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Impact of Directional Change Frequency in Sprint-Plyometric Protocols on Ankle Joint Adaptation and Lateral Injury Prevention

[1]Loganathan Thangavel
[*2]Senthilkumar S
[3]Sridharan Chinnaraj

ABSTRACT

Background: Ankle sprains are common during sports that involve frequent directional changes and, therefore, require efficient training regimens for joint stability and prevention of injuries. The purpose of this study is to examine the effects of sprint-plyometric training with varying directional change frequencies on ankle joint function and the prevention of lateral ankle sprains in recreationally active adults.

Methods: Ninety volunteers (45 Male and 45 Female), aged between 18 and 35 years, were allocated to High-Frequency Directional Change (HFDC, n=30), Moderate-Frequency Directional Change (MFDC, n=30), and Control (n=30) for a 12-week intervention. Outcomes included ankle joint stiffness (isokinetic dynamometry), proprioception (joint position sense via motion capture), neuromuscular activation (electromyography), biomechanical parameters (kinematics, ground reaction forces), and injury incidence (Poisson regression). Group × time interactions were quantified using linear mixed models, reporting effect sizes (Cohen's d) and percentage changes.

Results: The HFDC group demonstrated significant gains in ankle stiffness (31.1–31.6%, d=1.33–1.39, p<0.001), proprioception (52.0–56.5% error decrease, d=1.39–1.75, p<0.001), and neuromuscular activation (38.3–48.0% EMG increase, d=1.26–1.45, p<0.001). Biomechanical changes consisted of decreased inversion angles (33.3%, d=1.73, p<0.001) and lateral ground reaction forces (28.6%, d=1.60, p<0.001). There were no sprains experienced by the HFDC group (0 per 1000 hours) compared to 1.85 (MFDC) and 7.41 (Control) per 1000 hours (IRR=0.00, p<0.001). Females had larger proprioceptive improvements (d=1.89 vs. 1.60, p=0.028).

Conclusion: High-frequency directional change training significantly improves ankle function and avoids sprains, providing a strong strategy for sports with multi-planar movements.

Keywords: Ankle injuries, Electromyography, Motion capture, Proprioception, Sprint-plyometric training.

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[1]Saveetha College of Physiotherapy, Saveetha Institute of Medical and Technical Sciences (SIMATS), Chennai, India. Nandha College of Physiotherapy, Erode, India.
Email: logumpt@gmail.com
https://orcid.org/0000-0001-8489-4301
[3]SNS College of Physiotherapy, Coimbatore, India.
Email: Sridharan.chinnaraj28@gmail.com
https://orcid.org/0009-0003-1474-7885

CORRESPONDING AUTHOR

[*2]Senthilkumar S

Saveetha College of Physiotherapy, Saveetha Institute of Medical and Technical Sciences (SIMATS), Chennai, India.
Email: senthilkumar.scpt@saveetha.com
https://orcid.org/0000-0002-9260-7656

INTRODUCTION

Lateral ankle sprains remain the most frequently reported sports lower limb injury, typically occurring during sudden inversion and plantarflexion with changes of direction (COD). Approximately 40% of individuals engaged in sports experience Chronic Ankle Instability (CAI), characterized by sensorimotor impairments and recurrent episodes of the ankle "giving way," which compromise dynamic joint stability and heighten the risk of reinjury [1]. Plyometric training (PT) utilizing the stretch-shortening cycle (SSC) has repeatedly demonstrated improvement in reactive strength, tendon stiffness, neuromuscular coordination, and balance. Meta-analyses of PT frequency have shown that moderate frequency (1–3 PT sessions per week) improves jumping and sprint performance compared with high-frequency programs [2]. Huang WY et al. (2024) reported that both lateral and vertical plyometric jumps not only enhanced performance but also helped prevent lower-limb injuries by strengthening musculotendinous tissues [3].

In patients with functional ankle instability, PT—even when started later during rehabilitation—results in greater improvement in proprioception and dynamic stability than traditional protocols. Lee et al. (2020) demonstrated that plyometric training, relative to ankle stability training, dramatically enhanced shock absorption and overall joint stability in sprain patients [4]. Likewise, combined PT and balance training interventions minimize positioning error during plantarflexion and inversion tests, indicating better joint position sense in FAI populations [5]. Mechanically, proprioceptive and muscle strength deficits are highly related to compromised postural stability—especially in the medial-lateral (ML) direction, which best relates to inversion injury mechanics. Patients with CAI have greater time-to-stabilization (TTS) and increased proprioceptive thresholds in both AP and ML planes, with strength and sensory deficits accounting for most of their postural instability [6]. PT and COD training combined with a mix of sprinting and directional redirection is proving to be a handy way to improve agility and functional control. Marzouki et al. (2023) demonstrated that young soccer players who performed plyometric plus sprint-COD with ball drills, compared with peers who performed plyometric or sprint training in isolation, regardless of maturity status, achieved larger gains in agility and sprint measures [7]. In addition, organized implementation of balance-plus-PT in younger athletes (e.g., badminton players) resulted in COD speed improvements greater than those with PT alone, consistent with synergistic effects of neuromuscular improvements and joint-loading specificity [5,8].

Importantly, PT interventions in women's basketball players for 8 weeks enhanced COD capacity (effect size $d \approx 1.51$), reduced static balance path lengths ($d \approx 0.94$), and improved postural control—even in the absence of alterations of knee strength ratios—illustrating the efficacy of SSC-induced adaptations for functional joint resilience [9]. Despite abundant evidence for PT and COD training for performance and injury prevention, the systematic manipulation of the frequency of directional changes within sprint plyometric protocols remains underexplored—especially its isolated effects on ankle biomechanical adaptation and lateral indicators of injury prevention, such as inversion torque tolerance and inter-limb asymmetry. The present study thus quantitatively evaluates the impact of differing frequencies of directional changes during sprint plyometric training on ankle joint adaptation measures—such as stiffness, proprioceptive accuracy, neuromuscular timing, and inter-limb asymmetry—and on practical injury-resistance markers. Based on neuromechanical theory and rehabilitation science, this study aims to clarify how specific directional loading patterns within high-velocity training can develop both athletic agility and ankle joint resilience.

METHODOLOGY

Study design and structure

This study employs a parallel-group randomized controlled trial (RCT) to investigate how varying frequencies of directional changes in sprint-plyometric training influence biomechanical adaptations in the ankle joint and help prevent lateral ankle injuries. Participants will be randomly assigned to three groups: a high-frequency directional change (HFDC), a moderate-frequency directional change (MFDC), and a control group for linear sprint-plyometric exercises without directional changes. The intervention lasts for 12 weeks, and detailed pre- and post-intervention measurements collect biomechanical, neuromuscular, and injury-related outcomes. A mixed-methods strategy combines quantitative biomechanical and neuromuscular measures with qualitative injury monitoring to facilitate a comprehensive understanding of ankle joint responses. CONSORT guidelines are followed in this study. All testing is performed in a Nandha Sports Complex motion analysis laboratory with state-of-the-art biomechanical measurement systems, providing high-fidelity data acquisition. The training and testing protocols are designed to simulate sport-specific conditions with emphasis on sidestep cutting maneuvers characteristic of lateral ankle sprains.

Participant Recruitment and Screening

Eligible individuals will be selected from college sports programs and community recreation programs through door promotions at training facilities. The target population is 100 recreationally active adults aged 18–35 years who participate in sports or activities that include sprinting or agility at least three times a week. An analysis of power with G*Power 3.1.9.7, assuming a medium-sized effect ($f = 0.25$) for ankle joint stiffness, $\alpha = 0.05$, and power = 0.80, indicated a minimum of 90 (30 per group), with 10% more in addition to compensate for dropouts. Inclusion criteria are a normal ankle range of motion (dorsiflexion ≥20°, plantarflexion ≥40°, inversion ≥30°, eversion ≥15°, measured using goniometry) and no history of ankle surgery or severe ankle sprains in the last 12 months. Exclusion criteria include CAI (Cumberland Ankle Instability Tool score >11), active lower-limb injuries, neuromuscular

or cardiovascular conditions affecting performance, or enrolment in concurrent structured training programs. A clinical evaluation, such as Anterior Drawer and Talar Tilt tests conducted by a sports physiotherapy specialist, will establish the lack of mechanical ankle instability. Written informed consent will be acquired, and the study protocol received approval from the Institutional Human Ethics Committee (IHEC) at Nandha College of Physiotherapy (NCPT/IHEC/126/2024) following the Declaration of Helsinki and GDPR for data protection.

Randomization and Blinding Procedures

Balanced allocation will be ensured by stratifying participants by sex and baseline athletic ability, assessed using a 20-meter sprint test (timed to 0.01 seconds using photocell gates). Randomization will be performed using a computer-generated permuted block sequence, with concealed allocation in sealed, opaque envelopes until group assignment. Outcome assessors for biomechanical, neuromuscular, and injury data will be kept blinded to group allocation to reduce measurement bias. Given the nature of the intervention, blinding of trainers and participants cannot be achieved. An independent statistician will supervise randomization to maximize allocation integrity, while all data will be coded to preserve assessor blinding during analysis.

Protocols for Intervention

The intervention involves three different sprint-plyometric protocols, administered for 12 weeks (60 minutes per session, 3 times a week), under the supervision of a trained sports physiotherapist. Training volume (total sprint distance and jumps) and intensity (80–90% HRmax, tracked through Polar H10 heart rate monitors [20] are equated between groups to control for the effect of directional change frequency. All training sessions incorporate a 10-minute dynamic warm-up (e.g., high-knee runs, ankle circles, single-leg balance drills) and a 5-minute cool-down (e.g., static stretching, foam rolling). Training is on a synthetic turf surface to simulate sport-specific conditions, with directional change angles designated using laser-guided alignment tools for accuracy. The protocols are planned to gradually escalate in complexity and intensity, focusing on biomechanical and neuromuscular adaptation applicable to cutting maneuvers.

High-Frequency Directional Change (HFDC) Group

The HFDC group completes sprint-plyometric training with 15–20 directional changes per session, focusing on ankle joint stability and neuromuscular control during multi-planar movements. Exercisers perform:

- Zigzag Sprints: The players sprint around a series of 10 cones set 2 meters apart in a zigzag pattern, making quick 45° or 90° sidestep cuts at each cone, switching left and right plant legs.
- Lateral Hurdle Jumps: Players take lateral bounds over 30 cm hurdles and immediately change direction upon landing to mimic quick cuts.
- Multi-Directional Bounding: Participants bound in a pre-set pattern (forward, lateral, backward) with 45° or 90° turns, maintaining a high tempo.

Progression: Weeks 1–4: 10 changes/session at 80–85% HRmax, 45° cuts; Weeks 5–8: 15 changes/session at 85–90% HRmax, combined 45° and 90° cuts; Weeks 9–12: 20 changes/session at 85–90% HRmax, with mostly 90° cuts. Cutting technique is a focal point of the protocol, including correct knee-over-the-foot alignment and reduced trunk lean, supported by real-time coaching feedback.

Moderate-Frequency Directional Change (MFDC) Group

The MFDC group performs equal sprint-plyometric drills with 8–12 directional changes per session, alternating ankle stress and recovery. Drills include:

- T-Drill Sprints: Members sprint around a T-shaped pattern, making 60° sidestep cuts at marked points, with fewer than the HFDC group.
- Single-Leg Lateral Hops: Members hop laterally over a line and land on the same leg before reversing direction, emphasizing controlled landings.
- 60° Cutting Drills: Athletes sprint and execute 60° sidestep cuts at designated points, with an emphasis on stability.

Progression: Weeks 1–4: 8 changes/session at 80–85% HRmax, 60° cuts; Weeks 5–8: 10 changes/session at 80–85% HRmax, alternate 60° and 45° cuts; Weeks 9–12: 12 changes/session at 85–90% HRmax, mostly 45° cuts. Correct foot placement and body position are encouraged by coaching feedback.

Control Group

The control group engages in linear sprint-plyometric training with no direction changes, emphasizing forward movement to reduce ankle stress during inversion. Training includes:

- Straight-Line Sprints: Subjects undertake 20–30-meter sprints at 80–85% HRmax.
- Vertical Box Jumps: Subjects jump off 30–50 cm boxes, emphasizing vertical power.
- Forward Bounding: Subjects bound forward over designated distances, emphasizing propulsion in the linear plane.

Progression: Equated for volume and intensity to the experimental groups, with progression in sprint distance and jump height over 12 weeks. Training is on the same synthetic turf surface to maintain consistency.

Table 1: Training Protocol Details

Group	Weeks	Exercises	Sets/Reps	Directional Changes	Intensity (% HR-max)
HFDC	1–4	Zigzag sprints, lateral hurdle jumps, multi-directional bounding	3x10, 3x12, 3x10	10 (45°/90° cuts)	80–85%

HFDC	5–8	Zigzag sprints, lateral hurdle jumps, multi-directional bounding	4x10, 4x12, 4x10	15 (45°/90° cuts)	85–90%
HFDC	9–12	Zigzag sprints, lateral hurdle jumps, multi-directional bounding	4x12, 4x15, 4x12	20 (45°/90° cuts)	85–90%
MFDC	1–4	T-drill sprints, single-leg lateral hops, 60° cutting drills	3x10, 3x10, 3x12	8 (60° cuts)	80–85%
MFDC	5–8	T-drill sprints, single-leg lateral hops, 60° cutting drills	4x10, 4x10, 4x12	10 (60° cuts)	80–85%
MFDC	9–12	T-drill sprints, single-leg lateral hops, 60° cutting drills	4x12, 4x12, 4x15	12 (45° cuts)	85–90%
Control	1–4	Straight-line sprints, vertical box jumps, forward bounding	3x10, 3x12, 3x10	0	80–85%
Control	5–8	Straight-line sprints, vertical box jumps, forward bounding	4x10, 4x12, 4x10	0	80–85%
Control	9–12	Straight-line sprints, vertical box jumps, forward bounding	4x12, 4x15, 4x12	0	85–90%

Outcome Measures

Primary Outcomes

1. Ankle Joint Stiffness: Assessed with an Isokinetic Dynamometer (Biodex System 4 Pro) at passive and active dorsiflexion and plantarflexion at 5°/s and 30°/s. The participants are lying supine with the ankles strapped to the neutral position. Torque-angle curves are examined to compute stiffness (Nm/°) in the sagittal plane, which is averaged across three attempts per condition.
2. Proprioception: Joint position sense (JPS) was assessed using a 12-camera Vicon Nexus motion capture system operating at 200 Hz, during active repositioning tasks at angles of 10° dorsiflexion, 10° eversion, 15° plantarflexion, and 15° inversion. Individuals complete three practice trials and three test trials per angle, with angular error (degrees) measured as target versus achieved angle difference, averaged over trials. Reflective markers are positioned on anatomical landmarks (e.g., calcaneus, lateral malleolus) according to International Society of Biomechanics (ISB) standards.
3. Incidence of Lateral Ankle Injury: Monitored weekly through participant self-report on a standardized electronic case report form, confirmed by a sports medicine physician. Injuries are acute lateral ankle sprains necessitating ≥1 day of activity modification, with severity (Grade I–III) and mechanism (e.g., inversion while cutting) recorded. Mechanisms of injury are classified to determine associations with directional change tasks.

Secondary Outcomes

Biomechanical Measures during Cutting Task:

- Ankle Kinematics: Inversion-eversion, dorsiflexion-plantarflexion, and internal-external rotation angles over the course of a 45° sidestep cutting task, recorded using a 12-camera Vicon system (200 Hz) with the modified Helen Hayes marker set (23 markers). Peak angles and rates of change (degrees/s) are determined.
- Ankle Kinetics: Joint moments (Nm/kg) in inversion-eversion, dorsiflexion-plantarflexion, and internal-external rotation, calculated through inverse dynamics from synchronized motion capture and force plate data.
- Hip and Trunk Kinematics: Hip flexion, abduction, and rotation angles, and trunk lateral flexion and rotation, measured to evaluate whole-body mechanics that affect ankle stability.
- Electromyography (EMG): Surface EMG (DelsysTrigno, 2000 Hz, 90 dB common mode rejection ratio) of Peroneus Longus, Peroneus brevis, Tibilis Anterior, Gastrocnemius Medialis, and Gastrocnemius Lateralis during the cutting task. Parameters include time to peak activation (ms), peak amplitude (**μV**), and co-contraction ratios (peroneal/tibialis anterior). Electrodes are applied according to SENIAM guidelines, with the skin prepared to provide a high-quality signal.

Functional Performance:

- Star Excursion Balance Test (SEBT): Evaluates dynamic balance in anterior, posteromedial, and posterolateral directions. Reach distances (cm) are normalized to leg length and averaged over three trials.
- Agility Test: Time (s) to perform a 505-agility test, a 15-meter sprint followed by a 180° turn and return sprint, averaged over three trials per leg.
- Time to Stabilization: Derived from force plate measurements during the cutting task, specified as the time (ms) for center of pressure variability to decrease below a threshold (e.g., 5% of peak ground reaction force variability).

Table 2: Outcome Measures and Assessment Methods

Outcome	Measure	Method	Metrics
Ankle Joint Stiffness	Passive/active stiffness	Isokinetic dynamometer	Nm/° in dorsiflexion/plantarflexion

Proprioception	Joint position sense	3D motion capture	Angular error (degrees)
Injury Incidence	Lateral ankle sprains	Weekly reports, medical verification	Incidence rate, severity, mechanism
Ankle Kinematics	Inversion-eversion, etc.	3D motion capture	Peak angles (degrees), rates (degrees/s)
Ankle Kinetics	Joint moments	Inverse dynamics	Nm/kg in multiple planes
Hip/Trunk Kinematics	Flexion, abduction, rotation	3D motion capture	Peak angles (degrees)
EMG	Muscle activation	Surface EMG	Time to peak (ms), amplitude (μV), co-contraction ratios
Functional Performance	SEBT, 505 agility test	Marked grid, timing gates	Reach distance (cm), time (s)
Time to Stabilization	Dynamic stability	Force plate	Time (ms) to stabilize

Data Collection Procedures

Baseline Assessment

A 2.5-hour baseline testing session is completed in a laboratory setting with controlled conditions. Participants are subject to anthropometric measures (height, weight, leg length through 3D scanning), a 20-meter sprint test, clinical ankle stability tests (anterior drawer, talar tilt), and extensive biomechanical and functional tests. The cutting task is a 45° sidestep cut at 80% maximum speed sprint, executed with both legs as the plant leg (three trials for each leg). Kinematic data were processed using a fourth-order low-pass Butterworth filter set at 10 Hz. In comparison, EMG signals were band-pass filtered between 20 and 450 Hz, then rectified and root-mean-square (RMS) calculated over 200-millisecond intervals. Participants avoid strenuous exercise for 24 hours before participation, and a familiarization session helps with comfort during the cutting task.

Intervention Monitoring

Adherence to training is tracked through attendance records and heart rate measurements, with each week's check-in evaluating perceived effort (Borg RPE scale) and adverse events, reported to the research team and IHEC immediately. Training data are recorded through a secure online platform for traceability. Coaching feedback during the sessions focuses on the correct cutting technique to maximize biomechanical adaptations.

Post-Intervention Assessment

Post-intervention testing, identical to baseline, is conducted within 48 hours of the last session to reduce detraining effects. Two force plates (AMTI, 1000 Hz) are used to measure planting and push-off phases under the cutting task, providing extensive kinetic data. Data on injuries are collected from weekly reports and cross-checked with medical evaluations.

Data Analysis Plan

Quantitative data are processed with SPSS v28 and R for more advanced modelling. Primary outcomes (ankle stiffness, proprioception) are examined using a two-way mixed ANOVA (group × time), with Tukey post hoc tests for significant interactions ($p < 0.05$). Lateral ankle injury incidence is tested with Poisson regression, controlling for exposure time (training hours). Secondary outcomes (biomechanical tests, SEBT, agility, time to stabilization) are measured using repeated-measures ANOVA or linear mixed models to control for repeated measures and possible clustering effects. Baseline sprint performance and sex are used as covariates in ANCOVA models if group differences are identified. Effect sizes (partial eta-squared and Cohen's d) provide quantitative measures of the intervention's effects. Missing data are handled using multiple imputation for biomechanical outcomes and an intention-to-treat analysis for injury data. Qualitative reports of injury are analyzed thematically with NVivo and coded independently by two investigators (Cohen's kappa > 0.80) to define mechanistic patterns.

Ethical and Safety Considerations

The research adheres to the Declaration of Helsinki and GDPR for data protection. Withdrawal is possible without penalty, and anonymised data are kept on a secure, encrypted server. An on-site sports medicine team is available during training to manage adverse events, with a procedure for urgent injury assessment and referral. Serious adverse events are reported to the IHEC within 24 hours. Participants are provided with comprehensive risk information highlighting the possibility of minor muscle soreness or sprains, along with educational materials on preventing injury.

Methodological Rigor and Limitations

Rigor is addressed through validated, standardized measurement instruments, blinded assessors, and standardized procedures. The use of high-fidelity biomechanical systems (e.g., Vicon and AMTI force plates) and accurate data processing improves measurement fidelity. The limitations are not being able to blind participants, addressed by objective outcomes and blinded analysis. The population being studied is recreationally active adults, which may preclude generalizability to elite performers; this will be addressed in future research. Compliance is optimized through supervised sessions and weekly progress feedback. Confounding variables (e.g., shoes, surface) are addressed by equating conditions between groups. The clinical ankle stability tests reduced the likelihood that pre-existing conditions would confound results.

RESULTS

Participant Characteristics

A sample of 100 recreationally active young adults aged 18 to 35 was recruited from college sports programs, community sports clubs, and local fitness centres. Participants were randomly allocated to three groups: High-Frequency Directional Change (HFDC, n=33), Moderate-Frequency Directional Change (MFDC, n=33), and Control (n=34). Following adjustment for 10 dropouts (for scheduling issues, unrelated minor injuries, or personal reasons), 90 participants finished the 12-week intervention (HFDC:

30, MFDC: 30, Control: 30). Baseline parameters were controlled for between groups ($p > 0.05$, ANOVA): age (HFDC: 24.2 ± 4.1 years, MFDC: 23.9 ± 3.8 years, Control: 24.5 ± 4.0 years), sex split (HFDC: 50% female, MFDC: 47% female, Control: 53% female), body mass (HFDC: 23.1 ± 2.3 kg/m², MFDC: 23.4 ± 2.5 kg/m², Control: 23.2 ± 2.4 kg/m²), 20-meter sprint time performance (HFDC: 3.2 ± 0.3 s, MFDC: 3.3 ± 0.4 s, Control: 3.2 ± 0.3 s), leg length (HFDC: 90.1 ± 4.2 cm, MFDC: 89.8 ± 4.0 cm, Control: 90.3 ± 4.3 cm), and strength of the lower limb (isometric leg press, HFDC: 1.8 ± 0.3 BW, MFDC: 1.7 ± 0.3 BW, Control: 1.8 ± 0.3 BW). Clinical measurements with the CAIT supported no mechanical ankle instability (HFDC: 26.0 ± 2.1, MFDC: 25.8 ± 1.9, Control: 26.1 ± 2.0, $p = 0.874$). Adherence to training was excellent (HFDC: 95.2 ± 2.1%, MFDC: 94.8 ± 2.3%, Control: 96.1 ± 1.9%, $p = 0.921$), and heart rate recordings (Polar H10 monitors) reflected good intensity consistency (80–90% HR max, $p = 0.832$). Perceived exertion every week (Borg RPE scale) was 13.5 ± 1.2 across groups ($p = 0.783$). Baseline physical activity was moderate-to-high (IPAQ: HFDC: 2450 ± 620 MET-min/week; MFDC: 2380 ± 590 MET-min/week; Control: 2410 ± 610 MET-min/week; $p = 0.897$), making the groups homogeneous.

Table 3: Baseline Participant Characteristics

Group	Age (Years)	Sex (% Female)	BMI (kg/m²)	Sprint Time (s)	Leg Length (cm)	CAIT Score	Leg Press (BW)	IPAQ (MET-min/week)	Adherence (%)
Control	24.5 ± 4.0	53%	23.2 ± 2.4	3.2 ± 0.3	90.3 ± 4.3	26.1 ± 2.0	1.8 ± 0.3	2410 ± 610	96.1 ± 1.9
MFDC	23.9 ± 3.8	47%	23.4 ± 2.5	3.3 ± 0.4	89.8 ± 4.0	25.8 ± 1.9	1.7 ± 0.3	2380 ± 590	94.8 ± 2.3
HFDC	24.2 ± 4.1	50%	23.1 ± 2.3	3.2 ± 0.3	90.1 ± 4.2	26.0 ± 2.1	1.8 ± 0.3	2450 ± 620	95.2 ± 2.1

Primary Outcomes

Ankle Joint Stiffness

Passive ankle stiffness was assessed with an isokinetic dynamometer (Biodex System 4 Pro) in plantarflexion (5°/s and 30°/s) and dorsiflexion (5°/s and 30°/s), showing significant group × time interactions (plantar flexion 5°/s: $F(2.87) = 10.12$, $p < 0.001$, partial $\eta^2 = 0.19$; dorsiflexion 30°/s: $F(2.87) = 9.67$, $p < 0.001$, partial $\eta^2 = 0.18$). For 5°/s plantarflexion, the HFDC group exhibited a remarkable increase (pre: 0.45 ± 0.10 Nm/°, post: 0.59 ± 0.11 Nm/°, $p < 0.001$, Cohen's $d = 1.33$, 31.1% increase), whereas the MFDC group had a moderate increase (pre: 0.46 ± 0.11 Nm/°, post: 0.54 ± 0.10 Nm/°, $p = 0.003$, Cohen's $d = 0.76$, 17.4% increase). The control group remained unchanged (pre: 0.44 ± 0.09 Nm/°, post: 0.45 ± 0.09 Nm/°, $p = 0.789$, Cohen's $d = 0.11$). For 30°/s dorsiflexion, the HFDC group improved markedly (pre: 0.38 ± 0.08 Nm/°, post: 0.50 ± 0.09 Nm/°, $p < 0.001$, Cohen's $d = 1.39$, 31.6% increase), and the MFDC group improved to a lesser extent (pre: 0.39 ± 0.09 Nm/°, post: 0.45 ± 0.08 Nm/°, $p = 0.009$, Cohen's $d = 0.69$). Active stiffness at 30°/s also followed analogous patterns (plantarflexion: HFDC pre: 0.55 ± 0.12 Nm/°, post: 0.70 ± 0.13 Nm/°, $p < 0.001$, Cohen's $d = 1.19$, 27.3% increase; dorsiflexion: HFDC pre: 0.52 ± 0.11 Nm/°, post: 0.66 ± 0.12 Nm/°, $p < 0.001$, Cohen's $d = 1.21$). Quasi-stiffness (slope of the moment-angle curve) also rose in the HFDC group (pre: 0.42 ± 0.09 Nm/°, post: 0.55 ± 0.10 Nm/°, $p < 0.001$, Cohen's $d = 1.37$), reflecting higher tendon and muscle adaptations.

Table 4: Ankle Joint Stiffness (Nm/°) Across Conditions

Group	Motion	Speed (°/s)	Pre Intervention (Mean ± SD)	Post intervention (Mean ± SD)	Change (%)	P-VALUE	Cohen's d
Control	Plantarflexion	5	0.44 ± 0.09	0.45 ± 0.09	+2.3%	0.789	0.11
MFDC	Plantarflexion	5	0.46 ± 0.11	0.54 ± 0.10	+17.4%	0.003	0.76
HFDC	Plantarflexion	5	0.45 ± 0.10	0.59 ± 0.11	+31.1%	<0.001	1.33
Control	Dorsiflexion	30	0.38 ± 0.08	0.39 ± 0.08	+2.6%	0.801	0.13
MFDC	Dorsiflexion	30	0.39 ± 0.09	0.45 ± 0.08	+15.4%	0.009	0.69
HFDC	Dorsiflexion	30	0.38 ± 0.08	0.50 ± 0.09	+31.6%	<0.001	1.39
Control	Quasi-Stiffness	-	0.41 ± 0.09	0.42 ± 0.09	+2.4%	0.834	0.11
MFDC	Quasi-Stiffness	-	0.43 ± 0.10	0.49 ± 0.09	+14.0%	0.012	0.63
HFDC	Quasi-Stiffness	-	0.42 ± 0.09	0.55 ± 0.10	+31.0%	<0.001	1.37

Proprioception

Joint position sense (JPS) during inversion, eversion, plantarflexion, and dorsiflexion was measured using a 12-camera Vicon Nexus motion capture system (200 Hz), and it reported significant group × time interactions (inversion: $F(2,87) = 8.45$, $p < 0.001$, partial $\eta^2 = 0.16$; eversion: $F(2,87) = 7.89$, $p = 0.001$, partial $\eta^2 = 0.15$; plantarflexion: $F(2,87) = 7.23$, $p = 0.001$, partial $\eta^2 = 0.14$; dorsiflexion: $F(2,87) = 6.78$, $p = 0.002$, partial $\eta^2 = 0.13$). For inversion, the HFDC group lowered absolute error substantially (pre: 2.3° ± 0.9°, post: 1.0° ± 0.4°, $p < 0.001$, Cohen's $d = 1.75$, 56.5% reduction), and the MFDC group decreased it moderately (pre: 2.4° ± 1.0°, post: 1.4° ± 0.6°, $p < 0.001$, Cohen's $d = 1.17$, 41.7% reduction). The control group demonstrated very little change (pre: 2.2° ± 0.8°, post: 2.0° ± 0.7°, $p = 0.298$, Cohen's $d = 0.26$). Eversion JPS also demonstrated similar patterns (HFDC: pre: 2.5° ± 1.0°, post: 1.2° ± 0.5°, $p < 0.001$, Cohen's $d = 1.60$, 52.0% decrease; MFDC: pre: 2.6° ± 1.1°, post: 1.7° ± 0.7°, $p = 0.001$, Cohen's $d = 0.94$). Plantarflexion and dorsiflexion JPS significantly improved in the HFDC group (plantarflexion: pre: 3.8° ± 1.9°, post: 1.7° ± 0.8°, $p < 0.001$, Cohen's $d = 1.39$, reduction by 55.3%; dorsiflexion: pre: 3.5° ± 1.7°, post: 1.6° ± 0.7°, $p < 0.001$, Cohen's $d = 1.45$, reduction by 54.3%). Variation in JPS error (coefficient of variation) reduced in the HFDC group (pre: 0.35 ± 0.10, post: 0.25 ± 0.07, $p = 0.001$, Cohen's $d = 1.17$), reflecting enhanced consistency.

Table 5: Joint Position Sense Absolute Error (°) Across Planes

Group	Plane	Pre-intervention (Mean ± SD)	Post intervention (Mean ± SD)	Change (%)	P-Value	Cohen's d
Control	Inversion	2.2 ± 0.8	2.0 ± 0.7	-9.1%	0.298	0.26
MFDC	Inversion	2.4 ± 1.0	1.4 ± 0.6	-41.7%	<0.001	1.17
HFDC	Inversion	2.3 ± 0.9	1.0 ± 0.4	-56.5%	<0.001	1.75
Control	Eversion	2.4 ± 0.9	2.3 ± 0.8	-4.2%	0.412	0.12
MFDC	Eversion	2.6 ± 1.1	1.7 ± 0.7	-34.6%	0.001	0.94

HFDC	Eversion	2.5 ± 1.0	1.2 ± 0.5	-52.0%	<0.001	1.60
Control	Plantar-flexion	3.7 ± 1.7	3.5 ± 1.6	-5.4%	0.456	0.12
MFDC	Plantar-flexion	3.9 ± 1.8	2.6 ± 1.0	-33.3%	0.002	0.87
HFDC	Plantar-flexion	3.8 ± 1.9	1.7 ± 0.8	-55.3%	<0.001	1.39
Control	Dorsi-flexion	3.5 ± 1.7	3.3 ± 1.6	-5.7%	0.389	0.12
MFDC	Dorsi-flexion	3.6 ± 1.8	2.5 ± 1.0	-30.6%	0.003	0.78
HFDC	Dorsi-flexion	3.5 ± 1.7	1.6 ± 0.7	-54.3%	<0.001	1.45

Lateral ankle injury incidence

During the 12-week intervention, the combined groups accrued 1080 exposure hours (30 participants × 36 hours). The control group incurred eight lateral ankle sprains (incidence rate: 7.41 per 1000 hours), the MFDC group incurred 2 (1.85 per 1000 hours), and the HFDC group incurred 0 (0 per 1000 hours). Poisson regression showed that the HFDC and MFDC groups had significantly reduced injury rates (Incidence Rate Ratio (IRR) = 0.00, 95% Confidence Interval (CI): 0.00–0.09, $p < 0.001$; IRR = 0.25, 95% CI: 0.05–0.78, $p = 0.012$) as compared to the control. Qualitative analysis (NVivo; Cohen's kappa = 0.89) identified control-group sprain mechanisms: excessive inversion during cutting (4 cases), inadequate landing control (2 cases), fatigue-related missteps (1 case), and unexpected surface perturbations (1 case). Of these, 5 were Grade II (moderate swelling, partial ligament tear) and 3 were Grade I (mild swelling). MFDC group's sprains (both Grade I) resulted from recreational activities (e.g., basketball, hiking), indicating training adaptations mitigated severity. The lack of HFDC group sprains correlates with injury prevention programs placing value on dynamic stabilization. Post-trauma recovery duration was longer in control (Grade II: 14.2 ± 3.1 days, Grade I: 7.8 ± 1.9 days) than MFDC (Grade I: 6.5 ± 1.5 days, $p = 0.041$).

Table 6: Lateral Ankle Injury Incidence and Mechanisms

Group	Injuries	Exposure (Hours)	Incidence Rate (per 1000 Hours)	IRR (vs. Control)	95% CI	p-value	Primary Mechanisms	Recovery Time (Days)
Con trol	8	1080	7.41	Reference	-	-	Inversion (4), Landing (2), Fatigue (1), Surface (1)	Grade II: 14.2 ± 3.1, Grade I: 7.8 ± 1.9
MFDC	2	1080	1.85	0.25	0.05–0.78	0.012	Recreational (2)	Grade I: 6.5 ± 1.5
HFDC	0	1080	0.00	0.00	0.00–0.09	<0.001	None	-

Secondary Outcomes

Neuromuscular Control

Electromyography (EMG) analysis of peroneus longus, tibialis anterior, gastrocnemius medialis, and gastrocnemius lateralis while performing a 45° sidestep cutting task revealed significant group × time interactions (peroneus longus: $F(2,87) = 9.45$, $p < 0.001$, partial $\eta^2 = 0.18$; tibialis anterior: $F(2,87) = 7.67$, $p = 0.001$, partial $\eta^2 = 0.15$; gastrocnemius medialis: $F(2,87) = 6.89$, $p = 0.002$, partial $\eta^2 = 0.14$; gastrocnemius lateralis: $F(2,87) = 6.23$, $p = 0.003$, partial $\eta^2 = 0.13$). The HFDC group showed greater pre-landing activation for peroneus longus (pre: 50 ± 15 μV, post: 74 ± 18 μV, $p < 0.001$, Cohen's d = 1.45, 48.0% increase), tibialis anterior (pre: 45 ± 12 μV, post: 64 ± 15 μV, $p < 0.001$, Cohen's d = 1.37, 42.2% increase), gastrocnemius medialis (pre: 48 ± 14 μV, post: 67 ± 16 μV, $p < 0.001$, Cohen's d = 1.26, 39.6% increase), and gastrocnemius lateralis (pre: 47 ± 13 μV, post: 65 ± 15 μV, $p < 0.001$, Cohen's d = 1.29, 38.3% increase). The MFDC group had moderate rises (peroneus longus: pre: 52 ± 16 μV, post: 62 ± 17 μV, $p = 0.008$, Cohen's d = 0.60; tibialis anterior: pre: 46 ± 13 μV, post: 54 ± 14 μV, $p = 0.017$, Cohen's d = 0.58). Co-contraction ratios (peroneal/tibialis anterior) were higher in the HFDC group (pre: 0.85 ± 0.20, post: 1.25 ± 0.26, $p < 0.001$, Cohen's d = 1.67), and peroneus longus/gastrocnemius medialis ratios were similarly higher (pre: 0.90 ± 0.22, post: 1.30 ± 0.27, $p < 0.001$, Cohen's d = 1.60). Muscle onset latency reduced in the HFDC group (peroneus longus: pre: 45 ± 10 ms, post: 35 ± 8 ms, $p < 0.001$, Cohen's d = 1.11), reflecting quicker neural responses.

Table 7: Pre-Landing EMG Activation (μV) and Latency (ms)

Group	Measure	Pre intervention (Mean ± SD)	Post intervention (Mean ± SD)	Change (%)	P-Value	Cohen's d
Control	Peroneus Longus (μV)	51 ± 14	52 ± 14	+2.0%	0.834	0.07
MFDC	Peroneus Longus (μV)	52 ± 16	62 ± 17	+19.2%	0.008	0.60
HFDC	Peroneus Longus (μV)	50 ± 15	74 ± 18	+48.0%	<0.001	1.45
Control	Tibialis Anterior (μV)	44 ± 11	45 ± 11	+2.3%	0.876	0.09
MFDC	Tibialis Anterior (μV)	46 ± 13	54 ± 14	+17.4%	0.017	0.58
HFDC	Tibialis Anterior (μV)	45 ± 12	64 ± 15	+42.2%	<0.001	1.37
Control	Peroneus Latency (ms)	46 ± 11	45 ± 10	-2.2%	0.789	0.09
MFDC	Peroneus Latency (ms)	45 ± 10	40 ± 9	-11.1%	0.021	0.52
HFDC	Peroneus Latency (ms)	45 ± 10	35 ± 8	-22.2%	<0.001	1.11

Dynamic balance and agility

Significant group × time interactions were observed in the Star Excursion Balance Test (SEBT) across the anterior, posteromedial, and posterolateral directions (anterior: $F(2,87) = 7.45$, $p = 0.001$, partial $\eta^2 = 0.15$; posteromedial: $F(2,87) = 8.12$, $p < 0.001$, partial $\eta^2 = 0.16$; posterolateral: $F(2,87) = 7.89$, $p = 0.001$, partial $\eta^2 = 0.15$). For posteromedial reach, the HFDC group significantly improved (pre: 68 ± 6 cm, post: 77 ± 5 cm, $p < 0.001$, Cohen's d = 1.60, 13.2% increase), and then MFDC (pre: 67 ± 7 cm, post: 73 ± 6 cm, $p = 0.005$, Cohen's d = 0.89, 9.0% increase). The control group remained unchanged (pre: 66 ± 5 cm, post: 67 ± 5 cm, $p = 0.456$, Cohen's d = 0.20). The 505 agility test revealed the HFDC group (pre: 2.5 ± 0.3 s, post: 2.1 ± 0.2 s, $p < 0.001$, Cohen's d = 1.67, 16.0% reduction) and MFDC group (pre: 2.5 ± 0.3 s, post: 2.3 ± 0.3 s, $p = 0.012$, Cohen's d = 0.67) improved and time to stabilization during cutting tasks decreased in the HFDC group (pre: 0.85 ± 0.15 s, post: 0.62 ± 0.09 s, $p < 0.001$, Cohen's d = 1.83, 27.1% reduction) and MFDC group (pre: 0.84 ± 0.14 s, post: 0.72 ± 0.12 s, $p = 0.006$, Cohen's d = 0.94). Center of pressure (COP) excursion on SEBT decreased in the HFDC group (pre: 12.5 ± 3.0 cm, post: 9.0 ± 2.0 cm, $p < 0.001$, Cohen's d = 1.39), which reflected enhanced stability.

Table 8: SEBT Reach Distance (cm) and COP Excursion

Group	Measure	Pre intervention (Mean ± SD)	Post intervention (Mean ± SD)	Change (%)	P-value	Cohen's d
Control	Posteromedial (cm)	66 ± 5	67 ± 5	+1.5%	0.456	0.20
MFDC	Posteromedial (cm)	67 ± 7	73 ± 6	+9.0%	0.005	0.89
HFDC	Posteromedial (cm)	68 ± 6	77 ± 5	+13.2%	<0.001	1.60
Control	COP Excursion (cm)	12.0 ± 2.8	11.8 ± 2.7	-1.7%	0.789	0.07
MFDC	COP Excursion (cm)	12.3 ± 3.0	10.5 ± 2.5	-14.6%	0.015	0.65
HFDC	COP Excursion (cm)	12.5 ± 3.0	9.0 ± 2.0	-28.0%	<0.001	1.39

Biomechanical Adaptations During Cutting

Peak ankle kinematics at a 45° sidestep cutting task revealed significant group × time interactions (inversion angle: $F(2,87) = 7.67$, $p = 0.001$, partial $\eta^2 = 0.15$; internal rotation: $F(2,87) = 6.89$, $p = 0.002$, partial $\eta^2 = 0.14$). The HFDC group decreased inversion angle (pre: 18.0° ± 4.0°, post: 12.0° ± 2.5°, $p < 0.001$, Cohen's d = 1.73, 33.3% reduction) and internal rotation (pre: 10.0° ± 3.0°, post: 6.0° ± 2.0°, $p < 0.001$, Cohen's d = 1.60). The MFDC group demonstrated lesser reductions (inversion: pre: 17.0° ± 5.0°, post: 13.0° ± 4.0°, $p = 0.015$, Cohen's d = 0.89). Maximum ankle inversion moment reduced in the HFDC group (pre: 0.35 ± 0.10 Nm/kg, post: 0.24 ± 0.07 Nm/kg, $p < 0.001$, Cohen's d = 1.29). Proximal joint kinematics also comprised increased hip flexion (HFDC: pre: 30.0° ± 6.0°, post: 38.0° ± 5.0°, $p < 0.001$, Cohen's d = 1.45), hip abduction (pre: 15.0° ± 4.0°, post: 21.0° ± 3.5°, $p < 0.001$, Cohen's d = 1.60), and reduced trunk lateral flexion (pre: 12.0° ± 3.0°, post: 8.0° ± 2.0°, $p < 0.001$, Cohen's d = 1.60). Knee valgus angle reduced in HFDC group (pre: 5.0° ± 1.5°, post: 3.5° ± 1.0°, $p = 0.002$, Cohen's d = 1.15).

Table 9: Ankle and Proximal Joint Kinematics During Cutting Task

Group	Measure	Pre intervention (Mean ± SD)	Post intervention (Mean ± SD)	Change (%)	P-Value	Cohen's d
Control	Inversion Angle (°)	18.0 ± 4.0	17.5 ± 4.0	-2.8%	0.456	0.13
MFDC	Inversion Angle (°)	17.0 ± 5.0	13.0 ± 4.0	-23.5%	0.015	0.89
HFDC	Inversion Angle (°)	18.0 ± 4.0	12.0 ± 2.5	-33.3%	<0.001	1.73
Control	Hip Abduction (°)	14.5 ± 4.0	14.7 ± 4.0	+1.4%	0.834	0.05
MFDC	Hip Abduction (°)	15.0 ± 4.5	17.5 ± 4.0	+16.7%	0.021	0.58
HFDC	Hip Abduction (°)	15.0 ± 4.0	21.0 ± 3.5	+40.0%	<0.001	1.60

Ground Reaction Forces (GRF)

Peak vertical and lateral GRF of the cutting task also had significant group × time interactions (vertical: $F(2,87) = 6.45$, $p = 0.002$, partial $\eta^2 = 0.13$; lateral: $F(2,87) = 7.23$, $p = 0.001$, partial $\eta^2 = 0.14$). The HFDC group decreased lateral GRF (pre: 2.1 ± 0.4 N/kg, post: 1.5 ± 0.3 N/kg, $p < 0.001$, Cohen's d = 1.60, reduction by 28.6%) and vertical GRF (pre: 3.5 ± 0.6 N/kg, post: 3.0 ± 0.5 N/kg, $p < 0.001$, Cohen's d = 0.94). Loading rate was reduced in the HFDC group (pre: 150 ± 30 N/s, post: 110 ± 25 N/s, $p < 0.001$, Cohen's d = 1.45). The MFDC group demonstrated smaller decreases (lateral GRF: pre: 2.0 ± 0.5 N/kg, post: 1.7 ± 0.4 N/kg, $p = 0.021$, Cohen's d = 0.67). These results indicate optimized force distribution and absorption and decreased ligamentous stress.

Table 10: Ground Reaction Forces and Loading Rate

Group	Measure	Pre intervention (Mean ± SD)	Post intervention (Mean ± SD)	Change (%)	P-Value	Cohen's d
Control	Lateral GRF (N/kg)	2.1 ± 0.4	2.1 ± 0.4	0.0%	0.901	0.00
MFDC	Lateral GRF (N/kg)	2.0 ± 0.5	1.7 ± 0.4	-15.0%	0.021	0.67
HFDC	Lateral GRF (N/kg)	2.1 ± 0.4	1.5 ± 0.3	-28.6%	<0.001	1.60

Control	Loading Rate (N/s)	148 ± 29	147 ± 28	-0.7%	0.876	0.04
MFDC	Loading Rate (N/s)	145 ± 32	128 ± 27	-11.7%	0.029	0.56
HFDC	Loading Rate (N/s)	150 ± 30	110 ± 25	-26.7%	<0.001	1.45

Muscle Co-Activation Patterns

Co-activation ratios of landing exhibited substantial group × time interactions (peroneus longus/gastrocnemius medialis: $F(2,87) = 6.78$, $p = 0.002$, partial $\eta^2 = 0.13$; peroneus brevis/gastrocnemius lateralis: $F(2,87) = 6.12$, $p = 0.003$, partial $\eta^2 = 0.12$). The HFDC group enhanced peroneus longus/gastrocnemius medialis co-activation (pre: 0.90 ± 0.22, post: 1.30 ± 0.28, $p < 0.001$, Cohen's d = 1.56, 44.4% increase) and peroneus brevis/gastrocnemius lateralis (pre: 0.87 ± 0.23, post: 1.25 ± 0.27, $p < 0.001$, Cohen's d = 1.50). The MFDC group had smaller increases (peroneus longus/gastrocnemius medialis: pre: 0.88 ± 0.21, post: 1.05 ± 0.24, $p = 0.015$, Cohen's d = 0.76). These patterns enhance joint stability, reducing injury risk.

Table 11: Muscle Co-Activation Ratios During Landing

Group	Muscle Pair	Pre intervention (Mean ± SD)	Post intervention (Mean ± SD)	Change (%)	P-Value	Cohen's d
Control	Peroneus Longus/ Gast. Medialis	0.89 ± 0.20	0.90 ± 0.20	+1.1%	0.923	0.05
MFDC	Peroneus Longus/ Gast. Medialis	0.88 ± 0.21	1.05 ± 0.24	+19.3%	0.015	0.76
HFDC	Peroneus Longus/ Gast. Medialis	0.90 ± 0.22	1.30 ± 0.28	+44.4%	<0.001	1.56

Energy Absorption and Power Generation

Ankle joint power throughout the cutting task had substantial group × time interactions (absorption: $F(2,87) = 6.45$, $p = 0.002$, partial $\eta^2 = 0.13$; generation: $F(2,87) = 5.89$, $p = 0.004$, partial $\eta^2 = 0.12$). The HFDC group enhanced peak power uptake (pre: -2.5 ± 0.6 W/kg, post: -3.2 ± 0.7 W/kg, $p < 0.001$, Cohen's d = 1.06, 28.0% increase) and power output (pre: 2.8 ± 0.7 W/kg, post: 3.5 ± 0.8 W/kg, $p < 0.001$, Cohen's d = 0.94, 25.0% increase). The MFDC group also showed smaller increases (absorption: pre: -2.4 ± 0.5 W/kg, post: -2.8 ± 0.5 W/kg, $p = 0.029$, Cohen's d = 0.80). Energy dissipation efficiency (absorbed/generated power ratio) was enhanced in the HFDC group (pre: 0.89 ± 0.20, post: 1.10 ± 0.22, $p = 0.001$, Cohen's d = 1.00).

Table 12: Ankle Joint Power (W/kg) and Efficiency

Group	Measure	Pre intervention (Mean ± SD)	Post intervention (Mean ± SD)	Change (%)	P-Value	Cohen's d
Control	Power Absorption	-2.5 ± 0.6	-2.5 ± 0.6	0.0%	0.901	0.00
MFDC	Power Absorption	-2.4 ± 0.5	-2.8 ± 0.5	+16.7%	0.029	0.80
HFDC	Power Absorption	-2.5 ± 0.6	-3.2 ± 0.7	+28.0%	<0.001	1.06
Control	Efficiency Ratio	0.88 ± 0.19	0.89 ± 0.19	+1.1%	0.876	0.05
MFDC	Efficiency Ratio	0.89 ± 0.20	0.98 ± 0.21	+10.1%	0.034	0.44
HFDC	Efficiency Ratio	0.89 ± 0.20	1.10 ± 0.22	+23.6%	0.001	1.00

Training Volume and Frequency Effects

Dose-response analysis found high correlations between direction change frequency and results for the HFDC group (stiffness: $r = 0.75$, $p < 0.001$; proprioception: $r = 0.71$, $p < 0.001$; neuromuscular activation: $r = 0.68$, $p < 0.001$). Total frequency of ground contact (HFDC: 155 ± 22 contacts/session, MFDC: 105 ± 16 contacts/session, Control: 80 ± 10 contacts/session) was related to improvement ($r = 0.65$, $p < 0.001$). Session length (HFDC: 45 ± 5 min, MFDC: 40 ± 4 min, Control: 35 ± 3 min) affected outcomes too ($r = 0.58$, $p = 0.002$) and supported dose-response relations.

Table 13: Training Volume and Frequency Metrics

Group	Directional Changes/ Session	Ground Contacts/ Session	Session Duration (min)	Correlation with Stiffness (r)	p-value
Control	0	80 ± 10	35 ± 3	0.10	0.598
MFDC	8–12	105 ± 16	40 ± 4	0.50	0.008
HFDC	15–20	155 ± 22	45 ± 5	0.75	<0.001

Multi-Planar Movement Adaptations

Exposure to multi-planar movements of the HFDC group lowered ankle eversion angle (pre: 8.0° ± 2.5°, post: 5.0° ± 1.5°, $p < 0.001$, Cohen's d = 1.39) and adduction angle (pre: 6.0° ± 2.0°, post: 4.0° ± 1.5°, $p = 0.001$, Cohen's d = 1.15), improving control in non-sagittal planes. These adaptations are crucial in sports such as soccer and basketball, which involve multi-planar stability.

Proximal Joint Contributions

HFDC group demonstrated greater knee flexion (pre: 40.0° ± 8.0°, post: 48.0° ± 7.0°, $p < 0.001$, Cohen's d = 1.06) and less trunk rotation (pre: 8.0° ± 2.0°, post: 5.0° ± 1.5°, $p < 0.001$, Cohen's d = 1.67), showing a kinetic chain strategy to minimize ankle stress.

Neuromuscular Fatigue Resistance

During a fatigue protocol (25 repeated cutting tasks), the HFDC group preserved peroneus longus activation (6.8% reduction vs. 17.5% in control, $p = 0.005$, Cohen's d = 1.11) and tibialis anterior activation (7.2% reduction vs. 16.9% in control, $p = 0.008$, Cohen's d = 1.06), indicating improved fatigue resistance.

Sex-Specific Responses

Female subjects in the HFDC group demonstrated greater proprioception gains (inversion: Cohen's d = 1.89 compared to 1.60 for males, $p = 0.028$) and stabilization

decreases (Cohen's d = 1.94 compared to 1.72 for males, p = 0.021). Muscle activation increases were slightly greater in females (peroneus longus: Cohen's d = 1.50 compared to 1.39 for males, p = 0.041).

Table 14: Sex-Specific Outcomes in HFDC Group

Sex	Measure	Pre intervention (Mean ± SD)	Post intervention (Mean ± SD)	Change (%)	P-Value	Cohen's d
Male	Inversion Error (°)	2.3 ± 0.9	1.0 ± 0.4	-56.5%	<0.001	1.60
Female	Inversion Error (°)	2.4 ± 0.9	0.9 ± 0.4	-62.5%	<0.001	1.89
Male	Stabilization (s)	0.85 ± 0.15	0.63 ± 0.09	-25.9%	<0.001	1.72
Female	Stabilization (s)	0.86 ± 0.16	0.61 ± 0.09	-29.1%	<0.001	1.94

Statistical Considerations

Analyses were conducted using SPSS v28 and R, using linear mixed models that incorporate repeated measures to account for within-subject variability, clustering effects, and covariates (sprint performance, sex, BMI, leg length). Missing data (10% dropout) were handled using multiple imputation for biomechanical outcomes and intention-to-treat for injury data. Sensitivity analyses (bootstrap resampling, 1000 iterations) and outlier exclusion confirmed robustness. Effect sizes were large for HFDC (Cohen's d > 0.8) and moderate for MFDC (Cohen's d 0.3–0.8).

DISCUSSION

Ankle joint stiffness is essential for stability and maximizing force transmission during dynamic movements such as sprinting and high-frequency directional changes. Studies suggest that sprint-plyometric training, characterized by rapid stretch-shortening cycles, can enhance stiffness in the leg and ankle joints, particularly among athletes with functional ankle instability (FAI). Huang PY et al. (2021) reported that six weeks of plyometric training, whether in isolation or in addition to balance training, enhanced ankle joint position sense and neuromuscular control in recreational athletes with FAI, thereby indirectly increasing joint stiffness through greater muscle activation [5]. In particular, single-leg drop landings were reported to have decreased time to stabilization in the plyometric group (pre: 2.85 ± 1.15 s; post: 1.87 ± 0.97 s; p = 0.006), suggesting enhanced dynamic stiffness.

In comparison, a study focusing on healthy teenagers (12–15) found that integrated plyometric and balance training produced greater leg stiffness and running performance than plyometric training alone, likely due to reduced stretch-shortening stress on the neuromuscular apparatus. This is consistent with evidence that combined training augments joint stiffness by maximizing coactivation of ankle muscles, such as the tibialis anterior (TA) and plantar flexors. However, the inability to directly measure ankle joint stiffness in such studies limits the ability to draw conclusive findings. Biomechanical models should be used to quantify stiffness, as proposed by Huang PY et al. (2021), and it is suggested that training volume effects be investigated. In contrast, no measurable differences in ankle stiffness were found in studies that involved only proprioceptive training without a plyometric stimulus, suggesting that high-intensity, dynamic movements such as sprint-plyometrics are better suited to increased stiffness [5]. This would be especially pertinent to sports with high rates of directional change, as greater stiffness could potentially minimize energy loss during fast movement.

Proprioception, encompassing joint position sense (JPS) and kinaesthesia, plays a critical role in maintaining ankle stability and reducing the risk of injury. The research by Huang PY et al. (2021) was demonstrated that both isolated plyometric training and combined balance/plyometric training significantly reduced absolute errors in plantar flexion. Specifically, the plyometric group showed a decrease from 3.79° ± 1.98° to 2.20° ± 1.31° (p = 0.016), while the combined group improved from 4.10° ± 1.87° to 2.94° ± 1.01° (p = 0.045). Additionally, the combined group exhibited a notable reduction in inversion angle errors, dropping from 2.24° ± 1.44° to 1.48° ± 0.93° (p = 0.022) [5]. These results are in agreement with a systematic review by Yılmaz O et al. (2024), which identified that proprioceptive training enhances JPS, balance, and postural stability across different sports, such as soccer and basketball, with a notable benefit for ankle inversion and eversion [10]. Nonetheless, a systematic review by Shreyanshi et al. (2025) found that patients with chronic ankle instability (CAI) demonstrated decreased kinesthesia and JPS in inversion and plantar flexion compared with control subjects, suggesting that sprint-plyometric training could be particularly valuable for this group [11]. The review pointed towards active JPS deficits in inversion and eversion, corresponding with Chen et al.'s observation of enhanced proprioception after training. Also, Xue X et al. (2021) found that subjects with CAI showed less precise active JPS near maximal inversion, highlighting the need for targeted training to rehabilitate proprioceptive sensitivity [12]. Frequent high-frequency directional changes, typical for sports such as soccer and basketball, impose extreme requirements on proprioceptive feedback. A cross-sectional study by Shaghayegh ShamsiniGhiyasvand et al. (2025) reported greater angle reconstruction errors in athletes with dynamic balance deficits (P = 0.001), suggesting that proprioceptive deficits may exacerbate instability during rapid directional changes [13]. Sprint-plyometric training, by enhancing sensory feedback and muscle coactivation, appears to mitigate these deficits, as supported by Yılmaz O et al.'s findings of improved dynamic neuromuscular control.

Neuromuscular activation, as determined by electromyography (EMG), is improved by sprint-plyometric training, especially in FAI athletes. Huang PY et al. (2021) An increase in integrated EMG activity of the ankle plantar flexors prior to landing was observed, along with elevated tibialis anterior (TA) activation in the plyometric group, rising from 102.88 ± 20.93 to 119.29 ± 38.33 (p = 0.009) [5]. These results are consistent with a

meta-analysis of Vriend I et al. (2016), which concluded that neuromuscular training (NMT), including plyometric, significantly decreased ankle sprain incidence (RR = 0.60, 95% CI 0.51–0.71) due to partially improved muscle activation and dynamic stability. During high-frequency, directional changes in sports, neuromuscular control is key to stabilizing the ankle during abrupt force application [14]. A systematic review published by Akbar S et al. (2022) reported that NMT, including plyometrics, enhanced joint stability and muscle coactivation and minimized injury risk in team sports [15]. However, in a study, Han et al. (2015) concluded that passive interventions, such as taping or bracing, had no effect on ankle proprioception or neuromuscular activation. Thus, active training modalities, such as sprint-plyometrics, are preferable for enhancing muscle response times and coordination [16]. Chen et al.'s study found that the combined balance/plyometric group demonstrated enhanced neuromuscular control of the TA, GL, GM, and SOL during pre-landing, which means integrated training is more effective at promoting synergistic muscle activation than isolated plyometrics. This is particularly evident during directional changes, where coordinated muscle activation helps prevent excessive or unintended joint movement.

Ankle sprains frequently occur in sports that involve sprinting and rapid directional changes, and deficits in proprioception and neuromuscular function contribute to a heightened risk of recurrent injuries. A meta-analysis by Schiftan et al. (2015) also reported that proprioceptive training decreased the incidence of ankle sprain (RR = 0.65, 95% CI 0.55–0.77) but specifically in those with a history of sprain [17]. Likewise, Huang PY et al. (2021) showed that both plyometric and combined balance/plyometric training decreased the risk of ankle sprain by enhancing JPS and neuromuscular control, and that plyometric training resulted in faster stabilization times. In a Systematic review by McKeon PO et al. (2008), these conclusions were supported, with balance training in a part of integrated programs found to decrease ankle sprain incidence and improve dynamic neuromuscular control and postural sway [18]. The data on primary prevention (initial-time sprains) are inconclusive, as reported by Schiftan et al., suggesting that sprint-plyometric training is most effective in secondary prevention for athletes with FAI or prior sprains [17]. Conversely, a systematic review by Riva D et al. (2016) emphasized that proprioceptive training alone is effective for both preventing initial and recurrent ankle sprains, particularly in sports like basketball and volleyball where such injuries are highly prevalent [19]. This difference implies that while sprint-plyometric training improves injury prevention through dynamic stability, integrating it with balance training may confer broader benefits, as evidenced in Chen et al.'s integrated training group.

The results of Huang PY et al. (2021) concur with the overall literature in showing that sprint-plyometric training by itself, or in combination with balance training, increases ankle joint stiffness, proprioception, and neuromuscular activation and Is a critical factor contributing to injury prevention [5]. The better performance of combined training in adolescents and athletes with FAI indicates that inclusion of balance components reduces neuromuscular stress and maximizes joint stability. Yet, the absence of direct measurements of stiffness and conflicting evidence regarding primary prevention indicate areas where research is needed. In sports with frequent direction changes, sprint-plyometric training is especially effective because it focuses on rapid force development and muscle coactivation, as indicated by Verhagen et al. and Manojlović et al. Clinicians and coaches should emphasize integrated training regimens for FAI athletes that address both proprioceptive sensitivity and neuromuscular control to reduce sprain recurrence. Optimal training volumes and inclusion of biomechanical analyses of ankle stiffness should be examined in future studies to further prove these results.

CONCLUSION

This study demonstrates that a 12-week high-frequency directional change (HFDC) sprint-plyometric training program significantly enhances ankle joint function, neuromuscular control, proprioception, and biomechanical stability, leading to marked reductions in injury risk among recreationally active adults. However, its short duration, lack of long-term follow-up, and focus on the non-elite population limit generalizability to professional athletes or clinical groups. The absence of blinding, limited sport-specific performance measures, and incomplete injury surveillance further constrain interpretation. Future research should examine the protocol's long-term effects, its applicability across diverse athletic and rehabilitative settings, and its integration with sport-specific demands to validate its broader utility for injury prevention and performance enhancement.

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