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Effects of Micro-Dose Neuromuscular Training on Landing Mechanics, Knee Valgus Angle, and Jump Performance in Male Handball Players

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ABSTRACT

Objective: This study examined the effects of a 6-week micro-dose neuromuscular training (NMT) program integrated into the warm-up during the in-season period on frontal-plane knee valgus angle during landing and on jump performance in male handball players.

Methods and Materials: Competitive male handball players competing at the Regional League level in Ankara were randomly assigned to an experimental group (n = 15) or a control group (n = 15). The experimental group performed a 10-12 min micro-dose NMT warm-up three times per week for 6 weeks in place of part of the routine warm-up, whereas the control group maintained the routine warm-up and training content. The program included trunk-hip stabilization and motor control, controlled bilateral and unilateral jump-landing tasks, and short-distance acceleration-deceleration drills. Knee valgus angle was assessed with two-dimensional frontal-plane video analysis during a 30-cm drop-jump task, and jump performance was assessed using squat jump, countermovement jump, and drop-jump height.

Findings: In the experimental group, knee valgus angle decreased from 9.8 ± 2.1° to 7.2 ± 1.8° (mean change: -2.6°, p = 0.0001), and within-group jump outcomes improved, whereas no significant changes were observed in the control group. In the post-test comparison, knee valgus angle was lower in the experimental group than in the control group (7.2 ± 1.8° vs 9.4 ± 2.2°, p = 0.006), while between-group differences in jump outcomes did not reach statistical significance.

Conclusion: These findings suggest that micro-dose NMT integrated into the warm-up may improve landing mechanics in male regional-level handball players, whereas any performance-related benefit should be interpreted as preliminary and generalized cautiously to similar competitive settings.

Keywords: *micro-dose neuromuscular training; dynamic knee valgus; landing mechanics; jump performance; handball; injury prevention*

1. Introduction

Handball is a high-intensity team sport involving high-speed running, sudden stopping and changes of direction, repetitive jump–landing cycles, and frequent physical contact. These high mechanical and metabolic demands are associated with a substantial injury burden, particularly in the lower-extremity joints. Epidemiological studies published in recent years indicate that the majority of injuries in handball players occur in the lower extremity—especially in the thigh, knee, and ankle regions—and that ligamentous structures are frequently affected (1). It has also been reported that a significant proportion of injuries occur during competition (2).

Among lower-extremity injuries, anterior cruciate ligament (ACL) injuries have particular importance in many team sports, including handball, because they are associated with long periods away from sport, risk of re-injury, and early performance losses. Recent reviews on lower-extremity injuries in female handball players show that injury-focused protocols and functional and biomechanical tests in this field have been systematically evaluated (3). A substantial proportion of ACL injuries have been reported to occur through non-contact mechanisms and typically develop during sudden changes of direction, stopping, and landing movements (4). Prospective studies show that increased knee abduction (dynamic valgus) loading during landing is associated with ACL injury risk (5). A recent scoping review states that variables such as decreased hip and knee flexion, increased knee internal rotation, and knee valgus moment are also reported among possible biomechanical predictors (6).

Dynamic knee valgus is considered a biomechanical marker that can affect lower-extremity impact attenuation strategies—particularly during single-leg landing and the deceleration phase—and that can be modified with exercise (7, 8). Therefore, monitoring landing mechanics—especially the dynamic knee valgus angle in the frontal plane—is considered critical for assessing injury risk and targeting preventive interventions. In addition, a controlled study reported that a neuromuscular warm-up program could improve the jump–landing pattern and lumbopelvic function in female basketball players with dynamic knee valgus (9). This finding suggests that neuromuscular exercises integrated into the warm-up process may provide an applicable framework for interventions targeting landing mechanics.

Warm-up programs based on neuromuscular training (NMT) combine balance, strength, plyometric, and movement-control components in short modules and are widely used to reduce non-contact lower-extremity injury risk. When applied regularly, structured neuromuscular warm-up protocols can reduce injury incidence in young team-sport athletes and can be implemented without substantial additional equipment or training time (10, 11).

In periods when dense match schedules in team sports limit training volume, the “micro-dose” approach, which recommends implementing training content in shorter but more frequent sessions, has become prominent. Micro-dose plyometric training aims to maintain the neuromuscular stimulus through short but frequent applications, and in most implementations the total volume is kept at a relatively low/moderate level. Studies show that this approach can provide significant improvements in jump height and acceleration performance (12, 13). These findings indicate that low-volume but high-quality plyometric protocols that can be implemented within limited time may be effective in improving lower-extremity power and speed performance.

When handball-specific studies are examined, lower-extremity injury patterns and general neuromuscular risk factors have already been described, and warm-up-based or neuromuscular approaches have been studied in related team sports and, to a more limited extent, in handball. However, evidence remains limited regarding short micro-dose neuromuscular modules embedded directly within the in-season warm-up and targeted simultaneously at landing mechanics, frontal-plane knee valgus, and jump outcomes in male regional-level handball players. Accordingly, the specific contribution of the present study is not the general concept of neuromuscular training itself, but the evaluation of a brief, warm-up-integrated, in-season format in this competitive context.

In this context, the aim of the study was to examine the effect of a 6-week micro-dose neuromuscular training program integrated into the warm-up protocol on frontal-plane knee valgus angle related to landing mechanics and lower-extremity jump performance parameters in male handball players competing at the Regional League level in Ankara province. The specific focus was a brief, warm-up-integrated, in-season application in male regional-level players. It was hypothesized that the intervention would primarily improve landing mechanics, particularly frontal-plane knee valgus control during landing, whereas improvements in jump performance were considered secondary expectations.

2. Methods and Materials

2.1 Study design

This study was conducted as a prospective and randomized controlled experimental design with two groups (experimental–control) in a pre-test–post-test format. The training duration was determined as 6 weeks, and all measurements were performed at two time points: before the training period began and after it was completed. The study received approval from the Scientific Research and Publication Ethics Committee of Isparta University of Applied Sciences (Meeting No. 223, Decision No. 13, 10 February 2026), and written informed consent was obtained from all participants before enrolment. Assessments were performed by assessors blinded to group allocation.

2.2 Participants

The research consisted of male handball players competing at the Regional League level in Ankara province and playing for clubs registered with the Turkish Handball Federation. For inclusion in the study, athletes were required to be between 18 and 30 years of age, to have participated continuously in Regional League-level handball competitions for at least the last two seasons, and to attend regular team training at least three times per week. In addition, it was required that participants had no history of a serious cardiovascular, neurological, vestibular, or neuromuscular disease that would prevent them from performing the planned testing and training protocols during the study period.

The exclusion criteria were defined as having previously undergone ACL reconstruction or major knee surgery; having a history within the last six months of a lower-extremity joint injury requiring more than four weeks away from sport; being unable to safely perform jump–landing tests on measurement days due to lower-extremity pain, swelling, or functional limitation; attending less than eighty percent of the planned warm-up sessions during the intervention period; and having started an additional individual strength or plyometric training program during the study process. Sample size was calculated using the G*Power 3.1 program for the primary endpoint, knee valgus angle, based on the expected effect size between two independent groups (independent-samples t-test; two-tailed). With these parameters, the total sample size was determined as 30 (15 in each group). Thus, the sample size was planned to address the primary biomechanical endpoint, whereas inference regarding secondary performance outcomes should remain more cautious.

2.3 Randomization and Groups

Athletes who met the inclusion and exclusion criteria were randomly assigned into two groups: the “micro-dose neuromuscular warm-up group” and the “control group.” During randomization, athletes’ playing positions (e.g., center back, wing, pivot, goalkeeper) were taken into account, and care was taken to ensure that the distribution of positions in both groups was as similar as possible. This position-balanced allocation was used to reduce obvious positional imbalance in this small sample.

2.4 Micro-Dose Neuromuscular Warm-Up Protocol

In the experimental group, the micro-dose neuromuscular warm-up program was implemented at the beginning of team training sessions in place of a part of the routine warm-up. The main parameters of the program, the operational session structure, the exercise categories, and the progression principles are presented in Table 1. The implementation was planned without creating an additional training block, thereby preserving the practical warm-up character of the program. The control group continued with the routine training program.

Table 1 presents the short 10-12 min session structure integrated into the pre-training warm-up, which is the key operational feature of the micro-dose approach. In the present field setting, standardization was achieved primarily through exercise category, session order, technical feedback, and week-to-week progression rather than through a separate high-volume conditioning block.

The program sequence (trunk-hip control -> jump-landing -> acceleration-deceleration) and the technical criteria (knee-hip alignment, soft landing, and controlled deceleration) support standardization across sessions and target movement-quality components related to landing biomechanics. The progression principle was planned such that, in the first weeks, technical learning and basic control were prioritized; in the following weeks, task complexity and repetition or intensity were gradually increased. This approach aimed to maintain the quality of the neuromuscular stimulus while preserving the warm-up characteristic without inducing excessive fatigue.

Table 1. Micro-dose neuromuscular training program applied in the experimental group

Exercise	Order	Content (scope)	Technical criteria / feedback	Progression (by weeks)
Trunk–hip stabilization and motor control	1	Trunk and hip-region stabilization/control exercises.	Neutral trunk; pelvic control, knee–hip alignment; controlled tempo.	Weeks 1–2: technical learning and basic control. Weeks 3–4: increase task complexity. Weeks 5–6: gradually increase repetitions and/or difficulty level.
Controlled jump–landing tasks (bilateral/unilateral)	2	Low-to-moderate intensity multi-planar plyometric tasks; controlled jump–landing patterns.	Feet shoulder-width apart; soft/controlled landing; prevent medial knee collapse, symmetrical loading.	Weeks 1–2: focus on landing technique and alignment. Weeks 3–4: single-leg emphasis and multi-planar tasks. Weeks 5–6: increase volume/difficulty while maintaining quality.
Short-distance acceleration–deceleration	3	Short-distance basic running tasks; acceleration–deceleration components.	Postural control; step frequency, controlled braking; preparation for change of direction while maintaining knee–hip alignment.	Weeks 1–2: low intensity, technique focus. Weeks 3–4: increase repetitions.Weeks 5–6: increase braking-demand complexity while maintaining alignment quality.

Note. Program parameters: 6 weeks; 3 sessions per week; session duration 10-12 min; implemented before team training; total warm-up duration was matched with the control group. Exercises were planned at low-moderate intensity for warm-up purposes; movement quality (knee-hip alignment, soft landing, and trunk stability) was prioritized. Progression was achieved by increasing task complexity and/or repetitions across weeks while avoiding excessive fatigue. The table describes the operational structure used for field standardization.

2.5 *Jump Performance Measurements*

Jump performance was evaluated using the squat jump (SJ) and countermovement jump (CMJ) tests. All athletes were familiarized with the tests through a general warm-up and a few practice jumps prior to testing. Jump height was determined using a portable contact platform and an optical system that calculates based on ground contact and flight time. During the squat jump, athletes held a semi-squat position with approximately half flexion at the knee and hip for a short period, and then performed the highest possible vertical jump without additional knee flexion. In the countermovement jump, athletes attempted to achieve the highest jump height with a rapid squat–rise movement from an upright standing position. For each test, at least three valid trials were recorded and the highest value was considered. Short rest intervals were given between trials. In the analyses, the highest jump value obtained for each test was used. Because the study was conducted in a field setting, exact pre-test recovery status and individual time-of-day matching were not formally logged, which should be considered when interpreting performance outcomes. It has previously been shown that SJ and CMJ tests are reliable and valid field tests for assessing lower-extremity explosive power (14).

2.6 *Landing Mechanics and Knee Valgus Angle*

Landing mechanics and frontal-plane knee valgus angle were evaluated using a standardized bilateral drop jump task. Athletes stepped forward off a 30 cm platform, landed bilaterally on the ground, and were encouraged to jump as high as possible immediately after ground contact. During the task, hands were kept fixed on the hips and the feet were positioned at shoulder width. To determine the frontal-plane knee valgus angle, video was recorded from the front of the athletes, and the medial knee displacement at the moment of maximum knee flexion after landing was calculated using two-dimensional analysis software. Because the task was bilateral, the reported value represents a combined frontal-plane estimate from the landing trial rather than separate dominant- and non-dominant-limb scores. For each athlete, at least three valid trials were recorded, and the mean value of these trials was used in the analysis. Drop jump height was calculated from the same trials, and the mean of each athlete's three trials was used in the analysis. It has previously been reported that dynamic knee valgus and knee loading characteristics during jump-landing tasks are associated with the risk of anterior cruciate ligament injury (5). Although two-dimensional analysis is more accessible than three-dimensional systems and was therefore selected for this field study, it may be influenced by transverse-plane motion, camera or visual alignment, and landmark identification issues (15, 16).

2.7 Implementation Process

During the implementation, both groups continued their in-season match and training schedules as routine. The micro-dose warm-up sessions were integrated into the existing warm-up routine in a way that would not meaningfully increase the experimental group's total weekly training duration. Both groups therefore remained exposed to their usual team-based in-season practice and match demands, but a separate external-load quantification system was not available in the present field setting. Attendance status was recorded for each session; athletes who attended less than 80% of the planned sessions were flagged to be excluded from analysis. Any new lower-extremity injuries that might develop during the study were monitored in coordination with the team health staff.

2.8 Statistical Analysis

Data were presented as mean ± standard deviation. Within-group comparisons between pre-test and post-test values were performed using the paired-samples t-test. Between-group comparisons were conducted using the independent-samples t-test. Normality was evaluated using the Shapiro-Wilk test based on pre-post difference scores for each variable. Effect size was calculated as Cohen's dz for paired measurements. For the main outcomes, mean changes and 95% confidence intervals were also reported to improve interpretation of estimate precision. For between-group comparisons, t-values and p-values were reported. $p < 0.05$ was considered statistically significant. Because of the small sample and field-based design, a mixed-model or repeated-measures ANOVA was not applied; this should be considered a methodological limitation when interpreting group-by-time effects. Analyses were performed using SPSS 28.0.

3. Results

3.1 Within-Group Changes

Within the experimental group, knee valgus angle decreased significantly from 9.8 ± 2.1° to 7.2 ± 1.8° (mean change: -2.6°, 95% CI: -3.63 to -1.57°, p = 0.0001, dz = 1.40). Jump performance also improved within the experimental group (squat jump: 42.3 ± 4.5 to 45.1 ± 4.2 cm, mean change: 2.8 cm, 95% CI: 1.25 to 4.35 cm, p = 0.0017, dz = 1.00; countermovement jump: 45.6 ± 5.1 to 48.9 ± 4.8 cm, mean change: 3.3 cm, 95% CI: 1.78 to 4.82 cm, p = 0.0004, dz = 1.20; drop jump: 44.2 ± 4.8 to 47.5 ± 4.5 cm, mean change: 3.3 cm, 95% CI: 1.86 to 4.74 cm, p = 0.0002, dz = 1.27). No statistically significant within-group changes were observed in the control group (all p > 0.05). The descriptive pre-post profile for knee valgus angle is shown in Figure 1, and the descriptive profiles of the jump variables are shown in Figure 2.

Table 2. Effects of the Micro-Dose Neuromuscular Warm-Up on Biomechanical and Performance Parameters

Variable	Group	Pre-test (Mean ± SD)	Post-test (Mean ± SD)	t-value	p-value	Cohen's dz
Knee Valgus Angle (°)	Experimental	9.8 ± 2.1	7.2 ± 1.8	5.42	0.0001	1.40
Knee Valgus Angle (°)	Control	9.6 ± 2.3	9.4 ± 2.2	0.61	0.542	0.16
Squat Jump (cm)	Experimental	42.3 ± 4.5	45.1 ± 4.2	3.87	0.0017	1.00
Squat Jump (cm)	Control	41.8 ± 4.7	42.0 ± 4.6	0.28	0.780	0.07
Countermovement Jump (CMJ) (cm)	Experimental	45.6 ± 5.1	48.9 ± 4.8	4.65	0.0004	1.20
Countermovement Jump (CMJ) (cm)	Control	45.1 ± 5.3	45.3 ± 5.2	0.24	0.812	0.06
Drop Jump Height (cm)	Experimental	44.2 ± 4.8	47.5 ± 4.5	4.92	0.0002	1.27
Drop Jump Height (cm)	Control	43.9 ± 5.0	44.1 ± 4.9	0.31	0.754	0.08

Note. Effect size was calculated as Cohen's dz for the within-group paired t-test ($dz = t/\mathrm{sqrt}(n)$; n = 15). Experimental-group mean changes with 95% confidence intervals were as follows: knee valgus angle, -2.6° (-3.63 to -1.57); squat jump, 2.8 cm (1.25 to 4.35); countermovement jump, 3.3 cm (1.78 to 4.82); drop jump, 3.3 cm (1.86 to 4.74). Post-test between-group comparisons were as follows: knee valgus angle, t(28) = -3.00, p = 0.006, mean difference = -2.2° (95% CI: -3.70 to -0.70); squat jump, t(28) = 1.93, p = 0.064, mean difference = 3.1 cm (95% CI: -0.19 to 6.39); countermovement jump, t(28) = 1.97, p = 0.059, mean difference = 3.6 cm (95% CI: -0.14 to 7.34); drop jump, t(28) = 1.98, p = 0.058, mean difference = 3.4 cm (95% CI: -0.12 to 6.92). Descriptive pre-post profiles are presented in Figures 1 and 2.

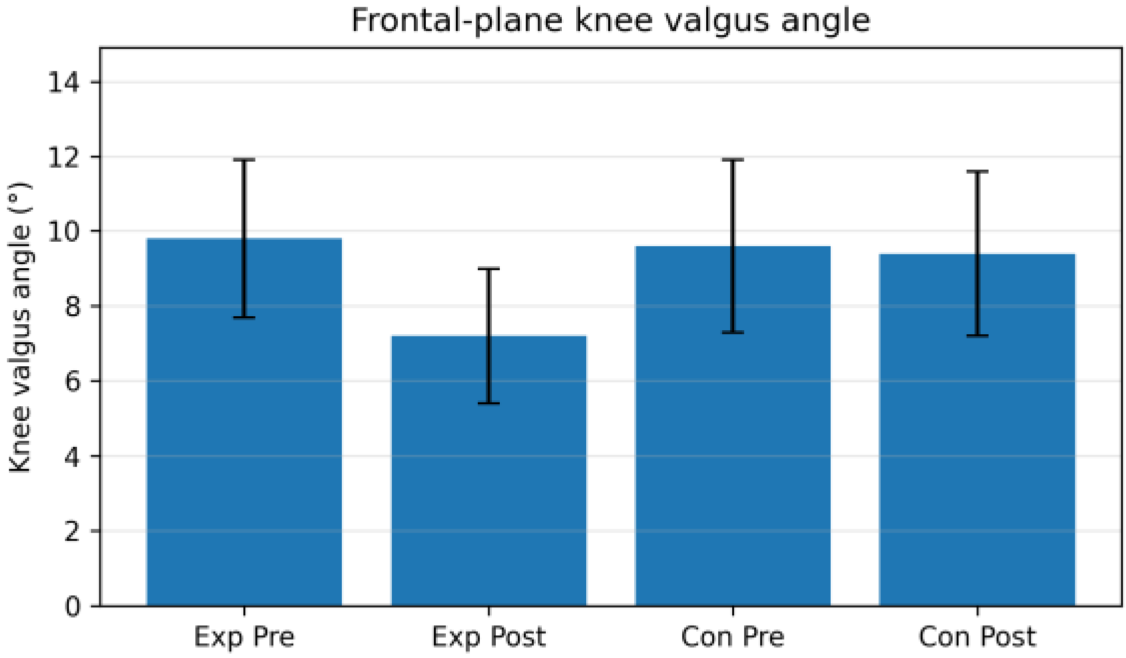

Figure 1. Pre-test and post-test frontal-plane knee valgus angle in the experimental and control groups (mean ± SD).

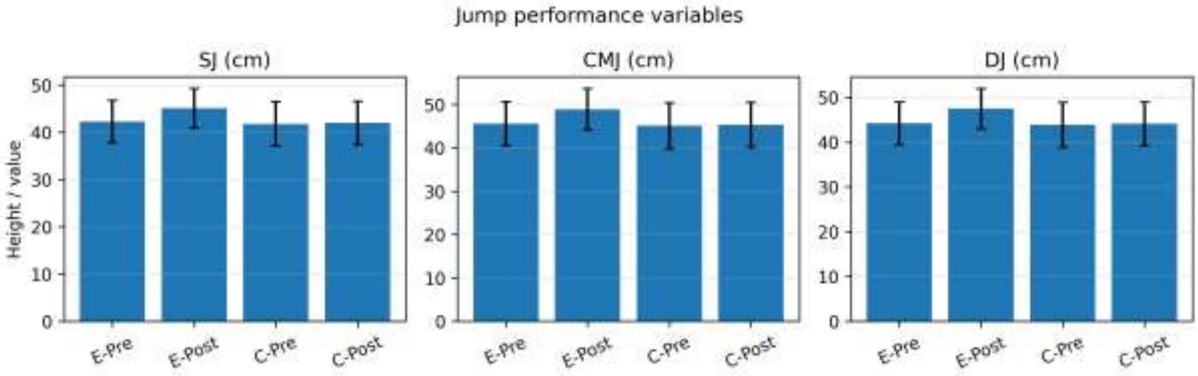

Figure 2. Pre-test and post-test jump performance in the experimental and control groups (mean ± SD). Panels show squat jump, countermovement jump, and drop-jump height.

3.2 Post-Test Between-Group Comparisons

In the post-test comparison, knee valgus angle was lower in the experimental group than in the control group (mean difference: -2.2°, 95% CI: -3.70 to -0.70, p = 0.006). By contrast, between-group differences in jump outcomes did not reach statistical significance, although they remained close to the threshold (squat jump mean difference: 3.1 cm, 95% CI: -0.19 to 6.39 cm, p = 0.064; countermovement jump mean difference: 3.6 cm, 95% CI: -0.14 to 7.34 cm, p = 0.059; drop jump mean difference: 3.4 cm, 95% CI: -0.12 to 6.92 cm, p = 0.058). Accordingly, the most robust comparative finding of the present study concerns frontal-plane knee valgus rather than a definitively established performance effect.

4. Discussion

This study examined a brief, warm-up-integrated, in-season neuromuscular format rather than the general effectiveness of neuromuscular training per se. In this respect, the innovation of the study lies in the micro-dose delivery format embedded within the routine warm-up in male regional-level handball players. The main finding was that knee valgus angle decreased significantly in the experimental group and was lower than in the control group at post-test. Accordingly, the clearest result of the study concerns frontal-plane knee control during landing. The jump findings are encouraging, but they should be interpreted more cautiously because the post-test between-group comparisons did not reach conventional statistical significance.

The reduction in dynamic knee valgus is directly supported by the present data and is consistent with the movement-control emphasis of the protocol. The program consisted of trunk-hip stabilization, controlled bilateral or unilateral landing tasks, and acceleration-deceleration components; it was also supported by technical criteria such as knee-hip alignment, soft landing, and symmetrical load distribution, thereby targeting key mechanisms for reducing frontal-plane deviations. The experimental group showed a mean reduction of 2.6° in knee valgus angle, which may be practically relevant as an indicator of improved frontal-plane alignment during landing, although a direct clinical threshold cannot be inferred from the present design. The literature reports that implementing neuromuscular training in a multi-component format both improves biomechanical risk factors and is associated with injury-reducing effects in sports (17). In this context, the valgus reduction observed in the present study should be interpreted as evidence of improved landing mechanics rather than as direct evidence of reduced injury incidence (18).

Because handball is an invasion sport dominated by high-intensity jump-landing cycles and rapid changes of direction, improving landing biomechanics and frontal-plane knee control is of critical importance for field applications. It has been reported that adding neuromuscular training during the in-season period in adolescent handball players improves knee biomechanics during the drop jump, and that improvements are more pronounced especially in athletes with more evident valgus alignment at baseline (19). These findings support the interpretation that the decrease in knee valgus angle in the present study reflects a functional improvement in landing quality and lower-extremity control required by handball.

An important advantage of the micro-dose approach applied in this study is that, instead of long-duration training programs that may be difficult to implement during the in-season period because of time constraints and training-load management, it provides a regular neuromuscular stimulus through short sessions that can be integrated into the warm-up. A meta-analysis examining the dose-response relationship of neuromuscular training in young athletes emphasizes that the most effective programs are generally short 10-15 min sessions performed 2-3 times per week and that this format can be integrated into the regular training process (20). The 10-12 min micro-dose format of the present study is consistent with these findings and supports field feasibility.

From a neuromuscular mechanism perspective, the reduction in knee valgus may be related to increased trunk-hip stability, more effective muscle activation timing during landing, and increased contribution of the hamstring muscle group, including the medial hamstrings. It has been reported that in-season neuromuscular training programs applied in elite football and handball athletes increase medial hamstring activation during change of direction, and that this may be associated with neuromuscular adaptations that can reduce dynamic knee valgus (21). However, these mechanistic explanations remain interpretative, because electromyographic or kinetic variables were not measured directly in the present study.

In terms of performance parameters, significant within-group increases were observed in the experimental group in squat jump, countermovement jump, and drop jump tests; however, these improvements were not accompanied by statistically significant between-group post-test differences. Therefore, the present data do not support a definitive performance effect beyond the primary biomechanical outcome. Instead, the performance findings should be regarded as promising but preliminary, and larger samples or longer interventions may be required for these changes to be demonstrated more clearly in comparative analyses. Systematic reviews nonetheless suggest that integrative neuromuscular training may positively influence jump and general motor performance in young athletes (22).

The assessment of knee valgus angle with two-dimensional analysis provides a feasible and accessible measurement approach under field conditions. It has been reported that two-dimensional measurements can show high validity with three-dimensional systems for some parameters and that reliability levels can be acceptable (16). Similarly, it has been reported that the reliability of measurements is acceptable when evaluating dynamic knee valgus with two-dimensional video analysis (15). However, two-dimensional frontal-plane estimates remain less precise than three-dimensional biomechanical analysis and may be affected by transverse-plane motion, camera or visual alignment, and landmark or marker placement error.

Therefore, the present valgus findings should be interpreted as practical field estimates rather than exhaustive biomechanical descriptors (15, 16).

Several limitations should be considered. First, the intervention period was limited to 6 weeks and no follow-up injury incidence data were collected. Second, although the sample size was consistent with the a priori power analysis for the primary endpoint, the modest number of players limits precision for the secondary performance outcomes and constrains external generalizability. Accordingly, the present findings should be generalized cautiously, primarily to male regional-level handball players in similar in-season settings. Third, although the analytical approach was acceptable for a small field study, a mixed-model or repeated-measures framework would have provided a stronger test of the group-by-time interaction. Fourth, detailed baseline descriptive variables such as age, stature, body mass, playing experience, and position distribution were not tabulated in the present report, which reduces the visibility of baseline comparability. Fifth, the protocol was standardized through session structure, exercise category, technical criteria, and progression, but the absence of drill-by-drill operational logs limits full reproducibility. Sixth, detailed external-load monitoring, exact time-of-day matching, and pre-test recovery status were not formally quantified, which should be considered when interpreting the performance-related findings. Finally, the manuscript states that assessors were blinded to group allocation, yet a separate coded-video workflow was not documented in detail. These points should be addressed in future studies with larger samples and more comprehensive reporting.

From an applied perspective, coaches can implement this format by replacing a short portion of the regular in-season warm-up with 10-12 min of trunk-hip control, technique-focused jump-landing drills, and brief acceleration-deceleration tasks performed three times per week. The present findings support this approach primarily as a feasible strategy to improve landing mechanics; any expectation of direct injury reduction or clearly established jump-performance enhancement would go beyond the evidence collected in this study.

5. Conclusion

In this study, a 6-week micro-dose neuromuscular warm-up integrated into the routine in-season warm-up reduced frontal-plane knee valgus during landing in male handball players. This was the clearest finding of the study. Although the intervention group also showed favorable within-group changes in squat jump, countermovement jump, and drop-jump performance, these outcomes were not supported by statistically significant between-group post-test differences. Accordingly, the program appears to be a feasible field-based strategy for improving landing mechanics in this competitive context, but these findings should not be interpreted as direct evidence of injury reduction because injury incidence was not measured.

Authors' Contributions

Sezer Taştan contributed to study conception, data collection, formal analysis, and original drafting of the manuscript. Mustafa Topraklı contributed to study design, supervision, interpretation of the findings, and critical revision of the manuscript. Harun Ertören contributed to methodological support, literature review, interpretation of the findings, and critical revision of the manuscript. All authors approved the final version and accepted responsibility for the content.

Declaration

None.

Transparency Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

The study was approved by the Scientific Research and Publication Ethics Committee of Isparta University of Applied Sciences (Meeting No. 223, Decision No. 13, 10 February 2026). Written informed consent was obtained from all participants before enrolment.

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