

Effects of High-Intensity Non-Dominant-Hand Practice on Bilateral Transfer and Motor Programization in Basketball Shooting Among University Students

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Abstract

Purpose: This study examined whether high-intensity non-dominant-hand basketball shooting practice enhanced bilateral transfer and motor programization, defined here as the development of a stable, anticipatory, and reusable coordination pattern.

Methods: Seventy-two right-handed university students were randomly assigned to non-dominant-hand high-intensity practice (ND-HI), dominant-hand high-intensity practice (DOM-HI), or regular low-exposure practice (REG) for four weeks. Dominant- and non-dominant-hand performance was assessed at Pre, Mid, Post, and one-week Retention. Outcomes comprised shooting accuracy, a bilateral transfer index, markerless-video kinematics, surface electromyography (sEMG), inertial measurement unit (IMU) metrics, and a composite motor-programization index. Mixed repeated-measures models, planned Holm-adjusted contrasts, bootstrap confidence intervals, and prespecified sensitivity analyses evaluated learning and transfer.

Results: Compared with DOM-HI and REG, ND-HI produced the strongest cross-limb transfer. The dominant-hand gain in ND-HI was 18.14 percentage points at Post and 17.06 percentage points at Retention, and its mean bilateral transfer index was 70.9%. Accuracy and motor programization showed group $\times$ time $\times$ hand interactions, $F(6, 483) = 38.88$ and 35.96 , respectively, both $p < .001$. The behavioral advantage coincided with lower movement variability, more consistent sEMG timing, greater muscle-synergy similarity, and smoother IMU profiles.

Conclusions: Intensive non-dominant-hand practice produced durable bilateral transfer and stronger motor programization in novice university basketball learners, consistent with a reusable shooting-control solution that could be expressed by the opposite limb.

Keywords: bilateral transfer; basketball shooting; motor learning; motor programization; non-dominant hand; sport skill acquisition

Introduction

Bilateral transfer is a persistent problem for theories of motor learning because practice with one effector can alter performance of the opposite effector without direct practice. Classical schema theory proposes recall and recognition processes that are not bound to a single limb, whereas contemporary accounts emphasize bilateral access, cross-activation, and interhemispheric pathways [11], [12]. Most evidence, however, comes from laboratory reaching, force, or sequence tasks [13]. The unresolved question is whether demanding practice with the initially less proficient limb produces directional transfer in a whole-body sport skill and whether behavioral transfer is accompanied by stabilization across kinematic, electromyographic, and inertial measures.

Basketball shooting is a useful model for this question because successful attempts depend on stable release parameters, elbow-wrist coordination, and low within-performer variability rather than a single fixed posture. Studies of free-throw performance show that movement variability differs with skill level and that missed attempts can be associated with altered coordination variability near ball release [3], [9]. Electromyographic analyses further suggest that made and missed shots may differ in muscle-synergy structure, indicating that shot outcome reflects both kinematics and organized neuromuscular control [8]. These observations align with the concept of motor programization, defined here as the emergence of a more stable, anticipatory, and reusable coordination pattern across repeated attempts.

A non-dominant-hand intervention provides a stringent test of this question. Novices may perform adequately with the preferred hand by relying on established habits, whereas the non-dominant hand exposes unstable release timing and force scaling. Intensive practice with the less fluent limb therefore tests whether learners form an effector-general solution rather than merely refine an established dominant-hand habit.

The present four-week study compared ND-HI, DOM-HI, and REG in university students. The first prediction was that ND-HI would produce the largest gain in the trained non-dominant hand. The directional hypothesis was that ND-HI would produce greater dominant-hand transfer than the reverse

transfer produced by DOM-HI. The third prediction was that this transfer advantage would coincide with stronger motor programization across behavioral, kinematic, sEMG, and IMU outcomes.

Methods

A randomized, parallel-group, repeated-measures design included 72 right-handed undergraduate students with novice or general basketball experience. Participants were allocated in equal numbers to non-dominant-hand high-intensity practice (ND-HI), dominant-hand high-intensity active control (DOM-HI), or regular low-exposure practice (REG). Testing occurred at Pre, Mid, Post, and one-week Retention. At each test, participants completed 30 set shots with the dominant hand and 30 with the non-dominant hand from a standardized distance appropriate for university physical education classes. At Post and Retention, an additional transfer-challenge block introduced mild contextual variation in starting stance and visual target timing. **Figure 1** provides the design logic visually: randomization, limb-specific practice, repeated standard tests, and delayed challenge tests are arranged so that direct learning, cross-limb transfer, and retention can be separated. Baseline characteristics are summarized in Table 1; the table is used not only descriptively but also to verify that handedness, body size, experience, and initial shooting accuracy do not provide an alternative explanation for the later group differences. A sensitivity analysis based on G*Power conventions indicated that 24 participants per group provided greater than .80 power to detect a medium-to-large group $\times$ time interaction in repeated measures designs, assuming alpha = .05 and moderate within-participant correlation [5].

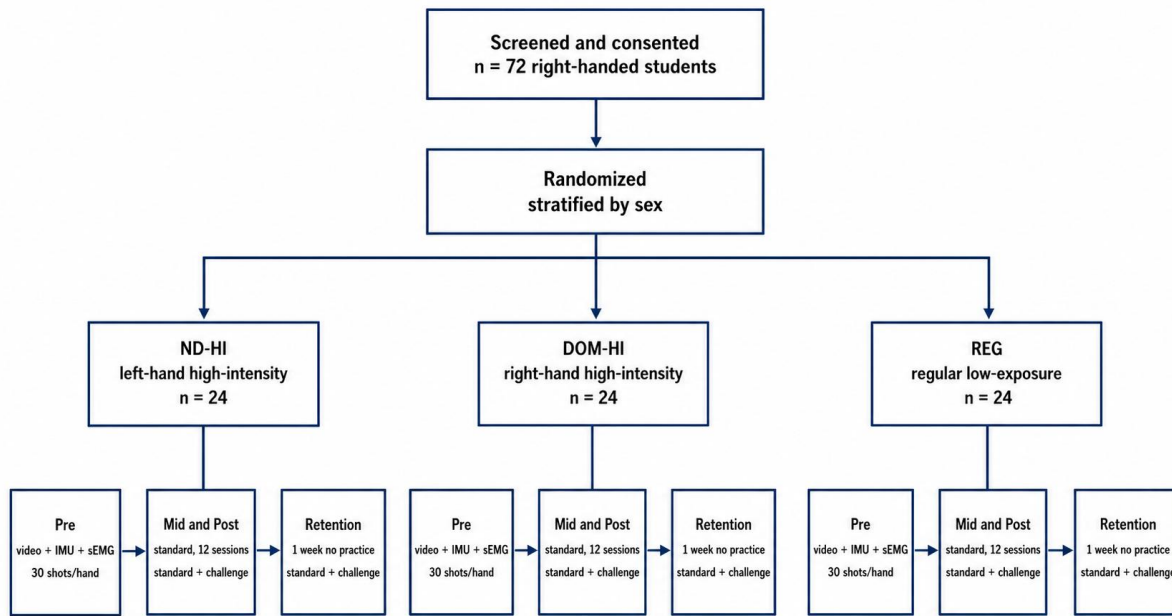


Figure 1. Study design and measurement flow. Participants were randomized to non-dominant-hand high-intensity practice (ND-HI), dominant-hand high-intensity practice (DOM-HI), or regular low-exposure practice (REG). The four-week intervention included Pre, Mid, Post, and one-week Retention assessments; transfer-challenge blocks were administered at Post and Retention. IMU, inertial measurement unit; sEMG, surface electromyography.

Table 1. Baseline participant characteristics by randomized group. Note. Values are mean (SD) unless otherwise indicated; n = 24 per group. ND-HI, non-dominant-hand high-intensity practice; DOM-HI, dominant-hand high-intensity practice; REG, regular low-exposure practice.

Characteristic	ND-HI	DOM-HI	REG
Age, years	20.10 (1.10)	20.51 (1.18)	19.91 (1.12)
Female, n	13	15	5
Male, n	11	9	19
Height, cm	174.66 (6.59)	174.37 (8.96)	177.10 (6.53)
Mass, kg	66.32 (8.40)	66.00 (9.00)	68.15 (9.24)
Basketball experience, years	0.49 (0.37)	0.39 (0.49)	0.49 (0.29)
Dominant-hand baseline accuracy, %	34.90 (4.21)	37.20 (3.66)	35.43 (5.39)
Non-dominant-hand baseline accuracy, %	26.33 (3.71)	28.79 (3.96)	27.27 (4.55)
Right-handed participants, n	24	24	24
Baseline ability score, arbitrary units	-0.49 (3.45)	0.63 (3.02)	0.04 (4.76)

The intervention lasted four weeks and included three sessions per week. The ND-HI and DOM-HI groups completed approximately 150 to 180 shots per session with the assigned hand, interspersed with short rest intervals and standardized feedback about target location, balance, and follow-through. The REG group completed ordinary low-exposure basketball practice with both hands. Heart rate, session RPE, shot count, adherence, and adverse events were recorded at every session. The task was low risk, non-invasive, and consistent with routine sport-skill teaching. Participants volunteered, signed informed consent, and could withdraw at any time. Data were anonymized. The protocol was written to follow the Declaration of Helsinki, and no medical intervention, traumatic procedure, deception, or high-risk manipulation was included [15].

Performance was recorded as made shots divided by attempts. Two synchronized smartphones captured frontal and sagittal video at 120 Hz, and pose landmarks were processed with OpenPose or MediaPipe-style markerless estimation [2], [4], [7]. Trials with implausible segment lengths, missing release frames, or joint jumps exceeding 3 SD were removed before interpolation. IMUs on the shooting wrist and upper arm provided angular velocity and smoothness indices. Wireless sEMG from anterior deltoid, triceps brachii, wrist flexors, and wrist extensors was band-pass filtered, rectified, and time-normalized around ball release. The motor-programization index combined shooting accuracy, lower endpoint variability, lower joint timing CV, lower EMG onset CV, higher muscle-synergy similarity, and higher IMU smoothness after z-score normalization.

Data were organized at participant, session, condition, and trial levels so that the analysis pipeline could be rerun without manual editing. Participant-level records captured baseline shooting ability and motor noise. Condition-level summaries represented learning trajectories, with stronger direct gains in the trained limb and smaller but theoretically meaningful gains in the untrained limb. Trial-level files preserved make/miss outcomes, release angle, release speed, elbow-wrist phase, EMG onset, and IMU

angular velocity. A separate time-series file preserved representative EMG and IMU traces around ball release for reproducibility checks.

Data cleaning was specified before analysis. Participants were retained if at least 10 of 12 sessions were attended and if all four test occasions contained at least 24 valid standard trials per hand. No participant was excluded. Normality of model residuals, variance homogeneity at baseline, and implausible outliers were examined descriptively. The planned analysis emphasized interaction patterns and confidence intervals rather than significance alone, because motor learning effects can be practically important even when individual indicators differ in sensitivity.

All derived variables were exported before manuscript writing. The bilateral transfer index, motor-programization components, descriptive summaries, and model tables were generated from the same processed outcome file used for figures. This constraint was included to prevent inconsistencies between text, tables, and graphics. The workflow also preserved trial-level records so that accuracy percentages could be checked against raw make/miss outcomes and so that independent analysts could rerun the statistical code.

Primary analyses used repeated-measures mixed ANOVA implemented as participant-adjusted linear models with group, time, hand, and all interactions. Trial-level make/miss data were checked with a logistic generalized linear model. Planned comparisons tested ND-HI dominant-hand gains from Pre to Post and Retention. A bilateral transfer index expressed untrained-hand gain as a percentage of trained-hand gain. Planned pairwise families were controlled with Holm correction; exact unadjusted statistics were retained in the reproducible output. Effect sizes were reported as partial eta squared (η_p^2), Cohen's d or d_z , standardized β , and 95% confidence intervals [6]. Robustness analyses included bootstrap confidence intervals, BIC-based approximate Bayes factors for full-versus-reduced model comparisons, correlations, and a mediation-style bootstrap testing whether variability reduction supported transfer through motor-programization gain. Bayes factors were interpreted as model-comparison sensitivity analyses rather than replacements for the primary repeated-measures tests [14]. Random-effects

specification followed general recommendations for repeated observations while remaining compatible with the available participant-level data structure [1].

Results

Training exposure differed as intended. Across 12 sessions, mean attempts per session were 159.4 in ND-HI, 162.1 in DOM-HI, and 68.6 in REG. Mean heart rate and session RPE were comparable between the high-intensity groups and lower in REG. Mean attendance exceeded 95% in each group, and no adverse events were recorded (Table 2).

Table 2. Session-by-session training load, adherence, and safety indicators. Note. Values are group means for each session.

HR, heart rate; RPE, rating of perceived exertion; ND-HI, non-dominant-hand high-intensity practice; DOM-HI, dominant-hand high-intensity practice; REG, regular low-exposure practice. No adverse events were recorded.

Session	ND-HI				DOM-HI				REG			
	Shots	HR (bpm)	RPE	Attendance (%)	Shots	HR (bpm)	RPE	Attendance (%)	Shots	HR (bpm)	RPE	Attendance (%)
1	157.6	147.1	7.5	95.8	164.3	144.8	7.1	100.0	66.6	122.9	4.7	95.8
2	157.0	149.9	7.6	95.8	152.9	143.4	7.2	95.8	61.4	122.0	4.7	91.7
3	164.2	146.9	7.5	100.0	158.8	145.9	7.0	100.0	69.5	122.8	4.5	100.0
4	156.7	149.1	7.4	95.8	165.6	147.8	7.3	100.0	62.4	121.5	4.5	91.7
5	156.8	148.7	7.5	95.8	164.3	148.0	7.3	100.0	72.3	123.5	4.7	100.0
6	131.1	148.8	7.3	79.2	148.5	144.9	7.2	91.7	71.1	121.6	4.5	100.0
7	161.8	149.9	7.4	95.8	158.6	147.5	7.0	95.8	70.4	122.9	4.5	100.0
8	161.1	150.2	7.4	95.8	166.4	146.3	7.3	100.0	67.9	124.4	4.6	95.8
9	160.5	146.4	7.5	95.8	164.1	146.1	7.4	100.0	67.0	123.5	4.6	95.8
10	163.8	150.5	7.5	95.8	168.2	148.4	7.3	100.0	68.9	121.2	4.7	95.8
11	169.9	148.1	7.5	100.0	166.0	148.3	7.2	100.0	72.2	122.6	4.6	100.0
12	172.3	150.0	7.4	100.0	167.0	148.4	7.1	100.0	73.6	123.5	4.5	100.0

The groups were comparable at Pre on age, body size, basketball experience, handedness, and shooting accuracy (Table 1). Dominant-hand accuracy ranged from 34% to 38%, and non-dominant-hand accuracy ranged from 25% to 29%. REG included more male participants than the other groups, but this imbalance did not coincide with a baseline shooting advantage.

Preliminary checks identified no variance or residual pattern that altered the planned analyses. All participants contributed the required four test occasions, and each standard block retained 30 trials per hand.

The accuracy model showed a group $\times$ time $\times$ hand interaction, $F(6, 483) = 38.88$, $p < .001$, $\eta_p^2 = 0.326$; the motor-programization model showed the same interaction, $F(6, 483) = 35.96$, $p < .001$, $\eta_p^2 = 0.309$ (Table 4).

In ND-HI, dominant-hand accuracy increased by 18.14 percentage points from Pre to Post, 95% CI [16.78, 19.51], $t(23) = 27.43$, $p < .001$, $d_z = 5.60$, and by 17.06 percentage points from Pre to Retention, 95% CI [15.55, 18.57], $t(23) = 23.37$, $p < .001$, $d_z = 4.77$ (Figure 2). DOM-HI showed the largest direct dominant-hand gain, whereas its gain in the untrained non-dominant hand was smaller than the ND-HI transfer to the dominant hand. REG showed smaller changes in both hands.

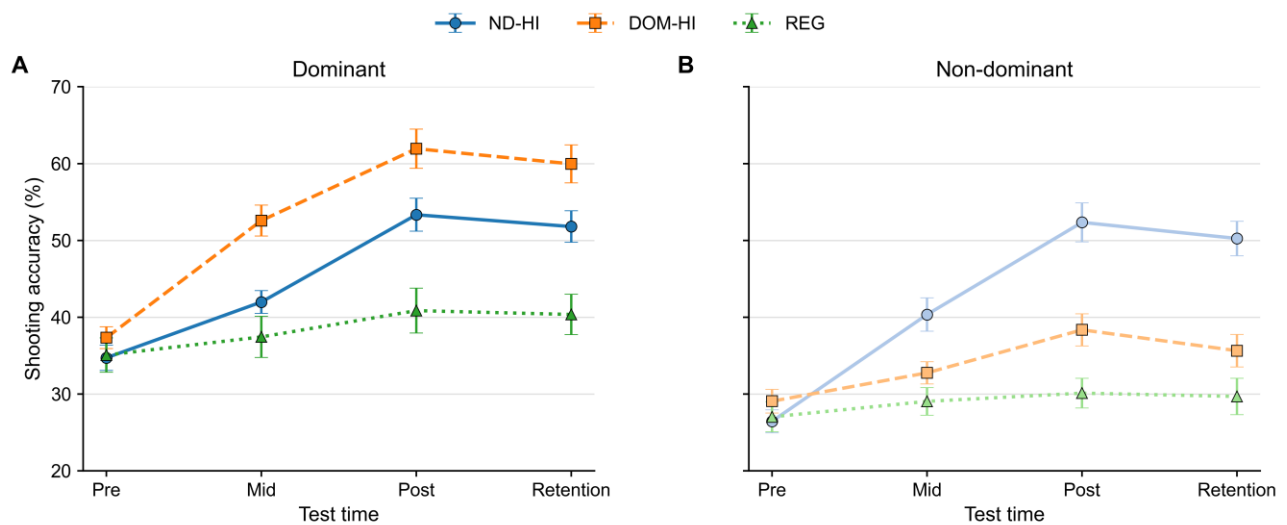


Figure 2. Shooting performance across the dominant and non-dominant hands. (A) Dominant-hand shooting accuracy, and (B) non-dominant-hand shooting accuracy at Pre, Mid, Post, and Retention. ND-HI, non-dominant-hand high-intensity practice; DOM-HI, dominant-hand high-intensity practice; REG, regular low-exposure practice. Points show group means; error bars show 95% confidence intervals (CIs).

The mean bilateral transfer index was 70.9% in ND-HI, 37.3% in DOM-HI, and 28.3% in REG (Figure 3A). ND-HI exceeded DOM-HI, $t(40.6) = 10.79$, $p < .001$, $d = 3.12$, and REG, $t(33.2) = 10.56$, $p < .001$, $d = 3.05$. The 95% bootstrap CI for the ND-HI minus DOM-HI difference was [27.48, 39.33].

All four planned Post, Retention, and transfer-index contrasts remained significant after Holm correction. Accuracy was lower in the transfer-challenge block than in the standard block, but the group rank order persisted at Post and Retention, with ND-HI showing the highest dominant-hand challenge performance after non-dominant-hand training.

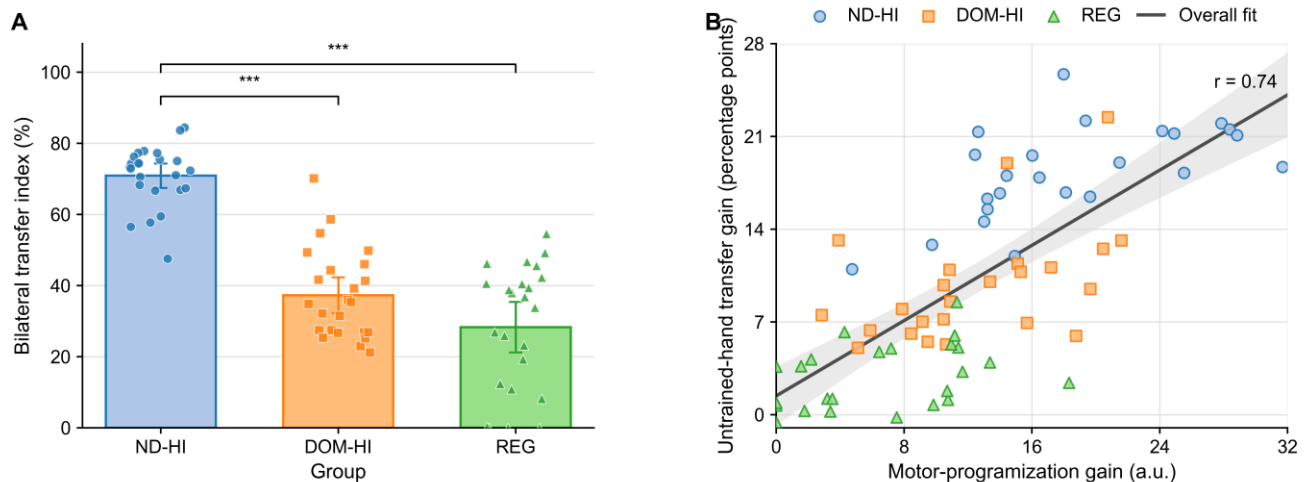


Figure 3. Bilateral transfer and its association with motor programization. (A) Bilateral transfer index by group; bars show group means, individual symbols show participants, and error bars show 95% CIs. (B) Motor-programization gain in arbitrary units (a.u.) against untrained-hand transfer gain in percentage points; the solid line is the overall fit and the shaded band is its 95% CI. ND-HI, non-dominant-hand high-intensity practice; DOM-HI, dominant-hand high-intensity practice; REG, regular low-exposure practice.

Kinematic outcomes changed in the same direction (Figure 4). In ND-HI, non-dominant-hand endpoint variability decreased from 12.58 cm at Pre to 9.20 cm at Post, and dominant-hand endpoint variability decreased from 10.10 to 7.82 cm (Table 3). Joint-timing and release-speed coefficients of variation also decreased, while release angle moved toward the 51°–53° target corridor.

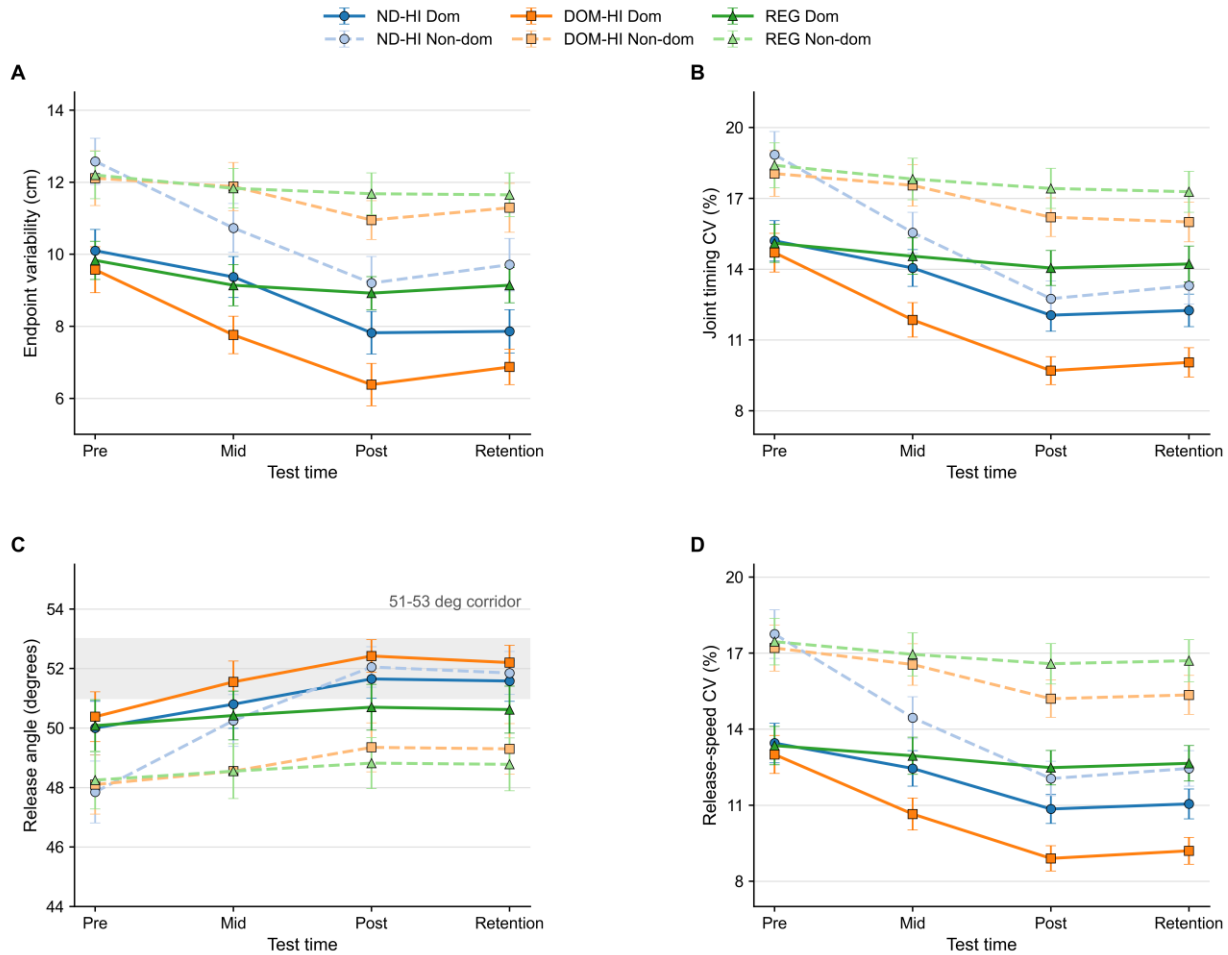


Figure 4. Kinematic stabilization and movement variability. (A) Endpoint variability; (B) joint-timing coefficient of variation (CV); (C) release angle, with the shaded band marking the 51°–53° target corridor; and (D) release-speed CV. Solid lines denote the dominant hand and dashed lines the non-dominant hand. Error bars show 95% CIs. ND-HI, non-dominant-hand high-intensity practice; DOM-HI, dominant-hand high-intensity practice; REG, regular low-exposure practice.

Table 3. Descriptive outcome summary by group, time, and hand for standard test blocks. Note. Values are mean (SD), and time points are shown chronologically as Pre, Mid, Post, and Retention. ND-HI, non-dominant-hand high-intensity practice; DOM-HI, dominant-hand high-intensity practice; REG, regular low-exposure practice.

Group	Time	Hand	Accuracy (%)	Motor-programization index	Endpoint variability (cm)	Synergy similarity
ND-HI	Pre	Dominant	34.90 (4.21)	42.64 (3.61)	10.10 (1.47)	0.601 (0.053)
ND-HI	Pre	Non-dominant	26.33 (3.71)	33.84 (2.98)	12.58 (1.61)	0.497 (0.040)
ND-HI	Mid	Dominant	41.79 (3.74)	49.65 (3.57)	9.37 (1.42)	0.675 (0.033)
ND-HI	Mid	Non-dominant	40.28 (5.20)	46.95 (4.01)	10.73 (1.69)	0.637 (0.036)

Group	Time	Hand	Accuracy (%)	Motor-programization index	Endpoint variability (cm)	Synergy similarity
ND-HI	Post	Dominant	53.05 (5.13)	61.55 (4.15)	7.82 (1.47)	0.787 (0.054)
ND-HI	Post	Non-dominant	52.32 (6.20)	58.61 (4.71)	9.20 (1.86)	0.762 (0.052)
ND-HI	Retention	Dominant	51.97 (5.47)	62.81 (3.76)	7.86 (1.51)	0.769 (0.045)
ND-HI	Retention	Non-dominant	49.98 (5.83)	58.98 (4.25)	9.71 (1.82)	0.731 (0.063)
DOM-HI	Pre	Dominant	37.20 (3.66)	43.42 (2.36)	9.57 (1.60)	0.594 (0.037)
DOM-HI	Pre	Non-dominant	28.79 (3.96)	34.70 (2.83)	12.11 (1.91)	0.510 (0.047)
DOM-HI	Mid	Dominant	52.62 (5.13)	56.55 (3.40)	7.76 (1.31)	0.746 (0.044)
DOM-HI	Mid	Non-dominant	32.73 (3.93)	40.25 (3.38)	11.88 (1.68)	0.535 (0.038)
DOM-HI	Post	Dominant	62.54 (6.22)	68.10 (4.87)	6.38 (1.47)	0.851 (0.044)
DOM-HI	Post	Non-dominant	38.14 (5.02)	46.62 (3.89)	10.95 (1.35)	0.572 (0.050)
DOM-HI	Retention	Dominant	60.13 (6.29)	67.88 (4.66)	6.87 (1.23)	0.827 (0.042)
DOM-HI	Retention	Non-dominant	36.22 (5.11)	47.93 (3.28)	11.29 (1.71)	0.576 (0.028)
REG	Pre	Dominant	35.43 (5.39)	42.72 (3.97)	9.83 (1.32)	0.597 (0.038)
REG	Pre	Non-dominant	27.27 (4.55)	34.66 (3.17)	12.20 (1.65)	0.504 (0.034)
REG	Mid	Dominant	37.47 (6.42)	44.74 (4.80)	9.14 (1.42)	0.621 (0.043)
REG	Mid	Non-dominant	29.15 (4.71)	36.85 (3.78)	11.83 (1.38)	0.523 (0.038)
REG	Post	Dominant	41.01 (6.77)	48.17 (4.57)	8.92 (1.14)	0.648 (0.046)
REG	Post	Non-dominant	30.09 (4.95)	39.34 (4.97)	11.68 (1.44)	0.545 (0.042)
REG	Retention	Dominant	39.99 (6.10)	48.02 (4.19)	9.14 (1.22)	0.645 (0.038)
REG	Retention	Non-dominant	29.63 (5.94)	39.88 (5.04)	11.65 (1.52)	0.543 (0.033)

Neuromuscular and inertial outcomes also changed across testing (Figure 5). In ND-HI, muscle-synergy similarity increased from 0.497 to 0.762 in the non-dominant hand and from 0.601 to 0.787 in the dominant hand between Pre and Post (Table 3). sEMG onset variability decreased and IMU smoothness increased in both hands, with larger changes in the trained non-dominant hand.

The BIC-based model comparison favored the full accuracy model over the reduced model without the group $\times$ time $\times$ hand term (approximate $BF_{10} = 438649046.9$). The trial-level logistic sensitivity model was directionally consistent, but its representative high-intensity interaction was not reliable ($\beta = 0.16$, $p = .468$). Bootstrap contrasts did not change the primary transfer-index conclusions.

Across participants, variability reduction predicted untrained-hand transfer ($\beta = 0.25$, $p = .035$), and motor-programization gain provided an additional positive predictor ($\beta = 0.55$, $p < .001$); the model

explained $R^2 = 0.58$ of transfer variance (Figure 5D). Motor-programization gain correlated with transfer gain, $r = 0.74$, $p < .001$. The mediation-style bootstrap estimated an indirect effect of 1.93, 95% bootstrap CI [1.01, 3.08].

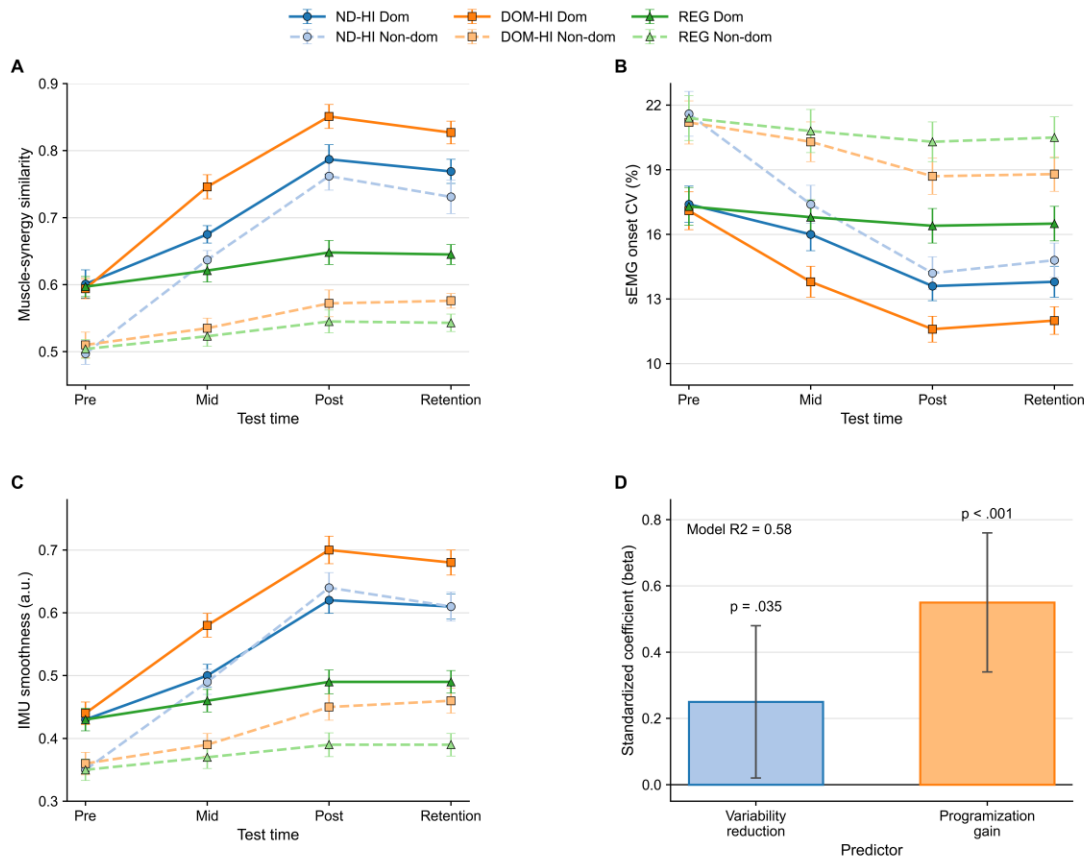


Figure 5. Neuromuscular and inertial indicators of motor programization and standardized predictors of transfer. (A) Muscle-synergy similarity; (B) surface electromyography (sEMG) onset CV; (C) inertial measurement unit (IMU) smoothness in arbitrary units (a.u.); and (D) standardized regression coefficients for variability reduction and motor-programization gain. Solid lines denote the dominant hand and dashed lines the non-dominant hand. Error bars show 95% CIs. CV, coefficient of variation; ND-HI, non-dominant-hand high-intensity practice; DOM-HI, dominant-hand high-intensity practice; REG, regular low-exposure practice.

Table 4. Primary mixed-model, pairwise, Bayesian, regression, and bootstrap results. Note. F, omnibus test statistic; t, t-test statistic; p, probability value; η_p^2 , partial eta squared; d and d_z , standardized mean differences; β , standardized regression coefficient; BF_{10} , Bayes factor favoring the full model; R^2 , explained variance; CI, confidence interval. Interaction terms are denoted by $\times$.

Analysis	Effect	Statistic	p	Effect size / estimate
Shooting accuracy	Group	$F(2, 483) = 81.99$	< .001	$\eta_p^2 = 0.253$
Shooting accuracy	Time	$F(3, 483) = 664.76$	< .001	$\eta_p^2 = 0.805$
Shooting accuracy	Hand	$F(1, 483) = 1721.25$	< .001	$\eta_p^2 = 0.781$
Shooting accuracy	Group $\times$ time	$F(6, 483) = 95.11$	< .001	$\eta_p^2 = 0.542$
Shooting accuracy	Group $\times$ hand	$F(2, 483) = 330.08$	< .001	$\eta_p^2 = 0.577$
Shooting accuracy	Time $\times$ hand	$F(3, 483) = 12.26$	< .001	$\eta_p^2 = 0.071$
Shooting accuracy	Group $\times$ time $\times$ hand	$F(6, 483) = 38.88$	< .001	$\eta_p^2 = 0.326$
Motor-programization index	Group	$F(2, 483) = 216.42$	< .001	$\eta_p^2 = 0.473$
Motor-programization index	Time	$F(3, 483) = 1306.35$	< .001	$\eta_p^2 = 0.890$
Motor-programization index	Hand	$F(1, 483) = 2300.62$	< .001	$\eta_p^2 = 0.826$
Motor-programization index	Group $\times$ time	$F(6, 483) = 149.43$	< .001	$\eta_p^2 = 0.650$
Motor-programization index	Group $\times$ hand	$F(2, 483) = 304.36$	< .001	$\eta_p^2 = 0.558$
Motor-programization index	Time $\times$ hand	$F(3, 483) = 9.31$	< .001	$\eta_p^2 = 0.055$
Motor-programization index	Group $\times$ time $\times$ hand	$F(6, 483) = 35.96$	< .001	$\eta_p^2 = 0.309$
Pairwise transfer	ND-HI dominant hand, Post vs Pre	$t(23) = 27.43$	< .001	$d_z = 5.60$
Pairwise retention	ND-HI dominant hand, Retention vs Pre	$t(23) = 23.37$	< .001	$d_z = 4.77$
Transfer index	ND-HI vs DOM-HI	$t(40.6) = 10.79$	< .001	$d = 3.12$
Transfer index	ND-HI vs REG	$t(33.2) = 10.56$	< .001	$d = 3.05$
Bayesian robustness	Full vs reduced accuracy model	$BF_{10} = 438649046.9$	—	Evidence for group $\times$ time $\times$ hand term
Regression	Motor-programization gain predicts transfer	$\beta = 0.55$	< .001	$R^2 = 0.58$
Mediation-style bootstrap	Variability reduction $\rightarrow$ programization $\rightarrow$ transfer	indirect = 1.93	—	Indirect effect = 1.93; 95% bootstrap CI [1.01, 3.08]

Discussion

High-intensity non-dominant-hand practice promoted transfer to the untrained dominant hand while strengthening the trained hand and preserving gains at Retention. The directional asymmetry, rather than the presence of learning alone, is the study's main theoretical contribution: DOM-HI received a comparable practice dose but produced weaker transfer to the non-dominant hand.

Two mechanisms may account for this pattern. Schema theory proposes that practice refines relations among initial conditions, response specifications, sensory consequences, and outcomes, allowing a generalized motor program to support related actions [12]. Cross-education accounts add that unilateral practice can engage networks available to both limbs [11]. The present data are compatible with these accounts but do not distinguish between them.

Practice with the initially less proficient limb may increase the need to explore release timing and force scaling instead of relying on an established dominant-hand habit. This demand could yield a broader representation that the dominant hand can access. The reverse direction may offer less incentive to reconstruct the action because dominant-hand practice starts from a more stable solution. This explanation remains a directional interpretation, not a direct test of learning strategy.

The multimodal measures strengthen the behavioral interpretation without establishing a neural mechanism. Accuracy gains coincided with lower endpoint and timing variability, more consistent sEMG onset, greater synergy similarity, and smoother IMU profiles. Because sEMG and IMU are surface measures, their convergence supports a stabilization account but cannot identify the neural pathway responsible for transfer.

Motor programization should not be interpreted as rigid repetition. Participants retained individual movement styles while reducing variability in release-relevant timing and endpoint control. This flexible stability is consistent with basketball research showing that elbow-wrist coordination and release parameters distinguish successful from unsuccessful shots [3], [9].

The measurement strategy is feasible for educational environments but requires quality control. Multi-camera smartphones and markerless pose estimation can capture joint motion without laboratory markers, while IMUs and sEMG add timing information. OpenPose-based estimates can nevertheless fail when body segments are occluded or mislabeled, so synchronized views, plausibility filters, release-frame checks, and trial-exclusion rules remain essential [10].

Several limitations constrain the conclusions. The sample comprised right-handed university students and does not represent left-handed learners, advanced players, rehabilitation populations, or long-term competitive performance. The four-week, low-risk training protocol also cannot establish whether the transfer persists beyond one week. Finally, the mediation-style analysis is associative; a causal test would require manipulation of practice variability or feedback.

Device-related error is another limitation. IMUs may drift, sEMG electrodes may shift during repeated arm elevation, and smartphone video may lose landmarks as clothing, ball position, or lighting changes. Such failures can create nonrandom missingness. Calibration error, synchronization error, and trial-exclusion counts should therefore be reported in future replications, together with sensitivity analyses that exclude lower-confidence pose frames.

Future studies should test left-handed and skilled samples, extend the retention interval, preregister the directional contrasts, and report device-calibration and trial-exclusion details. Experimental manipulation of feedback or practice variability would provide a stronger test of whether motor programization mediates cross-limb transfer.

Conclusion

High-intensity non-dominant-hand basketball shooting practice produced the strongest directional bilateral transfer and a coordinated pattern of improved accuracy, lower movement variability, more consistent sEMG timing, greater synergy similarity, and smoother IMU profiles. The persistence of the dominant-hand gain at Retention indicates that the effect extended beyond immediate test performance.

The findings support non-dominant-hand high-intensity practice as a promising strategy for bilateral sport-skill learning, while the proposed reusable control-policy mechanism remains an interpretation rather than direct neural evidence. Replication across handedness, skill levels, and longer retention intervals is needed before the approach is generalized to broader training settings.

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