcon) at 60°/s and the Functional Hamstring-to-Quadriceps ratio (Hexc:Qcon).

Active Knee Extension (AKE) Test: The AKE test was used to measure hamstring flexibility. Participants lay supine with the hip flexed to 90 degrees and were instructed to extend the knee until a maximal stretch was felt. The angle of knee extension was measured using a goniometer. Greater angles indicated better hamstring flexibility.

Quality Assurance and Fidelity Measures: All assessors involved in the study were qualified experts in sports sciences and physical education, with prior experience in isokinetic testing and biomechanical assessment. Tuck Jump Assessment (TJA) was evaluated by two blinded raters who independently scored the video recordings. The intra-class correlation coefficient (ICC) for their pre-intervention scores was excellent (ICC[2,1] = 0.91), indicating high inter-rater reliability. The Humac Norm isokinetic dynamometer was calibrated before each testing session according to the manufacturer’s specifications. For the Active Knee Extension (AKE) test, a standard universal goniometer was used, with its axis precisely aligned with the lateral femoral epicondyle. To ensure fidelity to the training protocol, all INT sessions were supervised by a certified strength and conditioning specialist. Attendance logs were maintained to monitor adherence. An overall adherence rate of 94 percent was recorded, reflecting strong participant compliance with the intervention protocol.

Statistical Analysis

Data were analyzed using the Statistical Package for the Social Sciences (SPSS), version 27. The Shapiro–Wilk test was applied to assess the normality of data distribution. Independent *t*-tests were used to compare baseline values between groups. A mixed-model analysis of variance

Table 1. Week-wise INT Training Schedule

Week	Warm-up Activities	Key Intervention Components	Cool-down
1–2	Jogging, dynamic stretches (15 min)	Basic plyometrics, bodyweight squats, balance on stable surface	Static stretching (10 min)
3–4	Jogging + mobility drills	Intermediate plyometrics, Nordic curls intro, single-leg balance	Dynamic stretches
5–6	Jogging + ladder drills	Advanced plyometrics, eccentric hamstring strengthening, unstable surface balance	Hamstring-focused stretches
7–8	Cone drills + coordination	Deceleration + cutting drills, peak strength work, combined tasks	Sport-specific stretches

(ANOVA) was employed to examine group-by-time interactions across outcome measures. Effect sizes were calculated using Cohen's *d*, with thresholds of 0.2, 0.5, and 0.8 indicating small, medium, and large effects, respectively [31].

Results

Baseline demographic and anthropometric characteristics of the participants are presented in Table 2.

Following the data in Table 2, no statistically significant differences were observed between the intervention and control groups at baseline across any measured variable ($p > 0.05$). This indicates that randomization was successful, ensuring that any post-intervention differences could be attributed to the effects of the intervention itself.

Pre- and post-intervention results for all primary

outcome measures in both groups are summarized in Table 3.

Following the results presented in Table 3, the intervention group showed statistically significant improvements in all assessed variables between pre- and post-test. In contrast, the control group exhibited no significant changes in any of the outcomes.

The results of the Shapiro–Wilk test used to evaluate the normality of distribution for all outcome variables are presented in Table 4.

As shown in Table 4, all *p*-values exceeded the conventional threshold of 0.05, indicating that the data for each variable were normally distributed at both time points in both groups. This confirmed the suitability of applying parametric statistical tests, such as mixed-model ANOVA and independent samples *t*-tests, in subsequent analyses.

Table 2. Baseline Demographic and Anthropometric Characteristics of Participants

Variable	Intervention Group (n=31)	Control Group (n=31)	p-value
Age (years)	17.1 ± 0.8	17.3 ± 0.7	0.45
Height (cm)	172.4 ± 5.6	173.1 ± 6.1	0.62
Weight (kg)	61.5 ± 7.2	62.8 ± 6.5	0.48
BMI (kg/m ²)	20.7 ± 1.9	21.0 ± 1.7	0.55
Playing Experience (years)	4.5 ± 1.2	4.7 ± 1.1	0.52

Note: Data are presented as mean ± standard deviation. p-values are based on independent samples t-tests.

Table 3. Pre- and Post-Intervention Scores for Primary Outcome Measures (Mean ± SD)

Outcome Measure	Group	Pre-Test	Post-Test	p-value (Within-Group)
TJA Score	INT	6.5 ± 1.4	3.2 ± 1.1*	<0.001
	CON	6.3 ± 1.6	6.1 ± 1.5	0.58
Hamstring PT 60°/s (Nm)	INT	98.2 ± 14.5	121.6 ± 16.8*	<0.001
	CON	96.8 ± 15.1	97.5 ± 14.3	0.84
Hcon:Qcon Ratio (%)	INT	52.1 ± 5.8	61.4 ± 6.2*	<0.001
	CON	51.7 ± 6.1	52.0 ± 5.9	0.82
Hexc:Qcon Ratio (%)	INT	72.3 ± 7.1	85.9 ± 8.4*	<0.001
	CON	71.8 ± 6.5	72.5 ± 7.0	0.67
AKE Test (°)	INT	142.5 ± 9.8	157.8 ± 8.5*	<0.001
	CON	141.2 ± 10.5	142.1 ± 9.7	0.71

Note: INT = Intervention Group; CON = Control Group; TJA = Tuck Jump Assessment; PT = Peak Torque; AKE = Active Knee Extension; denotes a statistically significant difference between pre- and post-test scores within the same group ($p < 0.001$); p-values are from within-group comparisons using repeated measures.

Table 4. Results of Shapiro–Wilk Test for Normality of Data

Variable	Group	Statistic (W)	p-value
Age (years)	Intervention	0.978	0.721
	Control	0.981	0.802
Height (cm)	Intervention	0.966	0.358
	Control	0.971	0.485
Weight (kg)	Intervention	0.961	0.267
	Control	0.974	0.612
TJA Score (Pre)	Intervention	0.970	0.467
	Control	0.968	0.412
TJA Score (Post)	Intervention	0.976	0.674
	Control	0.972	0.538
Hamstring PT 60°/s (Pre)	Intervention	0.986	0.934
	Control	0.977	0.693
Hamstring PT 60°/s (Post)	Intervention	0.973	0.558
	Control	0.983	0.865
Hcon:Qcon Ratio (Pre)	Intervention	0.984	0.889
	Control	0.979	0.755
Hcon:Qcon Ratio (Post)	Intervention	0.975	0.635
	Control	0.981	0.815
AKE Test (Pre)	Intervention	0.969	0.439
	Control	0.976	0.661
AKE Test (Post)	Intervention	0.977	0.687
	Control	0.974	0.599

Note: The Shapiro–Wilk test was applied to assess the normality of pre- and post-intervention scores for each outcome measure in both the intervention and control groups. p-values greater than 0.05 indicate no significant deviation from normality.

Effect sizes (Cohen’s *d*) were calculated to quantify the magnitude of between-group differences in outcome changes from pre- to post-intervention. These results are presented in Table 5.

As shown in Table 5, the intervention produced a very large effect on landing mechanics as measured by the Tuck Jump Assessment ($d = 2.41$). Additionally, large effects were observed for hamstring strength (PT at 60°/s), hamstring-to-quadriceps ratios (Hcon:Qcon and Hexc:Qcon), and hamstring flexibility (AKE test), indicating strong

practical relevance of the intervention across all key performance outcomes.

Discussion

This study aimed to evaluate the effects of an eight-week integrated neuromuscular training (INT) program on modifiable risk factors associated with anterior cruciate ligament (ACL) and hamstring strain injuries (HSIs) in adolescent football players. The findings demonstrated that participants in the INT group showed significant improvements

Table 5. Between-Group Effect Sizes (Cohen’s *d*) for Changes in Outcome Measures

Outcome Measure	Cohen’s <i>d</i> *	Magnitude
TJA Score	2.41	Very Large
Hamstring PT 60°/s	1.55	Large
Hcon:Qcon Ratio	1.56	Large
Hexc:Qcon Ratio	1.73	Large
AKE Test	1.89	Large

Note: Effect sizes were calculated using Cohen’s *d* to compare the magnitude of changes between the intervention and control groups. The following thresholds were used for interpretation: 0.2 = small, 0.5 = medium, 0.8 = large.

across all primary outcome measures, including landing biomechanics, eccentric hamstring strength, muscle strength ratios (Hcon:Qcon and Hexc:Qcon), and hamstring flexibility. In contrast, no statistically significant changes were observed in the control group. The magnitude of between-group differences, confirmed by large to very large effect sizes, further underscores the practical significance of the intervention.

Anterior cruciate ligament (ACL) and hamstring strain injuries (HSIs) are among the most prevalent and functionally limiting injuries in football [32]. The findings of the present study support the original hypothesis, demonstrating that participants in the INT group experienced significant improvements across all assessed variables compared to those in the control group, who continued with routine training.

The most notable result was a 51% reduction in the Tuck Jump Assessment (TJA) score within the intervention group, accompanied by a very large effect size ($d = 2.41$; see Table 4). This improvement highlights the effectiveness of the INT protocol in addressing neuromuscular risk factors associated with ACL injury. Kember [33] previously identified the TJA as a valid and practical tool for assessing high-risk movement patterns, particularly those linked to non-contact ACL injuries, such as hip internal rotation, dynamic knee valgus, and inadequate limb control.

The scale of improvement observed in this study exceeds that reported in earlier interventions with shorter session durations or lower training frequencies. This suggests that both the dosage and duration of the INT protocol played a critical role in producing measurable neuromuscular adaptations. Specifically, the eight-week program, which included four sessions per week lasting 80–90 minutes and followed a progressive overload structure, appears to have been sufficient to elicit meaningful improvements in landing mechanics among adolescent players.

Kember et al. [34] reported that reductions in Tuck Jump Assessment (TJA) scores are indicative of improved neuromuscular control. Consistent with this, the present study observed a 51% decrease in TJA scores among participants in the intervention group, reflecting substantial neuromuscular adaptations. These improvements were evident in enhanced biomechanical performance during landing tasks.

Similarly, Dhahbi et al. [35] concluded that proper knee alignment and stable trunk positioning during jumping contribute to improved balance, lower limb control, and overall athletic performance. In line with this, the present intervention emphasized safe landing techniques and correct knee positioning, which likely contributed to improved body control and stability upon landing.

These findings are further supported by Franco et al. [36], who demonstrated that integrated neuromuscular training positively influences the structural and functional stability of the knee joint, thereby enhancing protection of the ACL and surrounding soft tissues. Moreover, the current results align with the conclusions of Souaifi et al. [37], who emphasized that neuromuscular training provides a solid foundation for reducing ACL injury risk in youth sports.

Leahy et al. [38] emphasized that addressing dual injury risks, such as anterior cruciate ligament and hamstring injuries in adolescent football players, remains a key area of research. The development of training protocols that simultaneously enhance performance and reduce injury risk in youth football has been recognized as a promising and innovative approach [39]. Ribeiro et al. [40] noted that a lack of comprehensive studies examining interventions capable of concurrently improving performance indicators and mitigating injury risks among adolescent players represents a significant gap in the current literature.

Corroborating the findings of Liveris et al. [5], the present results confirm the efficacy of the

integrated neuromuscular training (INT) program in producing measurable improvements in risk factors related to hamstring injuries. A 24 percent increase in hamstring strength, along with improvements in both conventional and functional hamstring-to-quadriceps ratios, supports the role of INT in restoring muscular balance. From a biomechanical perspective, the functional ratio represented by Hexc:Qcon is particularly relevant. It reflects the capacity of the hamstring muscles to control rapid leg extension during high-speed running, which is a key factor in the prevention of hamstring strains [41]. The observed large effect sizes ($d = 1.56$ to 1.73) further validate the practical effectiveness of the intervention, as shown in Table 5. These improvements are likely attributable to the inclusion of the Nordic Hamstring Exercise (NHE) in the training protocol. Importantly, the incorporation of NHE within a broader neuromuscular framework contributes to the novelty of this study.

Afonso et al. [42] reported that hamstring stability, flexibility, and strength are essential for safe athletic performance and injury prevention. The combined effects of all components of the integrated neuromuscular training (INT) program, including the Nordic Hamstring Exercise (NHE), contributed to enhanced hamstring function. In addition, the incorporation of sport-specific deceleration drills alongside single-leg stability exercises likely facilitated improved movement control and muscular output.

The Active Knee Extension (AKE) test results demonstrated a significant improvement in hamstring flexibility, as shown in Table 2. This flexibility gain may serve as an additional protective factor during high-intensity sports activities [43]. Recognizing the dual importance of strength and flexibility, Muanjai et al. [44] emphasized their critical role in supporting safe muscle performance and long-term muscle-tendon health. Increased flexibility is particularly relevant for adolescents, who are undergoing physiological transitions that heighten susceptibility to muscular stress and strain [45]. The inclusion of both dynamic and static stretching exercises in the intervention protocol likely contributed to improvements in flexibility and the functional performance of the muscle-tendon unit.

The present study applied and evaluated the INT protocol for addressing both anterior cruciate ligament and hamstring injury risks in a previously unexamined, low-resource adolescent male cohort. The findings demonstrate that the protocol can be implemented in settings where the use of multiple specialized interventions is limited. Unlike many studies that focus on either ACL or hamstring injury prevention, this research examined both outcomes within a single intervention.

Bathe et al. [46] reported that integrated

neuromuscular training can improve muscular performance, which supports the current findings. Similarly, Ferrández-Laliena et al. [47] found that structured training contributes to improved landing mechanics and hamstring strength, which are essential for reducing injury risk. This type of combined approach may be suitable for addressing the multifactorial nature of neuromuscular control and injury prevention [48]. In line with the findings of Babayev et al. [49], the present results suggest that INT can be aligned with the physiological demands of sport in adolescent populations. By implementing a combined training protocol, the study provides information relevant to coaches and practitioners regarding feasibility and applicability under practical constraints.

Limitations of the Study

Several limitations should be considered when interpreting the findings. The sample included only 62 male adolescent football players from a single geographic location (Lakki Marwat), which may limit the generalizability of the results to broader or more diverse populations. Due to gender-related differences such as hormonal profiles, neuromuscular characteristics, and anatomical structure, the results are not applicable to female athletes. Furthermore, performance-related indicators such as sprinting, jumping, and dribbling were not assessed during this study. Including such metrics could have provided additional insights into the functional impact of the intervention.

Future Research Directions

Given the documented differences in injury risk profiles between male and female athletes, future studies should examine the effects of integrated neuromuscular training in adolescent female football players. Sex-specific interventions may support the development of targeted preventive strategies. Future investigations should also aim for larger, more diverse samples and consider long-term follow-up to assess sustained effects of the intervention. In addition, incorporating performance-based outcome measures into future protocols may enhance the practical applicability of the intervention in sports settings.

Conclusions

The findings of this study indicate that the 8-week integrated neuromuscular training (INT) program was effective in concurrently reducing modifiable risk factors associated with anterior cruciate ligament (ACL) injuries and hamstring strain injuries (HSIs) in adolescent male football players. Improvements in landing biomechanics, reflected by a substantial reduction in Tuck Jump Assessment scores, suggest a lower risk of movement patterns linked to ACL injuries. Additionally, increases in hamstring strength were accompanied by

enhancements in flexibility and both conventional and functional hamstring-to-quadriceps ratios, which are associated with reduced HSI risk. Large effect sizes observed across all measured variables support the relevance of the intervention. This study contributes to existing literature by evaluating a single, structured protocol that addresses multiple injury risk factors in a population with limited access to specialized training resources.

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Conflict of Interest

The authors declare no conflicts of interest related to this research.

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