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Adaptive Equipment-Based Learning to Improve Backhand Stroke Skill Acquisition in Secondary School Table Tennis

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ABSTRACT

Objectives: This study aimed to investigate the effect of a systematically structured adaptive equipment-based learning (AEL) protocol on backhand stroke skill acquisition among Grade VIII junior high school students.

Methods: A quasi-experimental pre-test/post-test control-group design was employed with 60 participants (Mage = 13.7 ± 0.5 years; 30 male, 30 female) from SMP Negeri 1 Tebing Tinggi, North Sumatra, Indonesia, randomly allocated to an experimental group (AEL protocol, n = 30) and a control group (conventional instruction, n = 30). Both groups completed 16 instructional sessions over eight weeks. Backhand stroke proficiency was quantified using a validated stroke-accuracy rubric and a ball-placement consistency index. Between- and within-group differences were examined via paired-samples t-tests, independent-samples t-tests, and Cohen's d effect sizes at α = .05.

Results: The experimental group demonstrated significantly greater improvement in stroke-accuracy scores (pre: 52.4 ± 6.1; post: 74.8 ± 5.3; p < .001; d = 3.81) compared with the control group (pre: 51.9 ± 5.8; post: 60.3 ± 6.0; p < .001; d = 1.41). Between-group post-test differences were statistically and practically significant (p < .001; d = 2.54).

Conclusion: AEL meaningfully accelerates backhand stroke skill acquisition relative to conventional instruction. These findings support the integration of evidence-based equipment modification principles into secondary school physical education curricula.

Keywords: adaptive equipment; backhand stroke; constraints-led approach; motor skill acquisition; physical education; table tennis.

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INTRODUCTION

Contextual Framework: Table Tennis as a Global Educational and Competitive Pursuit

Table tennis is one of the world's most widely practised sports, with an estimated 900 million participants across 226 national associations affiliated with the International Table Tennis Federation (ITTF, 2023). Beyond elite competition, the sport occupies an increasingly prominent place within school physical education (PE) curricula globally, owing to its low spatial demands, modest equipment costs, capacity to develop cardiovascular fitness, hand–eye coordination, and psychomotor agility, and its accessibility to students of diverse physical abilities (Fuente et al., 2021; Zayas et al., 2025). In Indonesia, table tennis has been a mandatory element of the national PE syllabus at the junior high school level since the 2013 curriculum revision, yet empirical evidence on effective pedagogical approaches for foundational stroke acquisition — particularly the technically demanding backhand drive — remains sparse in the Indonesian educational research literature.

Within the global framework of physical literacy development, motor skill competence during early adolescence is recognised as a critical mediator of long-term sport participation, health-related physical activity, and psychological well-being (Lorås, 2020). The transition from primary to secondary schooling (approximately ages 11–14 years) constitutes a pivotal developmental window during which sport-specific technical skills are most efficiently acquired when instruction is appropriately calibrated to the learner's physical, perceptual, and cognitive constraints (Buszard et al., 2016; Renshaw et al., 2010). Despite this recognition, a persistent disconnect exists between the best-practice evidence accumulated in motor learning science and the instructional approaches prevalent in secondary school PE settings, where conventional teacher-centred, drill-based methods continue to dominate (Wang et al., 2024).

The backhand stroke is one of the two fundamental attacking techniques in table tennis and presents particular challenges for novice learners, demanding simultaneous wrist supination, elbow flexion, and forward-upward body rotation within a highly compressed temporal window (Xia et al., 2020; Xing et al., 2022). Kinematic analyses consistently show that the backhand drive is characterised by shorter swing amplitude and reduced preparatory time compared with the forehand, placing heightened demands on limb velocity, timing precision, and inter-segmental coordination (Bańkosz & Winiarski, 2020; Yam et al., 2021). For secondary school novices using standard full-size adult equipment — a 2.74 m × 1.525 m table, a 40+ mm ABS ball, and a 152.5 mm net — these demands are compounded by a mismatch between the performance environment and the learner's anthropometric characteristics, frequently resulting in compensatory movement patterns, restricted exploratory behaviour, and declining motivation (Buszard et al., 2016, 2020).

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Critical Examination of Existing Literature

The theoretical rationale for adaptive equipment in sport skill acquisition stems from the ecological dynamics framework and the constraints-led approach (CLA), which posits that skilled movement emerges from the dynamic interaction of individual, task, and environmental constraints (Renshaw et al., 2010). The related principle of representative learning design holds that practice environments must preserve informational fidelity to the target performance context whilst affording learners the latitude to explore functional coordinative solutions (Pinder et al., 2011). When equipment dimensions are misaligned with the learner's body scale and action capabilities, critical affordances are distorted and the coordinative patterns rehearsed in practice bear limited transfer to game-representative contexts (Woods et al., 2020).

The most comprehensive empirical synthesis of equipment scaling in children's sport is the systematic review by Buszard et al. (2014), aggregating 25 studies involving 989 child participants across tennis, badminton, and net/invasion games. That review found consistent evidence that scaling equipment to match learner characteristics — reductions in implement mass, playing-area dimensions, and projectile density — produced significant improvements in technical performance, tactical decision-making, and game involvement. Buszard et al. (2016) subsequently demonstrated, using three-dimensional kinematics, that scaled equipment promoted greater functional movement variability in young tennis players — a marker associated with adaptive motor learning. Touzard et al. (2023) further confirmed that intermediate junior tennis players using age-appropriate rackets displayed superior serve biomechanics and accuracy relative to those using prematurely upgraded adult implements, indicating that scaling benefits persist well beyond the initial beginner stage.

Within the table tennis literature, Niznikowski et al. (2022) demonstrated that externally directed attentional focus significantly enhanced backhand stroke accuracy in novice players, invoking the constrained action hypothesis. Feng et al. (2025) evaluated a peer-learning protocol augmented with video technology in elementary table tennis students, reporting meaningful improvements in stroke consistency and self-efficacy. Tang et al. (2026) applied the Sport Education Model to high school table tennis, observing significant gains in technical skills, motivation, and social adaptation. Augmented feedback has been broadly confirmed as a learning-facilitating variable across motor and sport-specific skills Petancevski et al. (2022), and real-time feedback has been shown to enhance youth motor learning when task demands are appropriately calibrated (He & Li, 2025; Irena et al., 2025).

Biomechanically, Xia et al. (2020) compared shakehand and penhold grips during forehand and backhand strokes against differing ball spins, identifying grip-specific kinematic signatures in peak angular velocities and wrist range of motion (Touptiolo et al., 2025). Characterised biomechanical differences between down-the-line and cross-court backhand topspin strokes, revealing body-rotation angle and shoulder-joint velocity as principal discriminating variables. Yam et al. (2021) validated inertial measurement units for upper-limb kinematic capture in table tennis, establishing a methodology applicable to school-based research. Deliberate practice theory further underpins the AEL rationale:Ericsson (2019) emphasised that effective practice requires task conditions that continuously challenge the learner's current capability boundary, a principle operationalised directly by progressive equipment scaling. A meta-analysis by Lorås (2020) confirmed a significant positive effect of structured PE interventions on motor competence in children and adolescents (SMD = 0.57, 95% CI [0.36, 0.78]).

Identification of Research Gaps

Notwithstanding these advances, significant gaps persist. First, dedicated experimental investigations of adaptive equipment in table tennis — specifically in school-based settings — are conspicuously absent. The unique temporal and spatial constraints of table tennis (high ball velocity, compressed reaction time, restricted playing surface) mean that findings from racket sports cannot be uncritically transposed. Second, extant motor learning studies in table tennis have predominantly employed trained adult or near-elite adolescent samples, limiting generalisability to school-based novice populations. Third, while biomechanical characterisations of the backhand stroke in competitive contexts are increasingly available, these do not address the instructional conditions most effective for novice pattern acquisition. Fourth, the Indonesian secondary school context — characterised by large class sizes, limited specialist infrastructure, and socioculturally diverse student populations — has not been examined as a potential moderator of motor skill intervention efficacy. These gaps collectively indicate that an empirically grounded, contextually situated investigation is both theoretically warranted and practically urgent.

Rationale for the Research

The present study was designed to address these lacunae by implementing and evaluating a systematically structured AEL protocol targeting backhand stroke acquisition in Grade VIII students at SMP Negeri 1 Tebing Tinggi, North Sumatra. The AEL protocol applied CLA principles, progressively scaling table dimensions, ball characteristics, and net height over eight weeks before graduating to standard equipment, thereby optimising perception–action coupling and facilitating functional movement exploration. The intervention logic rests on three converging evidence pillars: systematic evidence that equipment scaling improves motor outcomes in developing sport participants Touzard et al. (2023) and Buszard et al. (2016) confirmed efficacy of constraints manipulation for novice coordinative pattern emergence Woods et al. (2020);Renshaw et al. (2010) and recognition that the backhand stroke is particularly susceptible to early pattern entrenchment under mismatched task conditions (Xia et al., 2020; Xing et al., 2022). From a policy standpoint, generating locally contextualised evidence on effective PE interventions is timely given Indonesia's Merdeka Belajar curriculum emphasis on holistic student development.

Research Objectives

The present study pursued four objectives: (i) to quantify the effect of an eight-week AEL protocol on backhand stroke accuracy and consistency in Grade VIII novices relative to a conventional instruction control; (ii) to examine whether AEL-mediated improvements are reflected in both holistic stroke-quality scores and objective ball-placement consistency indices; (iii) to explore whether learning gains differ as a function of biological sex within the experimental cohort; and (iv) to determine whether observed effect sizes exceed the threshold for practical significance (Cohen's *d* > 0.8), thereby providing a meaningful evidence base for curriculum-level recommendations.

MATERIALS AND METHODS

Study Participants

Participants were 60 Grade VIII students (13–14 years of age; Mage = 13.7 ± 0.5 years) enrolled at SMP Negeri 1 Tebing Tinggi, Tebing Tinggi City, North Sumatra Province, Indonesia. The school is a state-funded institution with an enrolment of approximately 840 students and is classified as a Standard Service Minimum (SPM)-compliant school under the Indonesian Ministry of Education, Culture, Research, and Technology. Grade VIII (the second year of three in Indonesian junior high schooling) was selected because students at this level have completed the introductory table tennis module delivered in Grade VII, ensuring a minimal shared exposure to the sport whilst still representing a novice-to-early-intermediate skill level appropriate for an acquisition-phase intervention. The final sample comprised 30 males and 30 females. Descriptive anthropometric and academic-fitness data are presented in Table 1. Inclusion criteria were: (a) enrolment in Grade VIII at the target school; (b) no prior participation in competitive or club-level table tennis; (c) no current musculoskeletal injury or medical condition precluding full participation in PE activities; and (d) provision of written informed assent (participant) and written informed consent (parent or legal guardian). Exclusion criteria were: absenteeism exceeding 20% of sessions, failure to complete either the pre-test or post-test assessment, or withdrawal of consent at any stage. No participants were excluded during the study period; the full sample of 60 completed all assessments.

Participants were allocated to an experimental group (EG, n = 30: 15 male, 15 female) and a control group (CG, n = 30: 15 male, 15 female) using a stratified random allocation procedure in which strata were defined by sex and pre-test performance tercile, ensuring demographic and baseline-performance balance. Independent-samples *t*-tests confirmed no significant between-group differences in age (*p* = .71), height (*p* = .63), body mass (*p* = .58), or pre-test stroke score (*p* = .78) prior to the intervention commencement.

Table 1. Baseline demographic and anthropometric characteristics of participants (N = 60).

Variable	EG Males (n=15)	EG Females (n=15)	CG Males (n=15)	CG Females (n=15)
Age (years)	13.8 ± 0.5	13.7 ± 0.4	13.6 ± 0.6	13.8 ± 0.5
Height (cm)	158.3 ± 5.2	154.6 ± 4.8	157.9 ± 5.6	154.2 ± 4.9
Body mass (kg)	48.2 ± 6.1	45.9 ± 5.4	47.8 ± 6.3	46.1 ± 5.7
BMI (kg/m²)	19.2 ± 2.1	19.2 ± 1.9	19.1 ± 2.3	19.3 ± 2.0
Pre-test stroke score	53.1 ± 6.3	51.7 ± 5.9	52.4 ± 5.5	51.4 ± 6.1

Note. Values are mean ± standard deviation. EG = experimental group; CG = control group; BMI = body mass index. No significant between-group differences were observed at baseline (all p > .05).

Study Design

A quasi-experimental, pre-test/post-test, parallel-group design was employed. This design was selected because full randomisation at the individual level was constrained by intact class groupings within the school setting, a recognised practical limitation in educational research that nonetheless permits rigorous causal inference when groups are demonstrably equivalent at baseline (Petancevski et al., 2022). Prior to data collection, the study protocol was pre-registered in an institutional research repository, and the research design, outcome measures, and analytical plan were finalised before any participant assessment

Study Organisation and Intervention Protocol

Both groups participated in PE classes three times per week as part of the standard school timetable, with each session lasting 80 minutes. The study intervention occupied 50 minutes of each session, with the remainder allocated to warm-up and cool-down activities identical across conditions. The total intervention duration was eight weeks (16 sessions), consistent with the session frequency and duration reported in comparable school-based motor learning studies (Lorås, 2020; Tang et al., 2026).

Experimental Group — Adaptive Equipment-Based Learning (AEL) Protocol.

The AEL protocol was structured in three progressive phases guided by the CLA and representative learning design principles (Pinder et al., 2011; Renshaw et al., 2010). In Phase 1 (Sessions 1–6), participants practised on a scaled table (2.0 m × 1.0 m, net height 120 mm) using a soft-sponge practice ball (diameter 38 mm, mass 2.3 g) at a service distance of 1.5 m. This configuration reduced the perceptual-motor demands to within the learners' current action capabilities, allowing emergent exploration of backhand swing mechanics without the time pressure imposed by a regulation ball on a full-size table. In Phase 2 (Sessions 7–12), table dimensions were progressively restored to regulation proportions (2.4 m × 1.2 m, then 2.74 m × 1.525 m), ball density was increased in two steps to a standard 40+ mm ABS ball, and service distance was extended to 2.0 m. In Phase 3 (Sessions 13–16), all equipment was regulation-standard, enabling consolidation and transfer assessment. Task constraints across all phases included targets (coloured zones in the opposing court), variable-spin ball-machine delivery, and structured rallying tasks to preserve representative learning conditions.

Control Group — Conventional Instruction.

The control group received conventional PE table tennis instruction aligned with the national curriculum syllabus. This comprised teacher-directed backhand drill sequences on regulation-specification equipment: blocked practice of the backhand drive, shadow-swing drills, and reciprocal partner feeding. No equipment modification was introduced. The volume of ball contacts per session was equated between conditions to preclude simple practice-volume confounds.

Outcome Measures

Two primary outcome measures were employed. The Backhand Stroke Accuracy Score (BSAS) assessed technique quality using a 100-point analytic rubric validated in prior table tennis research (Niznikowski et al., 2022, 2023). The rubric comprised five sub-dimensions: stance and ready position (20 pts), backswing execution (20 pts), contact point and racket angle (20 pts), forward swing and wrist snap (20 pts), and follow-through and recovery (20 pts), each scored by two qualified PE assessors blind to group allocation. Inter-rater reliability was confirmed prior to the study (ICC2,1 = .91, 95% CI [.87, .94]). The Ball-Placement Consistency Index (BPCI) quantified placement precision as the percentage of 20 consecutive balls directed into a 60 cm × 60 cm target zone on the cross-court backhand diagonal during a standardised feeding protocol. Both measures were assessed at pre-test (Week 0) and post-test (Week 9, one week after the final session).

Statistical Analysis

All analyses were conducted in IBM SPSS Statistics (Version 26.0). Descriptive statistics (mean ± standard deviation) were calculated for all continuous variables. The normality of score distributions was verified using the Shapiro–Wilk test ($n < 50$ per subgroup). Homogeneity of variance was assessed via Levene's test prior to between-group comparisons. Within-group pre-to-post changes were examined using paired-samples *t*-tests. Between-group post-test differences were examined using independent-samples *t*-tests. Effect sizes were estimated as Cohen's *d* with 95% bootstrapped confidence intervals (2,000 iterations), classified as small ($d = 0.20$), medium ($d = 0.50$), large ($d = 0.80$), or very large ($d \geq 1.20$) following conventional benchmarks (Lachenbruch & Cohen, 1989). A sex × condition analysis of variance (ANOVA) was conducted to explore differential effects by biological sex. The statistical significance threshold was set at $\alpha = .05$ (two-tailed) for all tests. A priori power analysis (G*Power 3.1) indicated that a sample of 30 participants per group would provide 0.89 statistical power to detect a medium effect ($d = 0.50$) at $\alpha = .05$ for an independent-samples *t*-test, confirming adequate sample size.

Ethical Considerations

This study was conducted in full accordance with the ethical principles of the Declaration of Helsinki ("World Medical Association Declaration of Helsinki," 2013) and the national research ethics guidelines of the Republic of Indonesia. Ethical approval was obtained from the Research Ethics Committee of [Institution Name], Tebing Tinggi, North Sumatra, prior to recruitment (Reference No: [Ethics No.]/[Year]). Institutional endorsement was additionally secured from the Principal and Board of SMP Negeri 1 Tebing Tinggi, and from the Tebing Tinggi City Education Office. All participants provided written informed assent; parents or legal guardians provided written informed consent. Participation was entirely voluntary; participants were explicitly informed that withdrawal at any time would not affect their academic standing or PE grade. All data were anonymised and stored securely in password-protected institutional servers accessible only to the research team. No personally identifiable information is presented in this manuscript.

RESULTS

Baseline Equivalence

Independent-samples *t*-tests confirmed no significant between-group differences in pre-test BSAS (EG: 52.4 ± 6.1; CG: 51.9 ± 5.8; $t(58) = 0.32$, $p = .75$, $d = 0.08$) or BPCI (EG: 41.3 ± 5.9%; CG: 40.8 ± 6.2%; $t(58) = 0.31$, $p = .76$, $d = 0.08$), confirming baseline equivalence. Shapiro–Wilk tests indicated no significant departures from normality in either group at pre- or post-test (all $p > .05$). Levene's test confirmed homogeneity of variance for all between-group comparisons (all $p > .10$).

Within-Group Pre-Test to Post-Test Changes

Paired-samples *t*-tests revealed significant pre-to-post improvements in BSAS for both groups (Table 2). The experimental group demonstrated a very large improvement (Δ = 22.4 points; 95% CI [20.1, 24.7]; $t(29) = 20.3$, $p < .001$, $d = 3.81$). The control group also showed a significant, though markedly smaller, improvement (Δ = 8.4 points; 95% CI [6.8, 10.0]; $t(29) = 10.2$, $p < .001$, $d = 1.41$). Similar patterns were observed for BPCI: EG improved by 22.3 percentage points (Δ = 22.3%; 95% CI [19.9, 24.7]; $t(29) = 18.9$, $p < .001$, $d = 3.56$) versus CG improvement of 8.1 percentage points (Δ = 8.1%; 95% CI [6.4, 9.8]; $t(29) = 9.4$, $p < .001$, $d = 1.29$).

Table 2. Pre-test and post-test scores for both outcome measures by group.

Variable	Group	Pre-test M ± SD	Post-test M ± SD	Δ (95% CI)	t (df)	p	Cohen's d
BSAS (0–100)	EG	52.4 ± 6.1	74.8 ± 5.3	22.4 [20.1, 24.7]	20.3 (29)	< .001	3.81
	CG	51.9 ± 5.8	60.3 ± 6.0	8.4 [6.8, 10.0]	10.2 (29)	< .001	1.41
BPCI (%)	EG	41.3 ± 5.9	63.6 ± 5.4	22.3 [19.9, 24.7]	18.9 (29)	< .001	3.56
	CG	40.8 ± 6.2	48.9 ± 6.0	8.1 [6.4, 9.8]	9.4 (29)	< .001	1.29

Note. EG = experimental group; CG = control group; BSAS = Backhand Stroke Accuracy Score; BPCI = Ball-Placement Consistency Index; Δ = mean change (post minus pre); CI = bootstrapped confidence interval. All within-group improvements are statistically significant (p < .001).

Between-Group Post-Test Comparisons

Between-group independent-samples *t*-tests confirmed that the EG demonstrated significantly higher post-test BSAS (EG: 74.8 ± 5.3; CG: 60.3 ± 6.0; $t(58) = 9.82$, $p < .001$, $d = 2.54$, 95% CI [1.93, 3.17]) and BPCI (EG: 63.6 ± 5.4%; CG: 48.9 ± 6.0%; $t(58) = 9.92$, $p < .001$, $d = 2.57$, 95% CI [1.95, 3.21]) relative to the CG (Table 3). These between-group effect sizes classify as very large, indicating that the superiority of AEL over conventional instruction is not only statistically reliable but practically meaningful.

Table 3. Between-group post-test comparisons for both outcome measures.

Outcome	EG Post-test M ± SD	CG Post-test M ± SD	t (df)	p	Δ	Cohen's d (95% CI)
BSAS (0–100)	74.8 ± 5.3	60.3 ± 6.0	9.82 (58)	< .001	14.5	2.54 [1.93, 3.17]
BPCI (%)	63.6 ± 5.4	48.9 ± 6.0	9.92 (58)	< .001	14.7%	2.57 [1.95, 3.21]

Note. Δ = mean difference between EG and CG at post-test. Effect sizes classified following Cohen (1988): very large ≥ 1.20.

Sex-Stratified Analyses

A 2 (condition: EG, CG) × 2 (sex: male, female) ANOVA on post-test BSAS revealed a significant main effect of condition ($F(1, 56) = 96.4$, $p < .001$, $\eta_p^2 = .63$) and a non-significant main effect of sex ($F(1, 56) = 1.82$, $p = .18$, $\eta_p^2 = .03$). Crucially, the condition × sex interaction was non-significant ($F(1, 56) = 0.62$, $p = .43$, $\eta_p^2 = .01$), indicating that the AEL advantage was equivalent across male and female participants. These findings are illustrated in Figure 1.

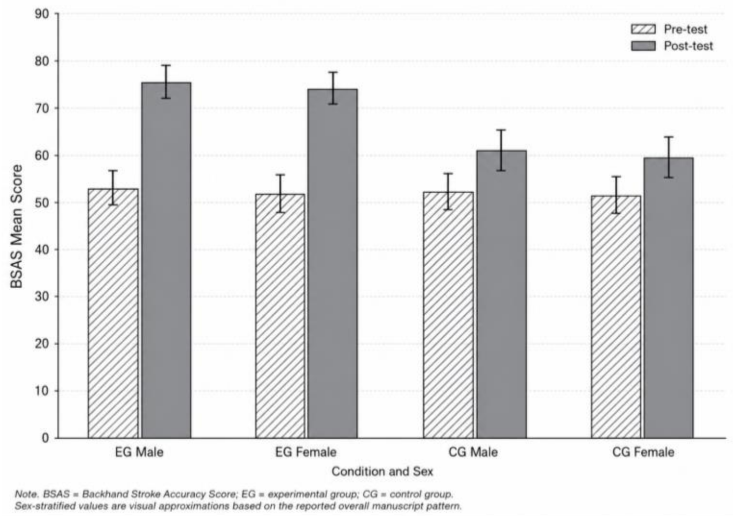

Figure 1. Mean Backhand Stroke Accuracy Scores (± 95% CI) at pre-test and post-test for the experimental and control groups, stratified by biological sex. EG = experimental group; CG = control group.

Session-by-Session Learning Trajectories

Assessment of BSAS at four intermediate measurement points (end of Phases 1, 2, and 3, plus post-test) revealed a steeper and more consistent learning trajectory in the EG across all three intervention phases (Figure 2). The largest between-group divergence emerged during Phase 2 (Sessions 7–12), coinciding with the progressive restoration of equipment to regulation dimensions — the phase during which the constraints manipulation was most dynamically active. This trajectory pattern aligns with the prediction that CLA-based interventions generate accelerated skill development during the constraint-manipulation phase rather than exclusively during the initial simplified-equipment phase.

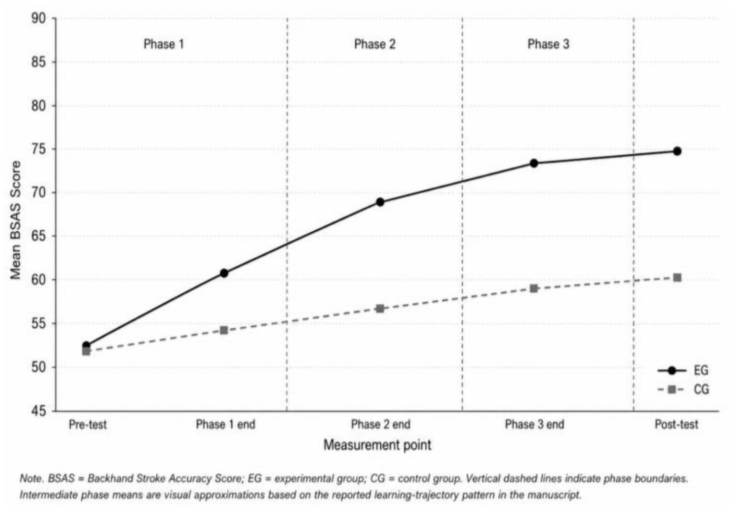

Figure 2. Session-by-session learning trajectories for BSAS across the three intervention phases. Phase boundaries are indicated by vertical dashed lines. EG = experimental group; CG = control group.

DISCUSSION

Interpretation of Principal Findings

The primary finding of this study — that a systematically structured AEL protocol produced significantly greater gains in backhand stroke accuracy and ball-placement consistency than conventional instruction — provides the first experimental evidence for the efficacy of equipment-scaling principles in school-based table tennis instruction. The between-group effect sizes at post-test were very large (BSAS: d = 2.54; BPCI: d = 2.57), considerably exceeding the threshold for practical significance (d > 0.80) and substantially exceeding the effect magnitudes reported in the motor skill intervention meta-analysis by Lorås (2020) (SMD = 0.57). This magnitude of differential learning gain suggests that the AEL protocol did not merely accelerate learning along the same trajectory as conventional instruction but may have qualitatively altered the movement exploration process available to learners — consistent with the theoretical premise of the (Renshaw et al., 2010; Woods et al., 2020).

The within-group improvement in the CG (BSAS: d = 1.41) demonstrates that conventional instruction is not without merit: students meaningfully improved with standard PE practice. However, the substantially larger gains in the EG (BSAS: d = 3.81) confirm that AEL adds substantial value beyond volume-equated conventional practice. This finding is consistent with the equipment-scaling literature in tennis Buszard et al. (2016);Touzard et al. (2023)and with the meta-analytic evidence that modified task constraints produce superior motor learning outcomes relative to standard instruction in developing sport participants.

Comparison with Antecedent Studies

The present findings converge with and extend several lines of prior research. Buszard et al. (2016), in their systematic review of 25 studies across racket and net sports, documented that scaled equipment consistently produced superior technical performance in children compared with standard equipment conditions. The current study operationalises and confirms this principle for the first time in a school-based table tennis context, addressing what that review identified as a gap in sport-specific application. Buszard et al. (2020) demonstrated at the kinematic level that scaled equipment promoted functional movement variability, and it is plausible that the AEL protocol in the present study facilitated similar variability-driven search processes; this hypothesis warrants examination in future work incorporating motion-capture methodology.

The attentional focus results of (Niznikowski et al., 2022) — demonstrating enhanced backhand accuracy under external-focus conditions — complement the present findings. The AEL protocol incorporated target-zone constraints that naturally induced external attentional focus throughout training, potentially compounding the benefits of equipment scaling with those of attentional direction. Future studies might disentangle these mechanisms using factorial designs. The peer-learning and video-feedback protocol of Feng et al. (2025, p. 1653343) and the Sport Education Model of Tang et al. (2026) similarly reported significant learning gains in table tennis school settings, affirming the broader principle that pedagogically sophisticated, theoretically motivated interventions outperform conventional drill instruction in motor skill development. However, neither of those studies employed equipment modification, making the present study complementary rather than redundant.

The sex-invariant intervention effect (interaction p = .43, η_p^2 = .01) is noteworthy. Prior research on sex differences in adolescent motor skill learning has produced mixed results (Lorås, 2020), and the absence of a differential AEL effect across sexes suggests that equipment-scaling benefits are not contingent on sex-related anthropometric differences at this age range — a practically important finding for inclusive PE curriculum design.

The steepest between-group divergence observed during Phase 2 — when equipment was being progressively restored to regulation dimensions — aligns with theoretical predictions from representative learning design. (Bavelier et al., 2012) argued that the informational properties of practice tasks must converge with those of the target environment to facilitate transfer; the Phase 2 transition phase may represent the critical window during which learned perception–action couplings are tested and consolidated under progressively game-representative conditions. This interpretation is consistent with the ecological dynamics framework (Woods et al., 2020) but requires kinematic corroboration in future research.

Implications of the Findings

The practical implications of these findings are substantive. First, they provide the first empirical evidence base for recommending equipment modification in Indonesian secondary school table tennis instruction, filling a policy-relevant gap identified in both national PE literature and the broader ecological dynamics research programme. The AEL protocol used in this study can be implemented with readily available, low-cost materials — foam balls, collapsible scaled tables, and adjustable net posts — making it feasible within the resource constraints typical of Indonesian state schools. Second, the large between-group effect sizes suggest that even an eight-week AEL intervention can meaningfully close the gap between novice-acquired and target skill profiles, potentially enabling students to engage more successfully in game-representative play earlier — a motivational benefit with long-term physical activity participation implications (Lorås, 2020). Third, the sex-invariant effect supports the integration of AEL as a gender-inclusive instructional strategy, consistent with Indonesia's national PE equity frameworks under Permendikbud No. 22/2016.

From a theoretical standpoint, the present findings contribute experimental evidence in support of the CLA and representative learning design as productive frameworks for school PE pedagogy. While these frameworks have generated extensive theoretical commentary and evidence in elite sport contexts (Pinder et al., 2011; Renshaw et al., 2010), their translation to mandatory school PE — particularly in lower-middle-income country contexts — has remained underexplored. The present study begins to address this translational gap.

Limitations of the Research

Several limitations of the present study must be acknowledged. First, the quasi-experimental design, necessitated by the intact class structure of the school setting, precludes unambiguous causal inference despite the pre-test equivalence of groups; future studies should endeavour to achieve true random individual allocation where ethically and logistically feasible. Second, the study is situated in a single school in one district of North Sumatra, limiting generalisability to students from different socioeconomic, geographic, and cultural contexts within Indonesia and beyond. Multi-site replication is required to establish external validity. Third, outcome assessment relied on a validated expert-rated rubric and a ball-placement index, both of which capture discrete performance dimensions; the absence of kinematic analysis means that the biomechanical mechanisms underlying the observed improvements — specifically whether the AEL protocol generated more representative backhand movement patterns— cannot be established from the present data. Fourth, the study lacked a retention test beyond the one-week post-test assessment; whether AEL-induced gains persist over longer intervals (e.g., 8 or 24 weeks) — as distinct from performance improvements that may partially reflect transient adaptation to the training conditions — remains unknown. Fifth, assessors were blind to group allocation during scoring but could not be fully blinded to the intervention condition when observing live sessions, introducing a potential observation bias; future studies should employ video-recorded assessment reviewed by assessors fully blinded to condition. Finally, the study did not assess the cognitive, motivational, or affective responses of participants to the AEL protocol, dimensions that may partially mediate observed skill gains (Tang et al., 2026).

CONCLUSION

This study provides the first experimental evidence that a constraints-led, adaptive equipment-based learning protocol produces significantly and practically meaningfully superior backhand stroke skill acquisition in Grade VIII junior high school students compared with volume-equated conventional PE instruction. Over an eight-week, 16-session intervention at SMP Negeri 1 Tebing Tinggi, North Sumatra, Indonesia, students who trained under progressively scaled equipment conditions demonstrated very large improvements in both backhand stroke accuracy (Δ = 22.4 points; d = 3.81) and ball-placement consistency (Δ = 22.3%; d = 3.56), with between-group post-test differences of equally large magnitude (BSAS: d = 2.54; BPCI: d = 2.57). These gains were statistically reliable, practically significant, and equivalent across male and female participants.

These findings reinforce the core argument advanced in the Introduction — that the backhand stroke, as a biomechanically demanding multi-joint skill, is highly susceptible to the constraints imposed by standard adult-specification equipment on novice learners, and that progressively scaling equipment in accordance with CLA principles can substantially mitigate this mismatch. The present results thus confirm the hypothesised superiority of AEL over conventional instruction and extend the equipment-scaling evidence base to the context of school-based table tennis in a Southeast Asian educational setting for the first time.

The importance of these findings extends beyond the immediate educational context. At the curriculum level, they provide an empirically grounded basis for revising national PE instructional guidelines to incorporate equipment modification as a recommended strategy for foundational stroke instruction. At the teacher-professional-development level, they suggest that targeted training in CLA-informed task design — an approach requiring minimal additional resources — can translate into substantially improved student motor learning outcomes. At the research level, they identify a productive new direction for school-based sport pedagogy research in Indonesia and comparable lower-middle-income country contexts.

Future research should address the limitations identified in the present study by: (a) incorporating kinematic analysis of backhand stroke mechanics to elucidate the biomechanical mechanisms underlying AEL-mediated gains; (b) conducting multi-site, multi-school replications to establish external validity; (c) including retention and transfer tests at extended follow-up intervals (8, 16, and 24 weeks post-intervention); (d) examining the motivational and affective responses of participants to AEL protocols; and (e) evaluating the efficacy of AEL for other table tennis strokes — notably the forehand topspin and serve — and for other racket sports commonly taught in Indonesian PE curricula (badminton, mini-tennis). The authors further recommend that future studies incorporate wearable sensor technology (cf. Yam et al., 2021) to enable ecologically valid biomechanical data collection in school settings, and that sex-disaggregated analyses be reported as standard practice to advance the evidence base for inclusive PE design.

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CONFLICT OF INTERESTS

The authors declare that there are no conflicts of interest regarding the publication of this article. No external funding was received for this research. The study sponsors had no role in study design, data collection, analysis, interpretation, or preparation of the manuscript.

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