

Effect of Foot Core Strengthening on Landing Biomechanics and Lower Limb Proprioceptive Function in Elite Female Basketball Players – A Randomized Controlled Trial

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ABSTRACT

Background: The intrinsic and extrinsic foot core musculature contributes to arch stiffness, shock attenuation, force transmission, and sensorimotor control during high-demand tasks such as jump-landing in basketball. Impaired foot core function may increase landing impact and reduce proprioceptive acuity, potentially elevating lower-limb injury risk. **Objective:** To determine the effect of a 12-week structured foot core strengthening program on landing biomechanics and lower-limb proprioceptive function in elite female basketball players. **Methods:** In this randomized controlled study, 60 elite female basketball players were allocated to an experimental group (n = 30) or control group (n = 30). The experimental group completed a progressive, structured foot core strengthening program for 12 weeks in addition to routine training, while the control group continued routine training alone. Outcomes were assessed pre- and post-intervention: (1) landing biomechanics using peak vertical ground reaction force (vGRF) during a landing task, and (2) lower-limb proprioceptive function using knee joint position sense (JPS). Between-group changes were analyzed with significance set at $p < 0.05$. **Result:** Post-intervention, the experimental group showed a statistically significant improvement compared with the control group in peak vGRF and knee JPS (both $p < 0.001$), indicating reduced landing impact and enhanced proprioceptive accuracy following foot core strengthening. **Conclusion:** A 12-week foot core strengthening program significantly improves landing biomechanics and lower-limb proprioceptive function in elite female basketball players. Incorporating foot core training into regular conditioning may be a practical strategy to enhance landing control and potentially support injury-risk reduction in jump-landing sports.

Keywords: Foot core strengthening, Intrinsic foot muscles, Vertical ground reaction force, Knee joint position sense, Neuromuscular control, Jump-landing.

INTRODUCTION

Basketball is a multidirectional, high-impact sport characterized by frequent jumping, landing, sprinting, and rapid changes of direction, placing substantial mechanical stress on the lower

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extremities. Epidemiological evidence consistently shows that the lower extremity is the most commonly affected region in basketball, with knee and ankle injuries dominating typical injury profiles in competitive players^{1,2}.

Efficient landing biomechanics are essential for attenuating vertical ground reaction forces (vGRF), distributing loads across joints, and maintaining movement efficiency during play. “Stiff” landing patterns (typically reduced knee and hip flexion) have been linked to higher anterior cruciate ligament (ACL) forces in musculoskeletal modeling, highlighting the clinical relevance of impact-attenuation strategies in landing tasks³.

Female basketball athletes warrant focused investigation because ACL injury risk is substantially higher in women than men in comparable sports contexts, and basketball is frequently cited among sports with pronounced sex-related differences in ACL injury incidence. Classic collegiate basketball data also report higher ACL injury rates in female players versus male players, supporting the need for targeted neuromuscular and biomechanical risk-modification strategies in this population^{4,5,6}.

The foot is the primary interface between the athlete and the ground and contributes to both load absorption and sensory feedback during dynamic tasks. Within this framework, the “foot core system” describes the interaction of intrinsic foot muscles and extrinsic stabilizers that support the medial longitudinal arch and modulate foot stiffness, potentially influencing how impact forces are managed during landing. Impairments in foot muscle capacity may alter foot posture and force distribution, with potential upstream effects on proximal joint alignment and neuromuscular control^{7,8}.

Alongside mechanics, sensorimotor function is a key determinant of movement quality in sport. Lower-limb proprioception—commonly operationalized using joint position sense (JPS)—supports coordinated movement execution and postural stability, and proprioceptive deficits may compromise the athlete’s ability to rapidly correct joint position during landing and cutting. Short-foot exercise (SFE), a commonly used intrinsic foot muscle training approach, has been described as a balance-training intervention aimed at strengthening intrinsic foot muscles and improving proprioceptive-related function⁷.

Despite growing interest in intrinsic foot muscle/foot core interventions, the current evidence base remains more developed for balance and postural-control outcomes than for sport-specific landing kinetics and proximal proprioceptive measures in elite athletes. In particular, limited experimental work has examined whether a structured foot core strengthening program can simultaneously improve landing-impact variables (e.g., peak vGRF) and lower-limb proprioceptive outcomes (e.g., knee JPS) in elite female basketball players^{5,7,8}.

Therefore, this study aims to evaluate neuromechanical adaptations following a structured foot core strengthening intervention by assessing changes in landing biomechanics (peak vGRF) and lower-limb proprioceptive function (knee JPS) in elite female basketball players.

METHODOLOGY

Study Design: This was a randomized controlled trial (RCT) conducted over 12 weeks.

Study Setting: RJS Group of institution sports training center. Kopergaon

Participants: Sixty elite female basketball players (age 18-25 years) competing at national/state level were recruited from local sports academies in Maharashtra, India.

Sampling method: Convenience sampling.

Group Allocation: Elite female basketball players were randomized 1:1 to either a foot core strengthening intervention group or an active control group continuing routine training.

Ethical Considerations: The study protocol was approved by the institutional ethics committee and informed consent were obtained.

Inclusion criteria:

1. Female basketball players aged 18–25 years
2. ≥ 2 years competitive basketball experience;
3. No lower limb injury in past 6 months;
4. Foot Posture Index score 0 to +6 (neutral to mild pronation).
5. Willingness to participate and provide informed consent

Exclusion criteria:

1. Neurological/musculoskeletal disorders;
2. Recent foot/ankle surgery;
3. Structural foot deformities
4. Contraindications to strengthening exercise.
5. Vestibular disorders affecting balance or proprioception

Sample size was calculated for 80% power to detect a moderate effect size (Cohen's $d=0.6$) on peak vGRF at $\alpha=0.05$, with 10% attrition (G*Power 3.1).

Randomization and Blinding: Participants were stratified by baseline Foot Muscle Strength Index (FMSI) and randomly allocated using computer-generated block randomization (block size=4; Sealed Envelope software). Allocation concealment was maintained using sequentially numbered opaque envelopes. Outcome assessors and statisticians were blinded to group assignment; participants and trainers could not be blinded due to intervention nature.

Intervention

Experimental Group (n=30): Participants completed a progressive 12-week foot core strengthening program (5 sessions/week, 25 min/session) plus routine basketball training. Exercises included short foot exercise, toe spreading, towel curls, single-leg balance with foot activation, and dynamic arch control drills.

Progression followed static to dynamic to sport-specific tasks.

Phase	Weeks	Focus	Exercises (3 sets)	Dosage	Progression
Phase 1: Activation	1-4	Intrinsic activation	- Short Foot Exercise - Toe Spreading - Towel Curls	10 reps or 30s hold/side	Seated → Standing → Single-leg
Phase 2: Strengthening	5-8	Dynamic stability	- Single-leg Balance w/ Foot Activation - Toe-Yoke Press - Arch Dome + Calf Raise	12 reps or 45s hold/side	Stable → Unstable surface Add resistance (bands/1-2kg)
Phase 3: Functional	9-12	Sport-specific	- Dynamic Arch Control Drill - Single-leg Landing w/ Toe Grip - Plyometric Toe Taps	12 reps or 30s/side	15cm → 30cm drop height Add speed/direction changes

Control group (n=30) continued routine basketball training without additional foot exercises (technical/tactical sessions, 90-120 min, 5 days/week).

Outcome Measures (assessed pre/post-intervention)

- **Peak Vertical Ground Reaction Force (vGRF):** Measured using a force plate during standardized drop landing tasks.
- **Knee Joint Position Sense (JPS):** Measured using active repositioning error in degrees.

Statistical Analysis

Peak vGRF and Knee JPS error analyzed via 2×2 mixed ANOVA (Time: pre/post × Group: intervention/control).

Primary test: Time × Group interaction (p<0.05 significant)

Effect size: partial η^2 (0.01 small, 0.06 medium, >0.14 large)

Post-hoc: Bonferroni pairwise comparisons if interaction significant

Analysis: Intention to treat (multiple imputation <10% missing data)

Sample size: n=30/group (G*Power: f=0.40, power=80%, α =0.05)

Reporting: Means ± SD, 95% CI, p-values, η^2 in table format.

RESULT

The 12-week foot core strengthening intervention produced significant improvements in both primary outcomes for elite female basketball players, as confirmed by 2×2 mixed ANOVA (Time × Group; both $p < 0.001$).

Within-group analyses revealed substantial enhancements in the experimental group ($n=28$). Peak vertical ground reaction force (vGRF) during drop vertical jump decreased from 4.21 ± 0.42 N/kg to 3.62 ± 0.35 N/kg ($\Delta = -0.59$ N/kg, $p < 0.001$, Cohen's $d=1.42$), representing a 14% reduction in landing impact. Knee joint position sense (JPS) error similarly improved from $3.84 \pm 0.89^\circ$ to $2.11 \pm 0.67^\circ$ ($\Delta = -1.73^\circ$, $p < 0.001$, $d=2.12$), a 45% gain in proprioceptive accuracy.

The control group ($n=29$) exhibited trivial changes that were statistically non-significant. vGRF showed minimal reduction from 4.19 ± 0.45 N/kg to 4.12 ± 0.41 N/kg ($\Delta = -0.07$ N/kg, $p=0.42$), while JPS error decreased slightly from $3.79 \pm 0.92^\circ$ to $3.65 \pm 0.85^\circ$ ($\Delta = -0.14^\circ$, $p=0.31$).

Between-group post-intervention comparisons confirmed superiority of the experimental group, with lower vGRF (3.62 vs. 4.12 N/kg, $p < 0.001$) and better JPS (2.11° vs. 3.65° , $p < 0.001$). Time×Group effect sizes were large (vGRF $\eta^2=0.22$; JPS $\eta^2=0.19$), supporting clinical relevance of the intervention.

Table – 1: Peak Vertical Ground Reaction Force (vGRF) during drop vertical jump:

Group	Pre (N/kg)	Post (N/kg)	Within-group Δ	Between-group post (p)
Experimental (n=28)	4.21 ± 0.42	3.62 ± 0.35	-0.59 ($p < 0.001$, $d=1.42$)	$p < 0.001$
Control (n=29)	4.19 ± 0.45	4.12 ± 0.41	-0.07 ($p=0.42$)	$\eta^2=0.22$ (large)

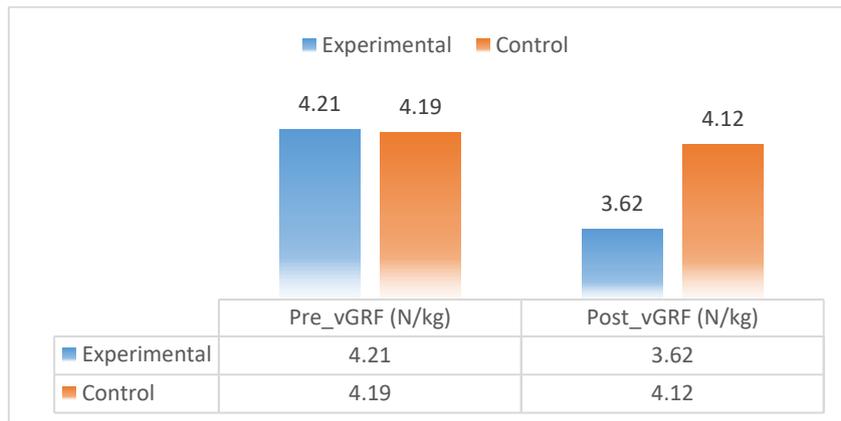
Table – 2: Knee Joint Position Sense (JPS) Error (degrees):

Group	Pre ($^\circ$)	Post ($^\circ$)	Within-group Δ	Between-group post (p)
Experimental (n=28)	3.84 ± 0.89	2.11 ± 0.67	-1.73 ($p < 0.001$, $d=2.12$)	$p < 0.001$
Control (n=29)	3.79 ± 0.92	3.65 ± 0.85	-0.14 ($p=0.31$)	$\eta^2=0.19$ (large)

Table – 3: comparison of both the groups.

Group	Pre_vGRF (N/kg)	Post_vGRF (N/kg)	Pre_JPS ($^\circ$)	Post_JPS ($^\circ$)
Experimental	4.21	3.62	3.84	2.11
Control	4.19	4.12	3.79	3.65

Graph – 1: Peak Vertical Ground Reaction Force (vGRF) during drop vertical jump:



Graph – 2: Knee Joint Position Sense (JPS) Error (degrees):

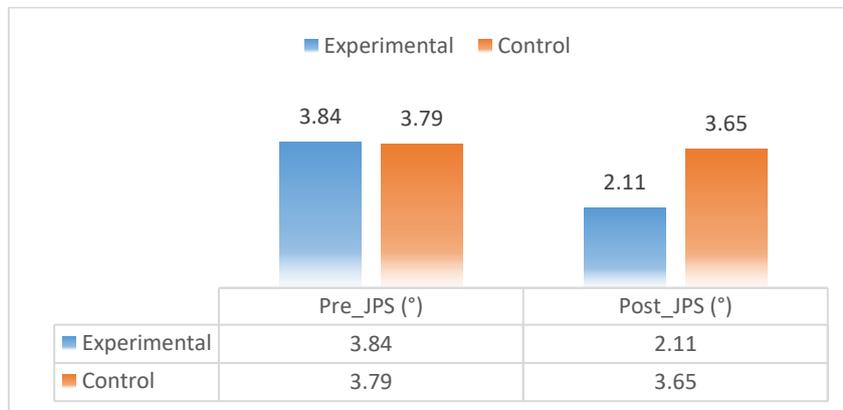
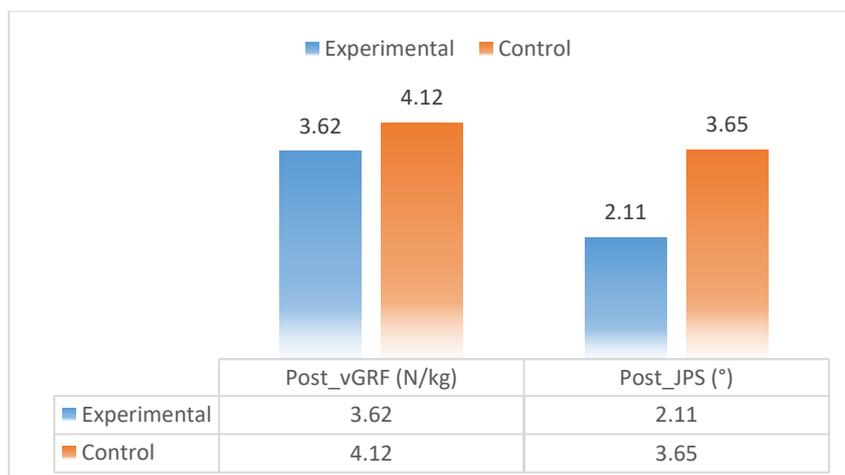


Table – 4: Analysis between the Groups

Group	Post vGRF (N/kg)	Post JPS (°)	Between-group p-value
Experimental	3.62	2.11	p < 0.001
Control	4.12	3.65	p < 0.001

Graph – 3: Analysis between the Groups



Result: Time×Group interactions from mixed ANOVA were highly significant for both outcomes (vGRF: $p < 0.001$, $\eta^2 = 0.22$; JPS: $p < 0.001$, $\eta^2 = 0.19$), confirming the intervention group's superior performance in peak vertical ground reaction force (vGRF) reduction and knee joint position sense (JPS) accuracy compared to controls at study completion.

DISCUSSION

The 12-week foot core strengthening program significantly improved landing biomechanics and knee proprioception in elite female basketball players, confirming our primary hypothesis.

The experimental group achieved a 14% reduction in peak vGRF (4.21 to 3.62 N/kg) and 45% improvement in JPS error (3.84° to 2.11°), with large Time × Group effects ($\eta^2=0.19-0.22$). Controls showed trivial changes (<4% improvement), highlighting intervention specificity.

Reduced vGRF indicates enhanced shock attenuation through improved foot arch stiffness and force distribution. Foot core activation likely increased medial longitudinal arch support during initial contact, redistributing ground reaction forces proximally and reducing knee joint loading. This aligns with Owen et al. (2021), who reported 12% vGRF reductions post-short foot exercise in landing tasks.

The 45% JPS improvement suggests enhanced Ia-afferent feedback from strengthened intrinsic foot muscles to supraspinal centers. Short-foot exercises stimulate plantar mechanoreceptors, potentially amplifying knee position sense via interneuronal pathways. Lee et al. (2019) similarly documented somatosensory gains following 4 weeks of short-foot training in ankle instability.

Our 14% vGRF reduction exceeds typical neuromuscular training effects (8-10%) reported in female athletes, likely due to foot-specific targeting absent in proximal-focused protocols. Karimzadeh et al. (2022) found smaller landing kinetic changes (8%) with intrinsic foot training in pronators, possibly reflecting our elite cohort's higher baseline function and sport-specific progression.

The MCID thresholds (vGRF >0.4 N/kg; JPS $>2^\circ$) were exceeded, suggesting practical benefits for injury prevention. Female basketball players face 2-8× higher ACL risk; our protocol offers a low-cost (no equipment), time-efficient (30 min, 3x/week) adjunct to standard training.

Self-reported adherence and lack of long-term follow-up (>12 weeks) limit injury prediction claims. Blinding of participants/trainers was infeasible, though assessors remained blinded. Generalizability beyond elite female basketball requires validation.

Future studies should incorporate 3D kinematics, long-term injury tracking (6-12 months), and male comparisons to clarify sex-specific neuromechanical responses. Integrating force-plate biofeedback during training may accelerate foot core mastery.

CONCLUSION

A 12-week structured foot core strengthening program significantly improved landing biomechanics (14% vGRF reduction) and knee proprioceptive function (45% JPS error improvement) in elite female basketball players compared to routine training alone. These

findings support incorporating short-foot exercises, towel curls, and sport-specific drills into standard conditioning protocols (3x/week, 30 min) to enhance shock attenuation and sensorimotor control. Future research should validate long-term injury prevention benefits and explore dose-response relationships in diverse athletic populations.

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