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Title: Effects of Stop-X and Knee Control Training on Knee Kinetics and Dynamic Knee Valgus During Single-Leg Drop Landing in Male Futsal Players: A Randomized Controlled Trial

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Abstract

Background: Most anterior cruciate ligament (ACL) injuries are noncontact. Modifiable risk factors such as dynamic knee valgus (DKV) and higher ground reaction force (GRF) may increase ACL loading by altering lower-limb alignment and joint stress. The goal of this study was to compare the effects of Stop-X training and Knee Control training on primary outcomes of GRF variables and DKV, and secondary outcomes of Loading rate (LR) and Center of pressure (COP) displacement during a single-leg drop landing (SLDL) task.

Method: In this randomized controlled experiment, 45 male futsal athletes with DKV were allocated to the Stop-X group (n=15), the Knee Control group (n=15), and a control group (n=15). Kinetics were documented with a force plate at a frequency of 1000 Hz, whereas DKV was assessed through two-dimensional (2D) motion analysis. Participants had 8 weeks of monitored training. Analysis of covariance (ANCOVA) was used in this study. Effects were considered significant at $P < 0.05$ for ANCOVA. To reduce Type I error, the Bonferroni correction (adjusted significance level: $P \leq 0.016$) was applied to pairwise post-hoc comparisons of significant interaction effects. This has been documented in the Iranian Clinical Trials Registry (Code: IRCT20241230064223N1, Date: 2025-01-18).

Results: After adjustment for baseline values using ANCOVA, significant between-group effects were observed for peak vertical GRF (Fz) ($F = 8.42$, $p < 0.01$, $\eta^2p = 0.29$), peak anterior – posterior GRF (Fymax) ($F = 3.63$, $p = 0.03$, $\eta^2p = 0.19$), minimum medial - lateral GRF (Fxmin) ($F = 5.20$, $p = 0.01$, $\eta^2p = 0.25$), and DKV ($F = 33.61$, $p < 0.01$, $\eta^2p = 0.69$). Bonferroni-adjusted pairwise comparisons showed that Stop-X and Knee Control had significantly lower Fz and DKV values than the control group. No significant differences were found between the Stop-X and Knee Control groups for any outcome.

Conclusion: The results indicate that both Knee Control and Stop-X training programs improved landing biomechanics compared to the control group by decreasing GRF variables and DKV. However, no statistically significant superiority was observed between the two intervention protocols. Thus, both programs can be regarded as effective neuromuscular training approaches for improving landing biomechanics in athletes performing high-risk landing tasks.

Keywords: Landing, Kinetic, Training, Dynamic knee valgus

1. Highlight

This research aimed to evaluate the impact of two injury prevention training regimens (Stop-X and Knee Control) on 1) GRF in all directions, 2) COP in the medial-lateral axis (COPx) and COP in the anterior-posterior axis (COPy), and 3) DKV during SLDL.

1.1. The findings showed:

1.1. The training interventions resulted in significant improvements in landing biomechanics during SLDL.

1.1.1. DKV was significantly reduced in both intervention groups, with greater within-group changes observed in the Knee Control group.

1.1.2. Vertical GRF (Fz) was significantly reduced following both training programs, accompanied by large effect sizes, particularly in the Knee Control group for selected outcomes.

1.1.3. Medial-lateral GRF (Fx) demonstrated significant reductions in the intervention groups, indicating improved frontal-plane landing control.

2. Primary Language Summary

The study compared two different injury prevention training programs (Stop-X and Knee Control) on an SLL task. Both training programs improved landing mechanics by improving movement control and reducing risky knee movement patterns. Both intervention groups showed improvements, with no clear differences between the two programmes. These findings suggest that structured neuromuscular training may be effective at improving landings in athletes performing high-risk movements.

Introduction

The SLDL, a specific form of single-leg landing (SLL) task, is a common post-jump movement in sports such as futsal and is also widely used to assess lower limb movement patterns and screen for ACL injury risk (1, 2). However, SLL with altered biomechanics, characterized by increased peak GRF, LR, and excessive DKV over and above that associated with excessive hip adduction and internal rotation, knee abduction, and tibial misalignment during dynamic weight-bearing tasks in the frontal plane, is considered a biomechanical indicator of increased ACL injury risk (3-6). Compared with two-legged landings, SLDL tasks demonstrate greater vertical and shear GRFs and are associated with greater knee joint loading (7-9). McNair et al. (10) reported a moderate positive correlation between the magnitude of the GRF and tibial acceleration during landing, highlighting a potential association between impact forces and ACL loading (10). Also, Zamankhanpour et al.(6) demonstrated that excessive DKV is associated with increased external loading of the knee joint and a higher GRF loading rate during landing, which may be linked to increased knee joint loading (6). In addition to kinematic measures, COP variables enhance the understanding of dynamic postural stability and neuromuscular control during landing tasks. Center of pressure displacement in both COPx and COPy directions is indicative of body positional control and post-impact stability (11). Increased COP fluctuations during SLDL are associated with impaired balance, altered neuromuscular function, and decreased dynamic stability, and affect loading patterns of the lower extremities, particularly the knee, in sports (11). The ACL injury is a significant issue in sports medicine, frequently leading to extended time away from athletic activities and competition, while also creating a considerable financial strain (12). A significant proportion of these injuries occur through non-collision mechanisms, estimated at 55% of all ACL injuries (13-16). Therefore, given this evidence, Therefore, SLDL performance, in combination with neuromuscular control deficits and lower-limb biomechanical alterations, may be associated with increased risk of non-contact ACL injury. DKV is considered one of the commonly observed movement patterns associated with this risk (15, 16). Due to the increase in ACL injuries, several exercise-based injury prevention programs have been developed in recent years to decrease the risk of ACL injury. Evidence suggests that multi-joint neuromuscular training techniques tend to be more effective than isolated single-joint exercises for improving movement quality and decreasing injury risk in athletic populations (17). The primary objective of these programs is to increase balance, muscle strength, and neuromuscular coordination while promoting safer movement strategies during basic athletic tasks such as running and landing after a jump (17, 18). The Knee Control and Stop-X protocols are two exercise-based injury prevention regimens that try to lessen the risk of ACL injury by enhancing neuromuscular components, balance, and lower-limb biomechanics (19, 20). Among these programs, the Stop-X and Knee Control protocols have gained considerable attention in team-sport settings. The German Medical Association's Stop-X training program has been associated with a reduction in ACL injuries of about 51% and knee injuries of 21% in team-sport athletes under structured intervention conditions (18). Similarly, meta-analysis evidence suggests that the Knee control training program, a targeted warm-up program designed by physiotherapists at the Swedish Medical Association, was more effective in reducing injury risk in team sports athletes, although the magnitude of effect varies across studies depending on population characteristics, compliance levels, and outcome definitions (18, 21). Given the high-pressure nature of futsal, which involves rapid acceleration and deceleration and frequent SLL, injury prevention strategies are particularly important for young male players. Although previous studies have primarily examined the effects of Stop-X and Knee Control interventions separately on DKV, their effects on kinetic variables related to altered landing mechanics have not been adequately compared with each other. Based on previous evidence regarding neuromuscular injury-prevention programs, we hypothesized that both the Stop-X and Knee Control training programs would significantly improve landing biomechanics by reducing DKV, GRF, LR, and COP displacement during SLDL compared with the control group. We further hypothesized that the Knee Control program might produce greater improvements due to its progressive exercise structure and emphasis on movement quality.

2. Methods

2.1. Study design

This study was designed as a randomized controlled trial (RCT). The primary outcome measures were GRF variables and DKV. LR and COP displacement were considered secondary biomechanical outcomes.

2.2. Participation

A total of forty-five male professional futsal players aged 18–25 years were recruited for this study (Table 1). Participants performed the tuck jump test, which was recorded using video analysis. DKV was then assessed through frame-by-frame analysis of the recorded videos. The tuck jump test was used as a standardized functional landing task to elicit lower-limb neuromuscular control patterns, similar to SLDL, rather than as a diagnostic instrument (please see 2.7.1 section). Participants also had at least three years of playing experience in national leagues. Sample size determination was performed using G*Power software [version 3.1.9.4, alpha level 0.05, type II error 0.20 (power 0.80)] based on effect sizes reported in a previous randomized controlled trial that investigated the effects of the Stop-X training program on DKV angle and balance outcomes in athletes with DKV (20). Unwillingness to continue participating in the study, absence from three consecutive training sessions, and any previous injury (six months before the study) that may have affected the ligaments, tendons, muscles, and bones of the lower extremities were our exclusion criteria for the study (22). The purpose and subject of the project were then explained to each participant, and participants and parents signed a written consent form.

2.3. Ethical considerations

An ethical approval code was obtained from the Ethics Committee in Biomedical Research of the University of Guilan (IR.GUILAN.REC.1403.170). The participant sample analyzed in the present study is identical to that reported in our previous publication and originates from the same registered randomized controlled trial (Code: IRCT20241230064223N1, Date: 2025-01-18). According to the pre-specified protocol, outcomes included three-dimensional (3D) peak GRF and DKV during multiple functional tasks (side-cutting and SLDL). In our previous publication, we reported only the side-cutting outcomes. The present manuscript reports the pre-specified but previously unpublished landing-related outcomes (SLDL). Therefore, no post hoc outcome selection was performed. The final analysis was performed on a per-protocol basis, including only those participants who completed the intervention and post-intervention assessment. CONSORT flow diagram (Figure 1) shows withdrawals, losses to follow-up, and the number of participants included in the final analysis.

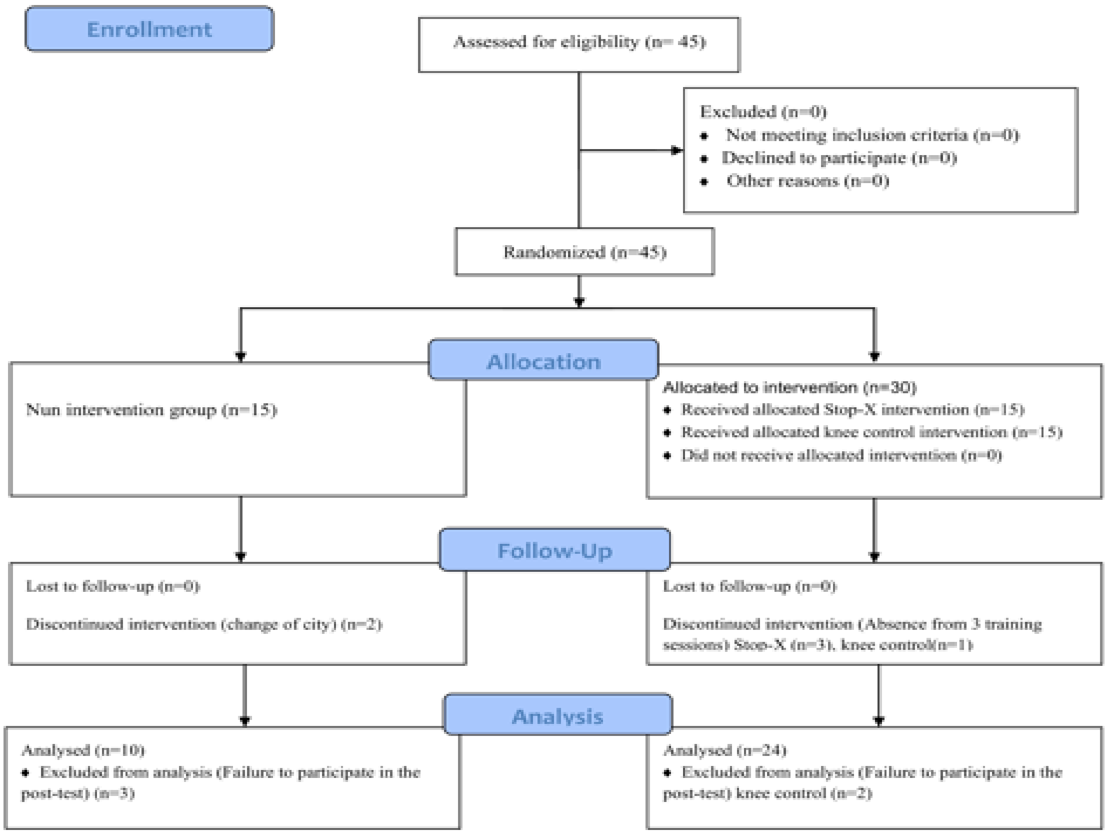

Figure 1. CONSORT flow diagram

2.4. Randomization

This study was a randomized controlled trial with concealed allocation. An independent investigator, who had no role in the recruitment or assessment of participants, created a computerized randomization sequence using Microsoft Excel software. The study groups were denoted by the letters A (control group), B (Knee Control group), and C (Stop-X group). Participants were assigned to one of three study groups using a concealed allocation method, with equal numbers assigned to each group (n = 15 per group). Allocation concealment was maintained until group assignment using sealed, opaque, consecutively numbered envelopes. Due to the nature of the supervised exercise interventions, blinding of participants and the physiotherapists supervising the training sessions after group allocation was not feasible, but participants were unaware of the upcoming group assignment until completion of the allocation process (Figure 1). Opaque envelopes and standardized procedures were used to minimize potential sources of bias. Also, to minimize detection bias, the laboratory technician responsible for force plate and video data acquisition and the investigator responsible for processing and analyzing the biomechanical data were blinded to group allocation throughout the study. However, a small amount of bias inherent in single-blind designs cannot be ruled out. After participants were assessed using the tuck jump test, eligible subjects who demonstrated DKV returned to the biomechanics laboratory after one week to collect kinetic data from the force plate and DKV data via camera analysis during SLDL as a pretest. The intervention groups performed Stop-X and Knee Control exercises in addition to their eight-week program, followed by a one-week post-test.

The control group also continued their team training before the post-test. The data were then analysed.

Table 1. Demography information

(Here)

2.5. Ground reaction force and Center of pressure measurement

GRF data were recorded using a force platform (Bertec, model number 4060-08, Columbus, Ohio, USA) set in the middle of an 18-m walking track. Signals were sampled at a frequency of 1000 Hz. Kinetic data processing followed established biomechanical procedures. We used a 4th-order Butterworth low-pass filter with zero delay at 20 Hz to filter the raw GRF data. The extracted kinetic variables included Fz, peak, Fymin and Fymax, and Fxmin and Fxmax, and LR (calculated as the average slope of the Fz–time curve from initial contact to the first peak vertical GRF and expressed in $BW \cdot s^{-1}$), during the landing phase. Additionally, GRF values were normalized to each participant's body weight (BW) and reported as a percentage of BW to facilitate comparisons between participants. In addition to GRF data, we also extracted COP data. In addition to the GRF data, we extracted COP data derived from the force platform signals. COPx and COPy excursions were calculated as the difference between the maximum and minimum COP values during the ground-contact phase of the landing task (COPmax − COPmin). COP variables were calculated for each trial and then averaged across trials. Pre- and post-intervention values were used for statistical analysis.

Before each kinetic data collection session, the force plate was calibrated using the manufacturer's standard instructions. This included zeroing the baseline signal, applying validated calibration weights to verify surface sensitivity, and identifying specific force constants for the Fz, Fy, and Fx force axes. These steps were performed to maintain the measurement accuracy and reliability of the collected data (23).

2.6. Dynamic valgus

A SONY Alpha series 120 fps camera recorded 2D DKV data in the frontal plane 230 cm from the force plane at knee height. Three correct movements were analyzed on a computer. The videos were analyzed frame by frame at the peak of knee flexion to identify the mechanical components of the landing. Kinovea motion analysis calculated the DKV angle. Employing the software's line drawing functionality, the DKV angle was calculated by linking anatomical reference points physically positioned on the anterior superior iliac spine (ASIS), the midway of the patella [approximately the intended location of the tibiofemoral joint], and the ankle joint (24). 2D motion analysis was selected because it provides a practical and clinically applicable method for assessing dynamic knee valgus during functional landing tasks. This 2D measure represents a frontal-plane projection of knee alignment during landing and should therefore be interpreted as an estimate of DKV rather than full three-dimensional (3D) joint motion. It has been reported that this software has shown high reliability (ICC: 0.82 - 0.99) for dynamic motion assessment and falls within the acceptable validity range (0.45 - 0.78) when compared to the gold-standard 3D analysis (25-27). Additionally, to enhance the reliability of the data, a second qualified evaluator reviewed the analysis, and measurements were reiterated to ensure precision. Moreover, owing to the constraints of our two-dimensional measurements, replicates exhibiting significant marker loss and diminished data quality were omitted from the analysis. This procedure aims to uphold the accuracy and integrity of the biomechanical data (26).

2.7. Functional test

All experiments were conducted under standard laboratory conditions in the Sports Biomechanics Laboratory of Mohaghegh Ardabili University. Also, to personalize the longitudinal distance of the participants' placement and the box from the force plate, the actual length of each participant's leg was measured from the ASIS to the medial malleolus, and 80% of this measurement was taken as the landing distance determination (28). Our functional tests included SLDL, which were measured in accordance with the study protocol.

2.7.1. Tuck jump

Participants were assessed for DKV through the tuck jump test. DKV was specifically defined as the medial displacement of the knee compared to the hip and ankle during landing in the frontal plane. Those who exhibited DKV at landing were deemed eligible for the study as evaluated by trained assessors. This functional screening tool is widely used to identify individuals at risk for ACL injury and jump-landing impairment and has demonstrated acceptable sensitivity and reliability (ICC 0.94–0.96) in previous research (29). Although the tuck jump Test involves bilateral landings, only the dominant limb was evaluated for DKV. Participants were asked which leg they naturally kicked a ball with to determine the dominant limb. The tuck jump uses a ten-point (0–10) scoring system, with scores of 6 or higher indicating severe motor impairment and increased risk of ACL injury. Each criterion is assessed in two parts to reflect the presence or absence of a motor impairment (30, 31). The criteria measured include various aspects of jump-landing performance, including knee and hip control in the frontal plane, foot contact during landing, foot position, and overall plyometric technique, all of which provide a comprehensive assessment of performance during repeated jump-landings (29). Participants performed serial squat jumps for 10 seconds, raising their legs to hip height, while movement patterns were recorded simultaneously from sagittal and frontal views. However, the main purpose of this screening method in the present study was to confirm the presence of DKV before biomechanical evaluation.

2.7.2 Single-leg drop landing

For the SLDL test, participants stood in their racing shoes and, as per the actual protocol, on the edge of a 35 cm high wooden box, at a distance of 80% of their leg length (measured from the ASIS to the medial ankle), with their hands free in front of a force plate. From an initial starting position, participants were instructed to step forward without jumping up from the box, perform a single-leg vertical landing from the box, and pause for three seconds after landing on the force plate (32). The tested limb was selected according to the predefined screening protocol. Before data collection, participants performed three familiarisation trials. Then, three successful trials were recorded for analysis. Additionally, Participants were given a 30-second rest period between trials to minimize potential effects of fatigue. Perceived exertion was measured at each rest interval using the Borg Rating of Perceived Exertion (RPE) scale. If a participant reported an RPE score>10, the rest period was extended until the participant indicated they had recovered sufficiently before proceeding to the next trial. There was no exclusion or repetition of trials due to fatigue, and all assessments were performed under standardized testing conditions (33).

2.8. Intervention

We performed Stop-X and Knee Control exercises under the supervision of a physiotherapist with 3 years of clinical experience in Mohaghegh Ardabili University's indoor gymnasium under standard lighting and temperature. A total of 24 training sessions were scheduled for participants, with missed sessions recorded in the attendance log. Participants who were unable to attend a scheduled session were encouraged to complete the session at the next opportunity if possible; otherwise, the missed session was recorded as a no-show, which was removed from the protocol if the absence was recorded for 3 consecutive days. Participants first warmed up for 5 minutes, performed basic exercises for 20 to 25 minutes, and then performed a cool-down exercise. The intensity and progression of the exercises were also defined based on predetermined progress criteria related to movement quality, postural control, balance function, and the ability to perform the prescribed exercises without compensatory movement patterns. Participants were promoted to the next level of training if they performed technically and controlled adequately. In the event of a disturbance in knee position (e.g., DKV) or a compensatory pattern due to fatigue, the training level was maintained until the correct movement quality was achieved.

2.8.1. Stop-X

The Stop-X training program is a structured intervention developed by the German Society of Sports Medicine for lower extremity injuries and is modeled after several injury prevention training programs, including FIFA 11+ and the Monica Santa Injury Program, among others (34). The Stop-X program includes running exercises, balance exercises, plyometric jumps, controlled landing tasks, and core-strengthening activities such as planks, side planks, lunges, and single-leg squats, performed on soft or Nordic surfaces. The training intervention was performed by the training groups for 8 weeks, three days a week, for an average of 20 to 25 minutes. The training level, including the degree of difficulty, number of repetitions, and number of sets, was increased every two weeks, as detailed in Appendix A1.

2.8.2. Knee Control

This targeted training intervention for knee injury prevention, developed by the Swedish Football Association's Medical Committee, emphasizes neuromuscular control and core stability and consists of six exercises, including hip raises, squats (two-legged and single-legged), chest presses, lunges, and jumps/landings. Participants performed the training program for an average of 20 to 25 minutes over 8 weeks, three sessions per week. Each exercise is gradually organized into four levels from level A to D, with the level of training increasing every two weeks. An interesting feature of this protocol is the use of a pair exercise at the end of each training session to increase variety and motivation, as detailed in Appendix A2 (35). Additionally, supervising trainers kept detailed session records to track participants' compliance, making sure that every assigned exercise was carried out properly during each session.

2.9. Statistical analyses

Before the main analysis, the Shapiro–Wilk test was used to assess the normality of the continuous variables, and Levene's test was used to assess homogeneity of variance. Before the ANCOVA, the regression slope uniformity hypothesis was tested and validated. One-way analysis of variance (ANOVA) was used to compare the baseline demographic features of the three groups. To assess the biomechanical effects of interventions, ANCOVA was performed for each post-intervention outcome, with the corresponding baseline value entered as a covariate to adjust for potential baseline differences. Bonferroni-adjusted pairwise comparisons were used to determine between-group differences when a significant main effect of group was found. Effect sizes were measured using partial eta squared (η^2p) and interpreted as small ($0.01 \leq \eta^2p < 0.06$), medium ($0.06 \leq \eta^2p < 0.14$), and large ($\eta^2p \geq 0.14$) (36). Pairwise comparisons were displayed as adjusted mean differences and 95% confidence intervals (95% CI). A p-value < 0.05 was considered statistically significant. All statistical analyses were conducted using IBM SPSS Statistics for Windows (Version 26.0; IBM, Armonk, NY, USA).

3. Results

Table 2 showed significant differences in baseline between-group comparisons for Fx GRFs, so ANCOVA with baseline correction was applied to all variables.

Table 2. Comparison of baseline characteristics of three groups during the single-leg drop landing task

(Here)

After adjustment for baseline values using ANCOVA, a significant group effect was observed for Fz ($F_{2,۳۰}$ = 8.42, p-value < 0.01, η^2p = 0.29 – large effect), Fymax ($F_{2,۳۰}$ = 3.63, p-value = 0.03, η^2p = 0.19 – large effect), Fxmin ($F_{2,۳۰}$ = 5.20, p-value = 0.01, η^2p = 0.25 – large effect) and DKV ($F_{2,۳۰}$ = 33.61, p-value < 0.01, η^2p = 0.69 – large effect) and although significant group effect was not observed in Fxmax ($F_{2,۳۰}$ = 3.23, p-value = 0.05, η^2p = 0.17 – large effect), LR ($F_{2,۳۰}$ = 2.23, p-value = 0.12, η^2p = 0.12 – large effect) and COPx ($F_{2,۳۰}$ = 1.39, p-value = 0.28, η^2p = 0.08 – medium effect) and COPy ($F_{2,۳۰}$ = 0.81, p-value = 0.45, η^2p = 0.05 – small effect).

The Knee Control group had significantly lower values than Control, according to Bonferroni-adjusted pairwise comparisons for Fz (mean difference = -187.57, 95% CI -274.77 to -100.37, p-value < 0.01). Similarly, Stop-X had significantly lower values than Control (mean difference = -108.59, 95% CI -190.25 to -26.93, p-value = 0.00). However, there were no significant differences between the Knee Control and Stop-X groups (mean difference=78.98, 95% CI -4.49 to 162.45, p-value = 0.06). For Fymax showed that the knee control group showed significantly higher values than the control group (mean difference = 6.21, 95% CI 1.11 to ۱۱.۳1, p-value = 0.01). Similarly, the Stop-X group also showed higher values than the control group (mean difference = ۵.۶۵, 95% CI ۰/۶۵ to ۱۰.66, p-value = 0.0۲), while no significant difference was observed between the Stop-X and Knee Control groups (mean difference = 0.۵۵, 95% CI -4.00 to 5.11, p-value = 0.80), Also, for Fxmin, the Knee Control group showed significantly lower values than the control group (mean difference = 20.11, 95% CI 6.36 to 33.87, p-value = 0.03). Although the Stop-X and Knee Control groups showed no significant difference (mean difference = 10.48, 95% CI -23.41 to 2.43, p-value = 0.14).

In addition to GRFS, Bonferroni-adjusted pairwise comparisons for DKV showed that the knee control group showed significantly lower values than the control group (mean difference = 4.83, 95% CI 3.25 to 6.41, p-value < 0.01). Similarly, the Stop-X group also showed a lower value than the control group (mean difference = 4.07, 95% CI 2.47 to 5.66, p-value < 0.01), while Stop-X and Knee Control groups did not differ significantly (mean difference = 0.76, 95% CI -0.73 to 2.26, p-value = 0.69).

Table 3. The results of ANCOVA for kinetic and kinematics data in three groups.
(Here)

4. Discussion

This study improves on the body of current literature findings by evaluating two injury prevention strategies, Stop-X and Knee Control, with an emphasis on kinetic and DKV metrics during the SLDL task. While previous research has individually examined the effects of these protocols, limited evidence exists regarding their comparative effectiveness on biomechanical outcomes during SLDL.

After normalizing for baseline values, both intervention groups had significantly lower Fz than the control group; however, the Stop-X and Knee Control groups did not differ. This may be relevant to biomechanical factors associated with ACL injury risk. Our findings are in line with those of Erickson et al. (37), McNair et al. (38), and Cousin et al. (39), who reported that exercise interventions can alter landing mechanics and reduce kinetic loading (37-39). Differences in intervention protocols, participant characteristics, and testing methods may also explain discrepancies with some previous reports, such as Slater et al. (40) Performing jump-landing tasks has been associated with an increased risk of lower extremity injuries. Athletes with ACL tears showed a 20% increase in maximum normalized Fzmax during a hard landing on the injured limb (41, 42). A decrease in Fzmax is considered a positive biomechanical adaptation, as lower Fz has been associated with decreased mechanical stress on lower extremity joints during landing in previous studies (5, 43). However, it should be noted that the present study did not directly measure the incidence of injury, and the observed changes should be interpreted as changes in biomechanical risk factors rather than direct evidence of injury prevention. In sports activities, the hip and knee extensors are crucial muscle groups that mitigate impact pressures upon landing. Knee Control had a higher Fz parameter reduction relative to the Stop-X group may indicate a change in lower extremity energy absorption strategies during landing. This interpretation, however, is speculative as direct measures of joint stiffness (e.g. calculation of the ratio of change in joint moment to change in joint angle) were not performed in this study (5). Strengthening these muscle groups may contribute to improved lower-limb alignment during landing (44, 45). However, Hewett et al. (45) reported that knee flexion alone did not explain the change in GRF and reported a significant relationship between GRF and DKV, highlighting the role of muscle control and DKV (45). Furthermore, one study reported that increasing the GRF by 35 N increased the knee force (46). Although biomechanical changes may be due to neuromuscular adaptations, the specific mechanisms, including proximal muscle strengthening, knee stiffness modulation, trunk control, and hip abductor function, are speculative in the absence of direct electromyographic or kinetic measurements. Future studies should include a direct measure of muscle activation patterns and joint moments to elucidate the underlying mechanisms. However, previous studies have shown that the interventions that target these neuromuscular components can affect landing biomechanics, which theoretically supports the changes found (18, 35). Therefore, interventions focusing on landing mechanics and core stability may contribute to more favorable landing biomechanics.

We also observed a decrease in Fxmin in SLDL. Fxmin during SLDL differed significantly amongst the three groups in ANCOVA. Knee Control, and Stop-X. In addition to Fxmin, we did not observe a significant effect of factor on Fxmax in SLDL, so the value of Fxmax in the intervention groups was lower than in the control group but showed a relatively large effect size. The lack of significant modifications in Fxmax GRF components might be explained by the multifactorial nature of these kinetic variables, which are influenced by landing strategy, limb coordination, movement technique, and task-specific demands (47). Previous studies also suggested that adaptations in these force components after neuromuscular training are inconsistent and may depend on intervention duration, exercise content, and participant characteristics (48, 49). Also, no significant difference was observed between the three groups in COP (medial-lateral and anterior-posterior direction), while the effect size was reported to be medium. Neuromuscular training programs for jump-landing technique tend to improve balance control, but effects on measures of COP may be modest. COP trajectories represent an objective measure of dynamic postural stability in which greater excursions of the COP reflect a poorer efficiency of balance control (50). In our study, no group differences were statistically significant for COP after the interventions, but the effect sizes were on the order of $\eta^2 \approx 0.5$ (η 2 partial ≈ 0.06–0.10 weak to moderate), which is conventionally considered to be a moderate effect. This suggests that the interventions may have had a real (clinically relevant) effect that did not reach $p < 0.05$ due to sample size. Therefore, this effect on center of pressure displacement is interpreted as a possible improvement in balance control that should be considered with caution. Our findings are consistent with those of Iakano et al. (51) and Wong et al. (52). The reasons for the consistency in our study could be that Iacano also used active male athletes, whereas our participants were professional futsal athletes whose specific athletic demands include frequent unilateral landings, rapid changes of direction, and repeated cutting maneuvers (51, 52). In addition, variations in intervention duration, training intensity, and the inclusion of neuromuscular and balance components may further explain the observed differences (51, 52). In contrast, our findings also contrast with those of Jafarnezhad et al. (53), except that the participants were non-athletic adults, suggesting that neuromuscular-based interventions may be effective in different populations, while the degree of adaptation may depend on baseline skill level and training history (53). The present interventions primarily emphasized landing technique and lower-extremity neuromuscular control rather than isolated balance training; therefore, the absence of significant COP adaptations is expected. Future studies incorporating more comprehensive balance assessments and longer intervention periods may provide further insight into the effects of neuromuscular training on COP characteristics (54).

In addition to reducing the GRF, we observed a reduction in the DKV angle at the post-test in both experimental groups. The results of this study align with the observations made by Rostami et al. (20), Nemati et al. (55), and Tamgüç et al. (56), as they reported a reduction in DKV after the intervention (20, 55, 56). Scientific sources have reported that stronger hip external rotators and abductors in athletes can have a positive impact on better DKV control and reduced GRF (57). DKV can be explained by the interaction of proximal and distal reaction chains, which maintain knee alignment with appropriate participation of the hip joint in the proximal part of the chain and the ankle joint in the distal part of the chain (58). In addition to the proximal and distal reaction chains, improving the function of the abductor and thigh muscles (quadriceps and hamstrings) can help increase lower limb control. Therefore, exercises based on the combination of core and neuromuscular stability components, such as Stop-X and Knee control exercises, were associated with reductions in DKV and GRF in SLDL task (59). Also, the quadriceps muscles play an important role in the initial landing phase (59). Targeted strengthening of the vastus medialis, combined with Nordic exercises that emphasize strengthening the medial hamstrings, may improve knee stability in the frontal plane. The reduction in DKV and the reduction in semitendinosus muscle activity may account for this adaptation in reducing stress on the ACL, especially since the semitendinosus muscle can act as an ACL agonist under certain dynamic conditions (60). Both training increases the strength (limitation) of hip abduction (25%) (61, 62).

Additionally, by strengthening the gluteus medius and gluteus maximus muscles, excessive knee abduction can be prevented (61, 62). Almost all the protocols had the same effect on DKV. Both exercises have upper and lower training chains, which include balance, side planks, and neuromuscular exercises. By strengthening and coordinating the upper and lower chains, they play an important role in reducing DKV. Additionally, considering the reduction in the GRF in the vertical direction, our exercises had a positive effect on reducing DKV (18, 35).

Finally, large effect sizes for several biomechanical variables suggest that the intervention programs resulted in substantial changes in landing mechanics. However, because the present study did not assess injury incidence, the results should be considered as positive changes in biomechanical risk factors, not as direct evidence of a reduction in the incidence of ACL injury.

5. Limitations

However, there are several limitations in the current research that should be recognised. In this study: i). We exclusively focused on male athlete subjects, and the extrapolation of results to female athletes and nonathletic populations should be undertaken with caution, requiring further investigation. ii). Due to our limitations in 2D measurement, we were unable to quantify and control for additional metrics, such as trunk and knee flexion.

6. Conclusion

According to the results obtained, both types of injury prevention exercises, especially Knee control exercise, were able to have a greater effect size when landing from a height than when landing on the ground with one foot, but Knee Control exercises resulted a greater decrease in kinetic data, In contrast, both types of exercise had the same effect on DKV, and no significant difference was found between the protocols. These findings suggest that neuromuscular injury-prevention training may positively influence biomechanical factors associated with ACL injury risk because these exercises, which use several strength and neuromuscular factors, can take a useful step in the injury prevention process by reducing the risk of injury factors, including GRF, as well as improved dynamic postural control during landing, indicated by reduced COP displacement and, most importantly, DKV. However, because ACL injuries were not directly assessed, the present findings should be interpreted as improvements in risk-related biomechanics rather than direct evidence of injury prevention.

Abbreviation

ACL: Anterior cruciate ligament; **DKV:** Dynamic knee valgus; **GRF:** Ground reaction force; **Fx:** medial-lateral reaction force; **Fy**: anterior-posterior reaction force; **Fz:** vertical reaction force**; LR:** Loading rate**; SLDL:** Single leg drop landing; **COPx:** Center of pressure in medio – lateral direction; **COPy:** Center of pressure in anterior–posterior direction.

Availability of data and materials

In order to protect individual privacy, the dataset created and analysed during the current study is not publicly available. However, upon reasonable request, researchers with institutional review board/ethics approval and an institutionally approved study plan can obtain the entire dataset from the Corresponding Author.

Contributors

All authors have contributed to either the design or execution of this study or analysis of the findings from this study. All authors have approved the final submitted version of the research manuscript.

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Ethical declarations

Ethical considerations were obtained from the Ethics Committee in Biomedical Research, Guilan University (IR.GUILAN.REC.1403.170).

Clinical trial registration

This study adhered to CONSORT guidelines for randomized controlled trials and was registered in the Iranian Registry of Clinical Trials (Code: IRCT20241230064223N1, Date: 2025-01-18).

Ethical principles were upheld in this article, including informing participants about the research purpose and stages, ensuring confidentiality, and allowing them to withdraw at any time. Written consent was obtained, and the principles of the Helsinki Convention were observed.

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AI Use Statement

Grammarly was used solely to edit and improve English grammar.

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Table 1. Demographic information

Variable	Stop-X	Knee control	control	P value
Age(year)	20.83±1.44	19.16±1.58	19.70±1.15	0.085
Height (Cm)	182±0.77	179.66±1.32	179.60±0.90	0.169
Weight (Kg)	66.08±1.06	63.08±1.42	67.30±1.82	0.075
Body mass index (Kg/m^2)	19.91±1.50	19.75±1.35	20.90±1.52	0.163

P value, one-way ANOVA, *Significant level p<0.05.

Table 2. Comparison of baseline characteristics of three groups during the single-leg drop landing task

Task	Variable	Mean ± SD Stop-X	Mean ± SD Knee control	Mean ± SD control	P value
Single-leg drop landing GRF	Minimum medial - lateral GRF (BW%)	-32.25±28.75	-32.25±16.40	-26.85±10.44	0.019*
	Peak medial - lateral GRF (BW%)	25.27±13.01	28.12±15.36	21.78±7.68	0.523
	Peak anterior - posterior GRF (BW%)	8.96±5.84	9.76±6.24	4.88±3.45	0.101
	Minimum anterior-posterior GRF (BW%)	-54.35±28.34	-75.91±28.92	-60.22±17.36	0.127
	Peak vertical GRF (BW%)	479.10±83.79	579.88±129.09	477.39±127.64	0.114
	COP in the medial – lateral (m)	0.16±0.07	0.14±0.05	0.08±0.8	0.113
	COP in the anterior-posterior (m)	0.27±0.06	0.31±0.08	0.25±0.09	0.814
	Loading rate (BW/s)	25.73±11.14	30.47±12.96	23.02±8.11	0.290
	Dynamic knee valgus (Degree)	26.00± 3.51	26.62± 4.51	25.95± 2.89	0.791

GRF, ground reaction force; COP, center of pressure; *Significant level p<0.05; BW, body weight; m, meter

Table 3. The results of ANCOVA for kinetic and kinematics data in three groups.

Variable	Group	Post-test Mean ± SD	ANCOVA F	P value	Partial η²
Peak vertical GRF (BW%)	Stop-X	99.00 ±412.06	۱۵/۰۹	<0.01*	۰/۵۰
	Knee Control	109.54 ±401.78			
	Control	115.22 ±519.48			
Peak anterior-posterior GRF (BW%)	Stop-X	6.63±9.69	۳/۶۳	۰/۰۳*	۰/۱۹
	Knee Control	5.77±10.06			
	Control	3.20±4.99			
Minimum anterior-posterior GRF (BW%)	Stop-X	17.38±-46.63	۰/۵۵	۰/۵۸	۰/۰۳
	Knee Control	19.98 ±-55.82			
	Control	14.00±-58.97			
Peak medial-lateral GRF (BW%)	Stop-X	11.34±18.02	۳/۲۳	0.05	0.۱۷
	Knee Control	12.06 ±18.70			
	Control	8.30±23.14			
Minimum medial-lateral GRF (BW%)	Stop-X	-29.49±16.79	5.20	0.0۳*	0.25
	Knee Control	-23.53±5.02			
	Control	-38.41±12.61			
Center of pressure in medial-lateral direction (m)	Stop-X	0.04±0.11	۱/۳۹	۰/۲۶	۰/۰۸
	Knee Control	0.04±0.10			
	Control	0.07±0.10			
Center of pressure in anterior-posterior direction (m)	Stop-X	0.04±0.23	۰/۸۱	۰/۴۵	۰/۰۵
	Knee Control	0.05±0.24			
	Control	0.07±0.24			
Loading rate (BW/s)	Stop-X	12.24±18.61	۲/۲۳	۰/۱۲	۰/۱۲
	Knee Control	12.26±18.73			
	Control	9.89±24.61			
Dynamic knee valgus (degree)	Stop-X	2.27±20.58	۳۳/۶۱	<0.01*	۰/۶۹
	Knee Control	3.09±20.16			
	Control	2.69±24.20			

GRF, ground reaction force; COP, center of pressure; *Significant level p<0.۰5; η2p, partial eta square (η2p) value were interpretd small (≤0.01), medium (0.01 < η2p< 0.06), and large (η2p ≥ 0.14); BW, body weight; BW/s, body weight per second, m, meter

Appendix 1. Stop–X Exercise Table

Appendix1-Stop X
Exercise Table.pdf

Appendix 1. Knee control Exercise Table

Appendix2-Knee
control ExerciseTabl