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ORIGINAL RESEARCH

Effects of different exercise rehabilitation programs on shoulder joint function recovery in male racket sport club members

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Abstract

Background: Shoulder dysfunction is prevalent among recreational racket-sport participants due to high mechanical demands and insufficient proximal control. Contemporary rehabilitation emphasizes kinetic-chain coordination and dynamical-systems principles, suggesting recovery reflects reorganization of neuromuscular synergies, rather than isolated joint correction. However, evidence on sequencing effects in coordination-based rehabilitation remains limited. This study compared two exercise sequences: pelvic–lumbar coordination followed by shoulder stabilization (LS) versus the reverse order (SL). **Methods**: Thirty-two adult male participants with shoulder discomfort were randomly assigned to LS (n = 16) or SL (n = 16). Each group completed two 20-minute programs in opposite orders, with assessments at pre-test, post-test 1, and post-test 2. Shoulder abduction tasks (discrete and continuous) were recorded at 240 fps and analyzed using MediaPipe Pose. Joint-angle data were processed in Python and MATLAB. Principal component analysis defined dynamical degrees of freedom (DDOF), and biomechanical degrees of freedom (BDOF). Range of motion (ROM) was analyzed using two-way Analysis of Variance (ANOVA), and DDOF/BDOF using nonparametric tests ($\alpha = 0.05$). **Results**: In discrete tasks, the LS group showed greater dominant shoulder ROM and higher DDOF at both post-tests compared with SL ($p < 0.05$), with no group differences in BDOF. In continuous tasks, LS demonstrated progressive increases in ROM across sessions (pre-test < post-test 1 < post-test 2), outperforming SL, while both groups showed time-related increases in BDOF. **Conclusions**: Prioritizing pelvic–lumbar coordination before shoulder stabilization led to superior improvements in shoulder function. Effects were task-specific: discrete tasks enhanced DDOF, whereas continuous tasks promoted earlier BDOF expansion. These findings support coordination reorganization as a key mechanism in rehabilitation. **Clinical Trial Registration**: ISRCTN15911792 (retrospectively registered, 30 March 2026).

Keywords

Shoulder joint; Exercise rehabilitation; Racket sport; Core stabilization and adjustment training (CSAT)

1. Introduction

Human beings possess an intrinsic drive toward well-being, within which health serves as an essential component. The World Health Organization conceptualizes health as the holistic integration of physical, social, and mental well-being. In pursuit of holistic health, modern individuals increasingly engage in lifelong sports, reflecting a lifespan developmental approach to physical activity and well-being. Racket sports—such as tennis and badminton—offer multifaceted benefits that extend beyond physical health. They facilitate motor development, social interaction, and psychological well-being, owing to their inherently interactive nature. Yet, these activities impose considerable demands on the shoulder joint due to the reliance on rapid, high-force forehand and overhead motions. This load often culminates in shoulder injuries, especially among recreational players who may lack sufficient strength-conditioning, leading to repetitive overload on proximal shoulder structures [1].

In rehabilitation science, kinetic chain theory posits that the body functions as a coordinated sequence of linked segments, rather than isolated parts. Optimal shoulder mechanics depend not only on local joint integrity, but also on coordination across core, pelvic, scapular, and lower limb structures. Indeed, rehabilitation incorporating kinetic chain principles—such as closed kinetic chain exercises, core stabilization, and movement pattern integration—has been shown to restore both function and neuromuscular control more effectively than isolated joint interventions [2–4]. Beyond improving local strength and stability, such approaches promote coordinated intersegmental interactions that allow the motor system to flexibly redistribute mechanical loads, suggesting that functional recovery involves reorganization of movement coordination, rather than isolated joint correction [4, 5]. From a motor learning perspective, rehabilitation can be viewed as a process of acquiring and refining coordinated movement patterns through practice and task-specific feedback, rather than merely restoring isolated joint capacity, as various motor learning strategies have demonstrated functional impacts in rehabilitation contexts [6].

Moreover, from a dynamical systems theory perspective, human movement emerges through self-organization across multiple neuromusculoskeletal subsystems. Recent theoretical work has advanced the muscle synergy concept by proposing an information- and network-theoretic framework that characterizes task-relevant, redundant, and complementary intermuscular couplings, emphasizing functional interactions beyond mere modularity [7]. Additionally, prior research has shown that during transitions between dynamical regimes, such as those observed in Fitts' task, muscle coordination patterns reorganize in parallel with behavioral changes, suggesting that synergies emerge as functional structures that support adaptable and stable motor behavior [8]. In this context, examining shoulder movement in terms of dynamical degrees of freedom (DDOF; *i.e.*, number of coordination groups) and biomechanical degrees of freedom (BDOF; *i.e.*, variety of joint motions involved) allows for a nuanced assessment of functional rehabilitation [9]. From this perspective, rehabilitation approaches that incorporate muscle synergy organization may better support adaptive motor recovery than protocols focused solely on isolated joint function. Moreover, evaluating rehabilitation outcomes through synergy-based coordination metrics and degrees of freedom may capture functional changes that are not detectable using conventional kinematic measures alone. Within a dynamical systems framework, such functional recovery is understood to emerge from changes in coordination organization. Accordingly, changes in motor behavior can be described at two complementary levels: DDOF, reflecting the number of coordination groups actively organized during movement, and BDOF, representing the diversity of joint motions contributing to task execution [10].

Therefore, the present study aims to develop and evaluate a novel rehabilitation program for adult male recreational racket-sport participants experiencing shoulder discomfort. The study (1) identified primary muscle synergies (coordination groups) and their constituent joint motions during shoulder movement, (2) designed a rehabilitation protocol emphasizing pelvic–lumbar to trunk–shoulder coordination, and (3) compared its efficacy when sequenced either before (pelvic–lumbar coordination followed by shoulder stabilization; LS) or after (shoulder stabilization followed by pelvic–lumbar coordination; SL) conventional shoulder stabilization. The outcomes of this study were evaluated across three primary domains. First, shoulder range of motion (ROM) was assessed to capture flexibility and mobility differences between groups. Second, DDOF was quantified as the number of extracted coordination groups identified through principal component analysis (PCA), providing an index of neuromotor coordination. Third, BDOF was examined by determining the total number of unique joint motions observed across all synergies, thereby reflecting the extent of multijoint involvement. All outcome measures were assessed under both discrete and continuous movement conditions to capture the full spectrum of motor behaviors inherent in racket sports. Specifically, discrete movements—such as those observed during a serve—entail a clear beginning and end and rely on event-timing mechanisms. In contrast, continuous movements—such as those seen during sustained rally play—lack discrete endpoints and are controlled via emergent timing processes [11]. By distinguishing between these two movement modalities, the study aims to ensure ecological validity, reflecting the dual nature of racket sport performance—alternating between isolated, high-impact actions (*e.g.*, serve or smash) and fluid, cyclic patterns of play (*e.g.*, returning rallies). Furthermore, shoulder abduction and adduction in the frontal plane are included as dependent variables because they are integral to both the generation of stroke power and the preservation of shoulder joint integrity. During overhead strokes, including serves and smashes, the glenohumeral joint frequently attains abduction angles approaching 90 degrees in the cocking phase, facilitating forceful internal rotation while mitigating impingement risks associated with excessive elevation [12, 13]. Therefore, measuring frontal-plane shoulder motion provides key insights into movement mechanics and potential injury mechanisms in racket sport contexts. While real-world racket-sport skills are executed in dynamic, multiplanar environments, isolating frontal-plane shoulder motion allows for a controlled assessment of a biomechanically essential component, thereby preserving ecological validity at the level of fundamental joint function [14].

We hypothesized that the LS group would exhibit significantly greater shoulder ROM compared with the SL group. We further hypothesized that the LS group would show a significantly higher number of coordination groups, indicating increased DDOF (*i.e.*, the number of extracted coordination groups identified via PCA). Finally, we hypothesized that the LS group would demonstrate significantly greater BDOF (*i.e.*, the total number of unique joint motions observed across all synergies), reflecting more diverse joint motion involvement.

2. Materials and methods

2.1 Participants

The required sample size was determined through an a priori power analysis using G*Power 3.1 software (University of Düsseldorf, Düsseldorf, NRW, Germany). Based on an assumed effect size of $f^2 = 0.30$, an alpha level of 0.05, and a statistical power of 0.80, the minimum sample size was calculated to be 24 participants. To account for potential dropout and to ensure sufficient power for both parametric and nonparametric analyses, 32 adult male participants were ultimately recruited for the study. Participants were recruited through online public announcements posted on social media platforms, including Instagram and blogs, specifically targeting young adult males. Individuals who expressed interest were subsequently screened according to the study's inclusion and exclusion criteria. Eligible participants were those who had received medical clearance to engage in shoulder rehabilitation exercises following the onset of shoulder pain, whereas individuals with neurological disorders or biomechanical alterations resulting from pathological conditions were excluded from enrollment. In addition, inclusion criteria specified that participants must have reported persistent shoulder discomfort lasting at least three months prior to study participation. Participants were recruited on a rolling basis from 01 March to 31 July 2025, during which the entire data collection and study procedures were completed. After screening, participants were randomly assigned to one of two rehabilitation groups, each consisting of 16 individuals. The LS group performed a coordination-focused lower–limb and trunk rehabilitation program centered on pelvic control prior to conventional shoulder stabilization. The SL group followed the opposite sequence, performing conventional shoulder stabilization before pelvic–lumbar coordination. Prior to participation, all subjects were fully informed of the study's purpose, procedures, and potential risks. Written informed consent was obtained from all participants in accordance with the Declaration of Helsinki. The study protocol was reviewed and approved by the Institutional Review Board (IRB) of Jeonbuk National University (approval no. 2025-02-021-001), ensuring compliance with established ethical research standards.

2.2 Procedure

In accordance with the study purpose, the experimental procedure consisted of pre-test, post-test 1, and post-test 2 assessments designed to evaluate whole-body coordination during discrete shoulder abduction and continuous shoulder abduction tasks performed for ten repetitions. Between the pre-test and post-test 1, and between post-test 1 and post-test 2, two types of Exercise Rehabilitation Programs were implemented in counterbalanced order across groups. In the SL group, a shoulder-focused rehabilitation program was administered between the pre-test and post-test 1, followed by a lumbar-focused rehabilitation program between post-test 1 and post-test 2. In the LS group, the order of these programs was reversed. The shoulder-focused rehabilitation program, commonly referred to as a shoulder stabilization exercise program, was designed to enhance local stability and neuromuscular control around the glenohumeral joint. The program consisted of four types of exercises, as illustrated in Fig. 1.

(1) Internal and external rotation of the humerus in the adducted position

Participants began in the supine anatomical position, lying face upward with the elbow flexed at 90° and the hand lightly clenched into a fist. From this starting position, they were instructed to maximally externally rotate the humerus, followed by maximal internal rotation, while maintaining the elbow and shoulder in a stable adducted position throughout the motion. The movement was performed slowly and under control to emphasize shoulder joint stability, rather than speed. This is illustrated in Fig. 1A.

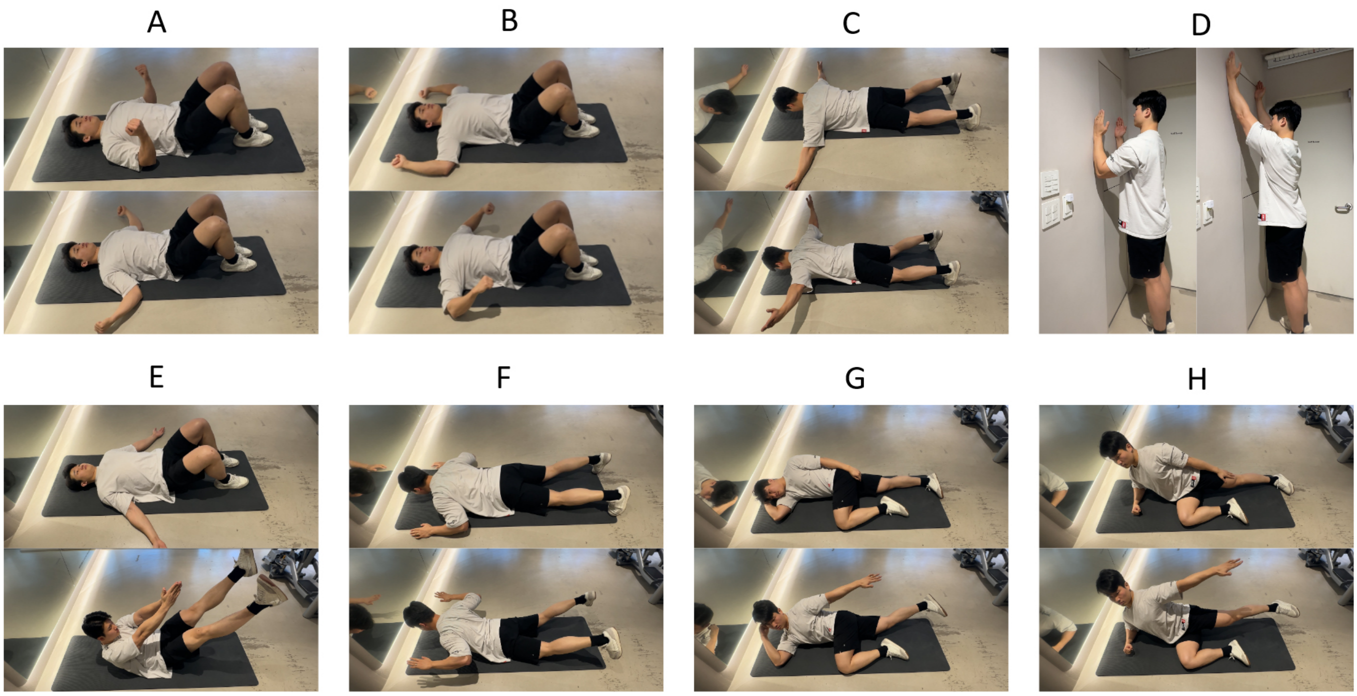

FIGURE 1. Illustration of the eight exercise movements included in the shoulder- and lumbar-focused rehabilitation program. (A) Internal and external rotation of the humerus in the adducted position. (B) internal and external rotation of the humerus in the 90° abducted position. (C) Wall slides. (D) T-raises. (E) simultaneous elevation of the upper and lower limbs in the supine position. (F) simultaneous elevation of the upper and lower limbs in the prone position. (G) simultaneous elevation of the upper and lower limbs in the side-lying position with activation of the hip adductor muscles. (H) simultaneous elevation of the upper and lower limbs in the side-lying position with activation of the hip abductor muscles.

(2) Internal and external rotation of the humerus in the 90° abducted position

Participants began in the supine position with the shoulder abducted to 90° and the elbow flexed at 90°, maintaining a neutral wrist posture with the hand lightly clenched into a fist. From this position, participants were instructed to maximally externally rotate and then maximally internally rotate the humerus, ensuring that the shoulder remained in the abducted plane throughout the motion. The movement was performed in a slow and controlled manner to promote shoulder stability and proper muscle activation. This is illustrated in Fig. 1B.

(3) Wall slides

Participants began by standing facing a wall, with the elbows flexed and the forearms placed flat against the wall. The scapulae were protracted to maintain a flat back posture and avoid excessive thoracic extension. From this position, participants were instructed to slide their forearms upward along the wall as high as possible, maintaining contact between the forearms and the wall throughout the motion. After reaching the maximal elevation, they slowly returned their forearms to the starting position while preserving scapular control. The exercise emphasized controlled scapular upward rotation and shoulder flexion to enhance shoulder stability. This is illustrated in Fig. 1C.

(4) T-raises

Participants laid prone on the floor with both arms abducted to 90° and elbows fully extended, forming a “T” shape with the body. From this position, they were instructed to lift both arms off the ground by actively extending the thoracic spine and retracting the scapulae, while keeping the elbows extended and maintaining a neutral neck alignment. The movement was performed slowly and under controlled conditions to emphasize scapular upward rotation, posterior shoulder activation, and thoracic extension control. After reaching the maximal elevation, participants gradually returned their arms to the starting position. This is illustrated in Fig. 1D.

Each exercise involved eight repetitions, taking approximately one minute to complete, and the four exercises together constituted one block. The entire program consisted of five blocks, resulting in a 20-minute rehabilitation session. All exercises were demonstrated and supervised by a certified trainer to ensure proper form and muscle engagement.

The lumbar-focused rehabilitation program consisted of the Core Stabilization Adjustment Training (CSAT) technique, which is designed to enhance lumbar stability by promoting coordinated activation of the deep trunk muscles and synchronized movement of the upper and lower limbs around the lumbar spine. The program consisted of four types of exercises, as illustrated in Fig. 1.

(5) Simultaneous elevation of the upper and lower limbs in the supine position

Participants began in the supine position with the knees flexed at 90° and the feet flat on the floor. From this starting position, they extended both arms forward with the hands together and lifted the upper trunk off the floor to maintain a stable position. While keeping the trunk elevated, participants extended the knees to raise the lower limbs off the ground, maintaining control throughout the motion. After reaching maximal extension, they flexed the knees again and lowered the upper body to return to the starting position. This movement emphasized simultaneous activation of the abdominal and hip flexor muscles for trunk and core stabilization. This is illustrated in Fig. 1E.

(6) Simultaneous elevation of the upper and lower limbs in the prone position

Participants began in the prone position, lying face down with the elbows flexed and the hands placed beside the shoulders, while keeping the knees fully extended and relaxed. From this position, participants were instructed to raise the lower limbs as high as possible while maintaining knee extension, followed by lifting the upper trunk off the floor to achieve maximal elevation of both upper and lower limbs simultaneously. After holding the peak position briefly, participants returned slowly to the starting position. This movement aimed to activate the lumbar extensors, gluteal muscles, and posterior chain, enhancing coordinated back and hip extension control. This is illustrated in Fig. 1F.

(7) Simultaneous elevation of the upper and lower limbs in the side-lying position with activation of the hip adductor muscles

Participants began in a side-lying position, with the upper hip flexed and stabilized near the torso and the upper arm resting lightly along the body. The lower limb, positioned closer to the floor, remained extended and relaxed at the start, while the upper hand supported the head in a comfortable alignment. From this position, participants were instructed to lift the lower leg upward toward the ceiling as high as possible, followed by reaching the upper arm toward the foot to raise the trunk slightly off the floor. They were then asked to extend the hand and foot in opposite directions (anteriorly and posteriorly) to maximize adductor engagement, and subsequently return slowly to the starting position. This exercise was designed to activate the hip adductor and contralateral oblique muscles, promoting coordinated control of lateral core and lower limb stabilization. This is illustrated in Fig. 1G.

(8) Simultaneous elevation of the upper and lower limbs in the side-lying position with activation of the hip abductor muscles

Participants began in a side-lying position, with the lower hip flexed and stabilized near the torso and the upper hand placed on the floor for support, maintaining a posture similar to the upper trunk position of a side plank. From this position, participants were instructed to raise the upper leg toward the ceiling as high as possible, followed by reaching the upper arm toward the foot to lift the trunk slightly off the floor. They were then asked to extend the hand and foot in opposite directions (anteriorly and posteriorly) to maximize hip abductor activation, and to cross the hand and foot alternately to increase movement amplitude. After completing the motion, participants returned slowly to the starting position. This exercise was designed to strengthen the gluteus medius and lateral core stabilizers, promoting coordination between the upper and lower limbs during lateral trunk movement. This is illustrated in Fig. 1H.

Each exercise type was repeated across five blocks, with eight consecutive repetitions per block, lasting approximately one minute per block. Consequently, a total of five blocks comprising the four exercise types constituted the 20-minute rehabilitation program. All participants commenced the first Exercise Rehabilitation Program 5 minutes after completing the pre-test. Post-test 1 was conducted 5 minutes after completing the first program. The second Exercise Rehabilitation Program was carried out 24 hours after post-test 1, and post-test 2 was administered 5 minutes after completing the second program. The assessments of both discrete and continuous movements were conducted at three time points: immediately before the Exercise Rehabilitation Program (pre-test), immediately after the first session of the program (post-test 1), and immediately after the second session of the program (post-test 2). At each time point, the measurements were performed in the same manner as described below. The timing of these assessments was deliberately standardized across sessions to ensure that comparisons between post-test 1 and post-test 2 reflected training-order effects under comparable acute physiological conditions.

For the discrete movement condition, we employed an assessment of shoulder abduction range of motion. Participants, while standing in the anatomical position, were instructed to fully extend their arms, face forward, and abduct both shoulders as high as possible. At the point of maximal abduction, participants were instructed to maintain the position while listening to two metronome beats set at 60 bpm, thereby ensuring a 2-second stationary phase, before lowering their arms and returning to the anatomical posture. This procedure was demonstrated and supervised by a certified trainer on the research team, and after one practice trial, each participant performed three actual trials for data collection. For the continuous movement condition, we employed an assessment of shoulder abduction coordination. Participants, while standing in the anatomical position with arms fully extended and facing forward, were instructed to perform cyclic shoulder abduction–adduction movements in synchrony with a metronome. One full cycle, consisting of abduction and adduction, was performed over 4 seconds, with 2 seconds allotted for maximal abduction and 2 seconds for returning to the anatomical position. Participants were pre-instructed to move smoothly without any pause at the transition points to ensure continuous movement. A metronome set at 60 bpm (1 Hz) provided auditory pacing throughout the task. This approach is consistent with previous studies employing rhythmic auditory pacing to standardize movement timing and examine neuromuscular and coordination responses during upper-limb tasks [15–17]. The same certified trainer demonstrated and supervised the procedure to ensure consistency and proper execution, and each participant performed four cycles including one practice trial.

2.3 Apparatus

Video-based motion analysis was conducted during the pre-test, post-test 1, and post-test 2 sessions. All recordings were captured using the rear camera of a Samsung Galaxy S9 smartphone (Samsung Electronics, Suwon-si, Korea) equipped with a slow-motion function operating at 240 frames per second (fps). In a preliminary pilot validation conducted by the authors, joint angles estimated using MediaPipe Pose under the same recording setup showed very high agreement with those obtained from an infrared marker-based motion capture system (Qualisys AB, Gothenburg, Sweden), with correlation coefficients exceeding $r = 0.98$ across whole-body joint angles during controlled movements. The camera was mounted on a tripod adjusted to the participant's hip height and positioned 3 meters directly in front of the participant, providing a frontal view during each recording. This setup ensured consistent perspective and measurement reliability across sessions. The recorded videos were analyzed using the Pose Landmark Detection module of MediaPipe Studio developed by Google. This system identifies 33 anatomical landmarks across the entire body and provides three-dimensional spatial coordinates (x, y, z) for each landmark over time. Using these coordinate data, a custom Python 3.10 (Python Software Foundation, Wilmington, DE, USA) script was implemented to compute joint angle trajectories for the upper and lower limbs. This allowed for quantitative analysis of shoulder joint kinematics and the evaluation of recovery patterns following the exercise rehabilitation interventions.

2.4 Data analysis

All kinematic data were processed and analyzed using Python 3.10 (Python Software Foundation, USA), Visual Studio 2022 (Microsoft Corp., Redmond, WA, USA), and MATLAB R2023b (MathWorks Inc., Natick, MA, USA). The shoulder joint function recovery was evaluated using three dependent variables: (1) ROM during shoulder abduction–adduction on both sides, (2) DDOF, and (3) BDOF. Video recordings obtained from the Galaxy S9 rear camera (240 fps, slow-motion mode) were processed using MediaPipe Pose Landmarker (Google, USA) to extract three-dimensional coordinates of 33 body landmarks. From these coordinates, time-series data of 28 joint angles were calculated using a custom Python script. Each motion trial was resampled to 400 data points through linear interpolation to normalize the temporal dimension across participants and trials. A fourth-order low-pass Butterworth filter (cutoff = 10 Hz) was applied to remove high-frequency noise, based on the result of a power spectral density analysis confirming that 99% of the signal power was below 10 Hz. The processed joint angle data were then subjected to PCA to identify the dominant coordination patterns among the multi-joint movements [18]. PCA with varimax rotation was applied to the joint-angle dataset to enhance the interpretability of coordination patterns, following previous methodological recommendations in motor coordination research [19, 20]. The DDOF was defined as the number of principal components (PCs) required to explain 90% of the cumulative variance, representing the number of coordination groups contributing to shoulder movement control.

The BDOF was determined as the total number of unique joint motions contributing to all PCs that formed the coordination synergies, thereby representing the biomechanical diversity of joint involvement across movement patterns. Specifically, within each PC identified as part of the DDOF, the three joint angles with the highest loading values were selected to represent the most influential contributors to that coordination pattern [21]. When a joint appeared repeatedly across multiple

PCs, it was counted only once to avoid redundancy in the estimation of biomechanical diversity. The BDOF was, thus, calculated as the sum of these non-overlapping joint angles across all significant PCs. Consequently, a higher BDOF indicates broader and more diversified joint participation across synergies, whereas a lower BDOF reflects more limited or overlapping joint involvement due to reduced or redundant PCs. Both DDOF and BDOF were analyzed separately for discrete shoulder movements and continuous shoulder movements, to reflect the distinction between isolated and sequential actions typical of racket sport performance.

2.5 Statistical analysis

Shoulder ROM was analyzed separately for the dominant and non-dominant arms, determined by the Waterloo Handedness Questionnaire and the racket hand, respectively. A two-way repeated-measures ANOVA, with group as the between-subjects factor and test session as the within-subjects factor, was conducted, and the assumption of normality was verified by inspection of the Quantile–Quantile plots. When significant main or interaction effects were found, *post-hoc* multiple comparisons were performed using Tukey's Honestly Significant Difference (HSD) test to adjust for Type I error inflation. For the whole-body degrees of freedom (DDOF and BDOF), the normality assumption was not satisfied due to the nature of the measurements. Therefore, non-parametric analyses were performed. Between-group comparisons were conducted using the Mann-Whitney U test, while within-subject comparisons across time points were analyzed using the Friedman test. When significant differences were observed, *post-hoc* pairwise comparisons were performed using the Wilcoxon signed-rank test with Bonferroni correction. The significance level was set at α = 0.05.

3. Results

The mean age of participants in the LS group was 38.8 $\pm$ 3.1 years, and in the SL group 37.5 $\pm$ 3.7 years. Additionally, the mean duration of racket-sport participation was 53.1 $\pm$ 10.4 months in the LS group and 51.4 $\pm$ 9.2 months in the SL group. At the pre-test, there were no significant differences between the LS and SL groups in any of the measured variables. Group comparisons also revealed no significant differences in age ($p > 0.05$) or racket-sport experience ($p > 0.05$), indicating that the two groups were demographically comparable prior to the intervention. Specifically, during the discrete movement task, no group differences were found in dominant shoulder ROM (p = 0.904), non-dominant shoulder ROM (p = 0.880), DDOF (p = 1.000), or BDOF (p = 0.813). Similarly, during the continuous movement task, no significant differences were observed between groups in dominant shoulder ROM (p = 0.776), non-dominant shoulder ROM (p = 0.949), DDOF (p = 0.585), or BDOF (p = 0.832). These results indicate that both groups had comparable baseline levels across all dependent variables prior to the intervention.

3.1 Discrete movement

3.1.1 Shoulder ROM

As shown in Fig. 2a, there were significant differences between groups in the dominant shoulder ROM ($F(1, 30) = 4.4678$, p = 0.043, $\eta^2 = 0.1296$), and a significant difference was observed among test sessions in the dominant shoulder ROM ($F(2, 60) = 7.0301$, p = 0.002, $\eta^2 = 0.1898$). However, the interaction effect between group and test session was not significant ($F(2, 60) = 1.6081$, p = 0.211, $\eta^2 = 0.0509$). As a result of the *post-hoc* analysis, the dominant shoulder ROM was found to be significantly higher for LS compared with SL (p = 0.043, 95% Confidence Interval (CI) (0.09, 5.49)), and significantly higher for post-test 2 compared with pre-test ($p < 0.001$, 95% CI (2.75, 9.92)).

As shown in Fig. 2b, there were no significant differences between groups in the non-dominant shoulder ROM ($F(1, 30) = 0.004$, p = 0.950, $\eta^2 = 0.0001$), and no significant differences were observed among test sessions ($F(2, 60) = 2.648$, p = 0.079, $\eta^2 = 0.0811$). In addition, the interaction effect between group and test session was not significant ($F(2, 60) = 0.189$, p = 0.828, $\eta^2 = 0.0063$).

3.1.2 DDOF

As shown in Fig. 2c, there were no significant differences in the DDOF at the pre-test between groups (U = 128.0, p = 1.000, Cliff's δ = 0.000, 95% CI (−0.354, 0.352)). At post-test 1, the LS performed significantly higher DDOF than the SL, with a small-to-moderate effect size (U = 177.5, p = 0.043, Cliff's δ = 0.387, 95% CI (0.043, 0.691)). At post-test 2, this difference became more pronounced, with a moderate effect size (U = 188.0, p = 0.014, Cliff's δ = 0.469, 95% CI (0.141, 0.750)).

For the LS, the Friedman test indicated a significant effect of time, $\chi^2(2) = 8.91$, p = 0.012, with a moderate effect size (Kendall's W = 0.278, 95% CI (0.102, 0.568)). *Post-hoc* Wilcoxon signed-rank tests revealed that performance at post-test 1 was significantly higher than at the pre-test ($Z = -2.53$, p = 0.011, r = 0.956, 95% CI (0.919, 1.000), median difference = 0.000). Similarly, performance at post-test 2 was significantly greater than at the pre-test ($Z = -2.31$, p = 0.021, r = 0.770, 95% CI (0.385, 1.000), median difference = 0.500). No significant difference was observed between post-test 1 and post-test 2 ($Z = -0.333$, p = 0.739, r = 0.136, 95% CI (0.000, 1.000), median difference = 0.000). In contrast, the Friedman test for the SL was not significant, $\chi^2(2) = 0.053$, p = 0.974, W = 0.002 (95% CI (0.002, 0.225)); therefore, no *post-hoc* comparisons were conducted.

3.1.3 BDOF

As shown in Fig. 2d, there were no significant differences in BDOF between the groups at any of the test sessions. Consistently, no group differences were observed at the pre-test (U = 134.0, p = 0.813, Cliff's δ = 0.047, 95% CI (−0.320, 0.395)), at post-test 1 (U = 136.0, p = 0.751, Cliff's δ = 0.063, 95% CI (−0.312, 0.414)), or at post-test 2 (U = 146.0, p = 0.456, Cliff's δ = 0.141, 95% CI (−0.215, 0.496)).

For the LS group, the Friedman test did not reveal a significant effect of time, $\chi^2(2) = 0.412$, p = 0.814, Kendall's W = 0.013 (95% CI (0.002, 0.278)); therefore, no *post-hoc* analyses were conducted. Similarly, for the SL group, the Friedman

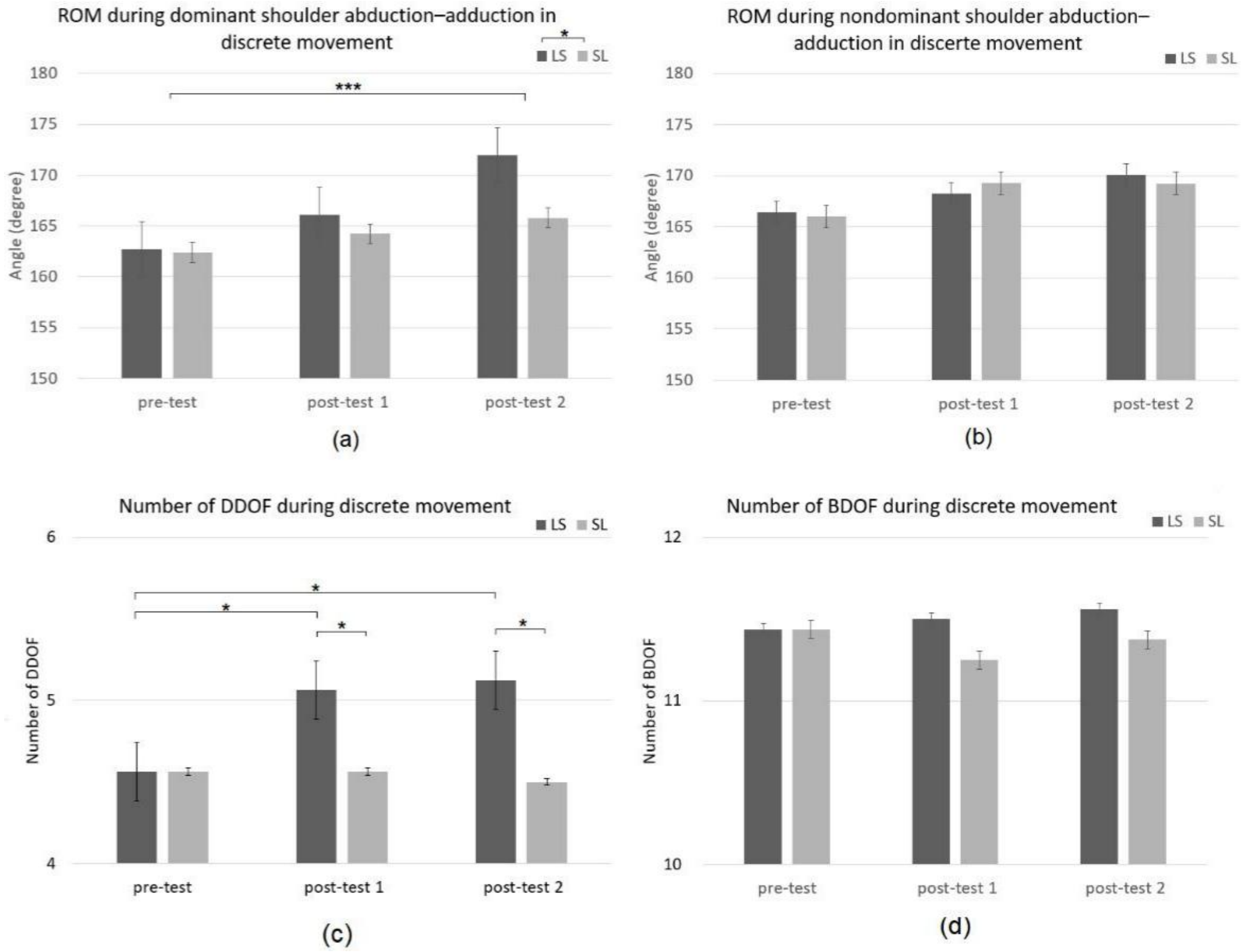

FIGURE 2. Changes in shoulder ROM and coordination variables during the discrete movement task. (a) ROM during dominant shoulder abduction–adduction across test sessions by group. (b) ROM during nondominant shoulder abduction–adduction across test sessions by group. (c) Number of DDOF during discrete movement across test sessions by group. (d) Number of BDOF during discrete movement across test sessions by group; *$p < 0.05$; ***$p < 0.001$. ROM: range of motion; LS: pelvic–lumbar coordination followed by shoulder stabilization; SL: shoulder stabilization followed by pelvic–lumbar coordination; DDOF: dynamical degrees of freedom; BDOF: biomechanical degrees of freedom.

test was not significant, $\chi^2(2) = 0.211$, $p = 0.900$, Kendall's $W = 0.007$ (95% CI (0.002, 0.241)), and thus no *post-hoc* comparisons were performed.

3.2 Continuous movement

3.2.1 Shoulder ROM

As shown in Fig. 3a, there were significant differences between groups in the dominant shoulder ROM ($F(1, 30) = 14.596$, $p < 0.001$, $\eta^2 = 0.3273$), and a significant difference was observed among test sessions in the dominant shoulder ROM ($F(2, 60) = 17.600$, $p < 0.001$, $\eta^2 = 0.370$). Also, the interaction effect between group and test session was significant ($F(2, 60) = 3.749$, $p = 0.029$, $\eta^2 = 0.111$). As a result of the *post-hoc* analysis, the dominant shoulder ROM was found to be significantly higher for LS compared with SL ($p < 0.001$, 95% CI (2.898, 9.555)), and significantly higher for post-test 2 compared with pre-test ($p < 0.001$, 95% CI (5.663, 15.355)), and post-test 1 ($p = 0.002$, 95% CI (2.245, 10.199)). *Post-hoc* multiple comparisons were performed to provide detailed information on pairwise differences among test sessions and groups. At post-test 2, the LS group demonstrated significantly greater dominant shoulder ROM compared with the SL group ($p < 0.001$, 95% CI (5.74, 14.95)). At post-test 1, the LS group also showed significantly higher ROM than the SL group ($p = 0.008$, 95% CI (2.07, 12.92)), while no significant difference was observed at pre-test ($p = 0.776$, 95% CI (−5.12, 6.80)). In addition, within the LS group, dominant shoulder ROM was significantly higher at post-test 2 than at pre-test ($p < 0.001$, 95% CI (9.206, 21.316)), and post-test 1 ($p = 0.001$, 95% CI (1.652, 13.543)). Furthermore, post-test 1 also showed a significantly higher ROM compared to the pre-test ($p = 0.014$, 95% CI (1.501, 13.726)) in the LS group.

As shown in Fig. 3b, there were no significant differences between groups in the non-dominant shoulder ROM ($F(1, 30) = 1.004$, $p = 0.324$, $\eta^2 = 0.032$). However, a significant main effect of time was observed ($F(2, 60) = 3.892$, $p = 0.026$, $\eta^2 =$

0.115), indicating that non-dominant shoulder ROM changed across the test sessions. In addition, the interaction effect between group and time was not significant ($F(2, 60) = 0.275$, $p = 0.760$, $\eta^2 = 0.009$). As a result of the *post-hoc* analysis, a significant increase in non-dominant shoulder ROM was observed at post-test 2 compared with the pre-test ($p = 0.009$, 95% CI (2.317, 15.840)), whereas no significant differences were found between post-test 1 and pre-test ($p = 0.209$, 95% CI (−2.900, 15.584)), or between post-test 2 and post-test 1 ($p = 0.591$, 95% CI (−4.411, 9.885)).

3.2.2 DDOF

As shown in Fig. 3c, there were no significant differences in the DDOF between the LS and SL groups at any time point. Specifically, no group difference was found at the pre-test ($U = 115.0$, $p = 0.585$, Cliff's $\delta = -0.102$, 95% CI (−0.449, 0.250)), post-test 1 ($U = 148.5$, $p = 0.422$, Cliff's $\delta = 0.160$, 95% CI (−0.234, 0.523)), or post-test 2 ($U = 153.0$, $p = 0.333$, Cliff's $\delta = 0.195$, 95% CI (−0.188, 0.553)). These results indicate that DDOF did not differ significantly between groups across all test sessions.

For the LS group, the Friedman test revealed no significant effect of time, $\chi^2(2) = 2.471$, $p = 0.291$, with a moderate effect size (Kendall's $W = 0.077$, 95% CI (0.005, 0.391)). Similarly, the Friedman test for the SL group was not significant, $\chi^2(2) = 0.533$, $p = 0.766$, $W = 0.017$ (95% CI (0.002, 0.279)); therefore, no *post-hoc* comparisons were conducted.

3.2.3 BDOF

As shown in Fig. 3d, there were no significant differences in the BDOF between groups at the pre-test ($U = 122.0$, $p = 0.832$, Cliff's $\delta = -0.047$, 95% CI (−0.447, 0.355)) or post-test 2 ($U = 128.0$, $p = 1.000$, Cliff's $\delta = 0.000$, 95% CI (−0.379, 0.379)). However, at post-test 1, the LS group demonstrated significantly higher BDOF than the SL group ($U = 195.0$, $p = 0.007$, Cliff's $\delta = 0.523$, 95% CI (0.195, 0.785)), indicating a moderate positive effect size.

For the LS group, the Friedman test revealed a significant effect of time, $\chi^2(2) = 12.72$, $p = 0.002$, indicating a moderate to large effect size (Kendall's $W = 0.397$, 95% CI (0.129, 0.737)). *Post-hoc* Wilcoxon signed-rank tests showed that BDOF was significantly higher at post-test 1 ($p = 0.004$, $r = 0.808$, 95% CI (0.565, 0.894)) and post-test 2 ($p = 0.002$, $r = 0.845$, 95% CI (0.691, 0.903)) compared with the pre-test, whereas no significant difference was observed between post-test 1 and post-test 2 ($p = 0.927$, $r = 0.028$, 95% CI (0.009, 0.701)). For the SL group, the Friedman test also revealed a significant effect of time, $\chi^2(2) = 9.55$, $p = 0.008$, with a moderate effect size (Kendall's $W = 0.298$, 95% CI (0.108, 0.601)). *Post-hoc* analyses indicated that BDOF at post-test 2 was significantly higher than at both the pre-test ($p = 0.006$, $r = 0.735$, 95% CI (0.424, 0.886)) and post-test 1 ($p = 0.003$, $r = 0.830$, 95% CI (0.651, 0.903)), while no significant difference was found between the pre-test and post-test 1 ($p = 0.954$, $r = 0.015$, 95% CI (0.008, 0.570)).

In summary, during the discrete movement task, the LS group demonstrated significantly greater dominant shoulder ROM compared with the SL group. Dominant shoulder ROM was significantly greater at post-test 2 compared with the pre-test. For DDOF, significant group differences were observed at post-test 1 and post-test 2, with the LS group outperforming the SL group. Moreover, time effects were significant only in the LS group, indicating progressive improvement across sessions. In contrast, BDOF showed no significant changes across time or between groups during the discrete task. During the continuous movement task, a clear interaction effect emerged for dominant shoulder ROM. The LS group showed substantial increases in ROM across all test sessions (pre-test $<$ post-test 1 $<$ post-test 2), while the SL group exhibited minimal change. The LS group also consistently outperformed the SL group at both post-test 1 and post-test 2. DDOF remained stable across time and between groups, indicating no significant modulation due to training. For BDOF, both groups exhibited significant time effects, with LS showing higher values at post-test 1 compared with SL, and both groups demonstrating enhanced coordination at post-test 2 relative to earlier sessions. Collectively, these findings indicate that the LS rehabilitation program effectively enhanced shoulder mobility and multi-joint coordination, particularly during continuous movements, whereas the SL rehabilitation program produced limited adaptation effects.

4. Discussion

The primary finding of this study is that sequencing pelvic lumbar coordination training before conventional shoulder stabilization produced more favorable improvements in dominant shoulder function than the reverse order. Importantly, the superiority of LS was not limited to joint excursion, but was accompanied by task-specific changes in coordination structure as indexed by synergy-derived degrees of freedom. During the discrete movement condition, BDOF remained largely unchanged, whereas LS exhibited higher DDOF than SL across post-intervention sessions, indicating that the intervention primarily influenced the organization of coordination groups, rather than expanding joint-level participation. In parallel, dominant shoulder ROM increased over sessions, suggesting that enhanced coordination-group organization may have supported more effective ROM expression under discrete, event-like actions. Importantly, this increase in ROM should not be interpreted as a simple expansion of joint mobility, but rather as a functional expression of available range enabled by more efficient inter-joint coordination. In contrast, during the continuous movement condition, DDOF was relatively stable, but LS showed an earlier advantage in BDOF, indicating a broader distribution of joint contributions during cyclic movement. Collectively, these results suggest that LS confers functional benefits through distinct coordination pathways depending on whether the task demands discrete or continuous control [22].

These findings can be interpreted within a kinetic chain framework in which shoulder mechanics depend on coordinated interactions across the pelvis, trunk, scapula, and upper limb, rather than isolated joint function [23]. Implementing pelvic–lumbar coordination training first may have improved proximal control and load redistribution, thereby creating more favorable conditions for subsequent shoulder stabilization to translate into functional movement. From a dynamical systems perspective, the temporal structure of a task acts as a key con-

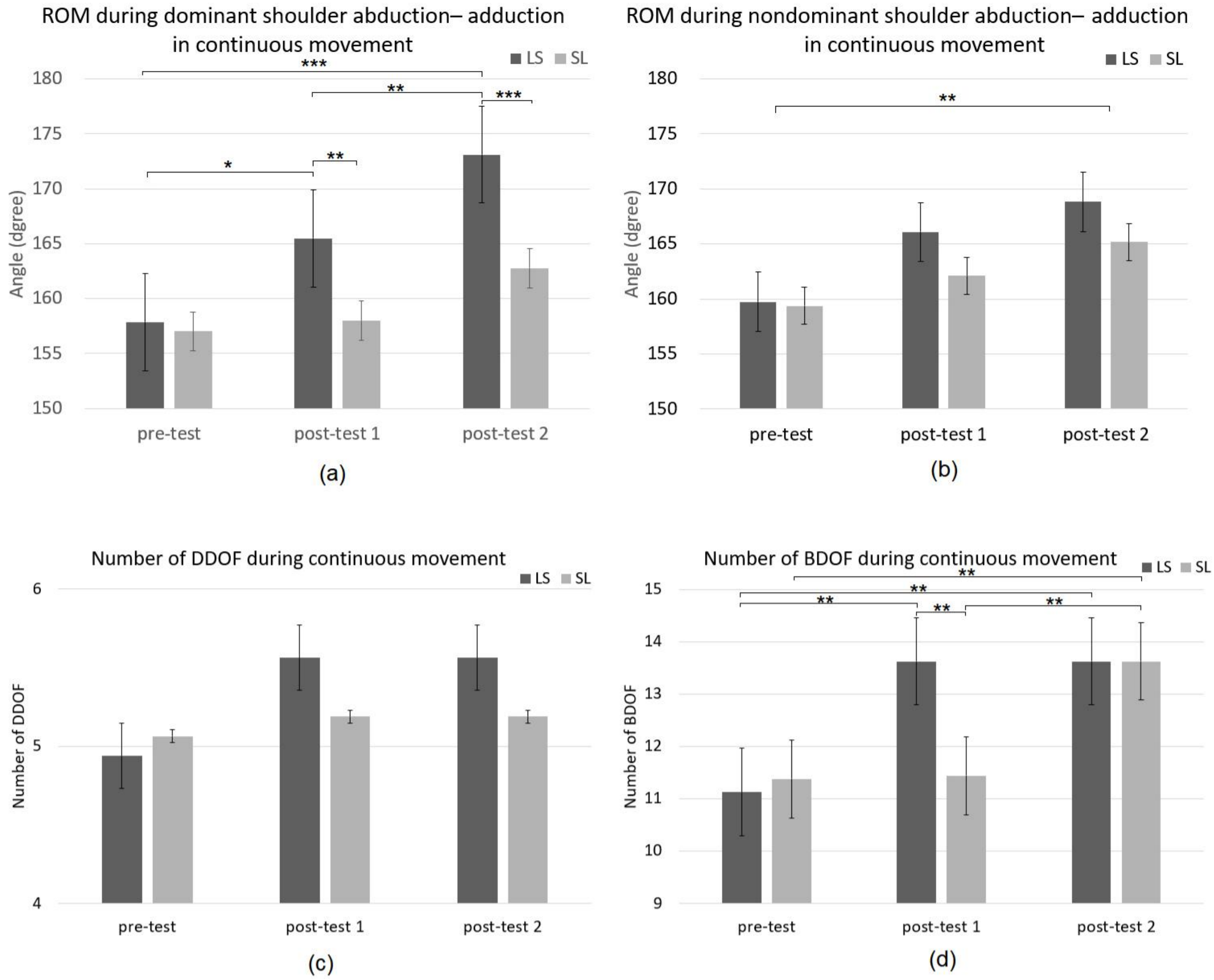

FIGURE 3. Changes in shoulder ROM and coordination variables during the continuous movement tasks. (a) ROM during dominant shoulder abduction–adduction across test sessions by group. (b) ROM during nondominant shoulder abduction–adduction across test sessions by group. (c) Number of DDOF during discrete movement across test sessions by group. (d) Number of BDOF during discrete movement across test sessions by group; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$. ROM: range of motion; LS: pelvic–lumbar coordination followed by shoulder stabilization; SL: shoulder stabilization followed by pelvic–lumbar coordination; DDOF: dynamical degrees of freedom; BDOF: biomechanical degrees of freedom.

straint shaping how degrees of freedom are reorganized during learning and rehabilitation. Accordingly, discrete actions, characterized by clear endpoints and event-based control, may preferentially benefit from reorganization at the level of coordination groups, reflected by increases in DDOF [24]. By contrast, continuous cyclic actions rely on emergent timing and sustained intersegmental coupling, placing greater demands on the distribution of movement across multiple joints over time. In such contexts, functional adaptation may, therefore, be expressed through expansion of BDOF, rather than changes in the number of coordination groups. In this view, LS may have enhanced the capacity to distribute work across a larger set of joint motions during continuous movement, reducing reliance on proximal shoulder structures while allowing greater ROM expression. Thus, the sequencing effect appears to operate through coordination-level adaptations that are selectively tuned to the temporal demands of the task [25].

The observed changes in shoulder movement in the present study are unlikely to be explained solely by passive mechanical changes in soft tissue properties. Rather, from a motor control and motor learning perspective, these findings may reflect adaptive changes in centrally mediated movement strategies. Two potential mechanisms may account for this process. First, the improvements may reflect a release of protective "freezing" of degrees of freedom. According to Bernstein's motor control theory, the central nervous system temporarily reduces system complexity by constraining degrees of freedom during early learning stages or when stability is threatened [26]. In the present sample, pelvic instability may have posed a challenge to whole-body postural control, leading the motor system to increase co-contraction around the shoulder to enhance joint stiffness and ensure global stability. In this context, reduced shoulder range of motion may not represent a local joint limitation, but rather an adaptive control strategy that sacrifices mobility to preserve overall system stability. Pelvic–lumbar coordination training may have reduced the need for such protective stabilization, allowing the previously constrained degrees of freedom to be released and functionally expressed. Second, the findings may reflect changes in motor planning at supraspinal control levels. According to Optimal Feedback Control theory, the central nervous system generates motor commands by minimizing a cost function that includes not only movement error, but also effort and predicted risk [27]. Under conditions of pelvic instability, the motor system may predict increased postural disturbance or balance loss during large-amplitude shoulder movements. Consequently, the system may adopt a conservative control policy that restricts movement amplitude even when structural joint capacity is available. The pelvic coordination intervention may have altered this cost structure by reducing perceived postural risk, enabling updating of internal models and allowing the motor system to adopt a new optimal control strategy permitting greater functional range of motion. Taken together, these findings suggest that the intervention effect may reflect a transition in neural control strategy from protective stabilization toward flexible movement coordination. Future studies incorporating electromyographic co-contraction analysis and three-dimensional intersegmental coordination analysis may help clarify the neurophysiological mechanisms underlying these adaptations.

From a dynamical systems perspective, rehabilitation-induced recovery can be understood as emerging from reorganization of coordination, and synergy-based degrees-of-freedom metrics provide a multilevel description of such changes beyond conventional kinematics [28]. In the present study, DDOF and BDOF captured complementary aspects of recovery: discrete-task improvements were accompanied primarily by changes in coordination-group organization, whereas continuous-task improvements were linked to earlier expansion in joint-level involvement. Clinically, this pattern supports prioritizing proximal coordination-focused training before shoulder-specific stabilization for recreational racket-sport participants, while also emphasizing that the relevant coordination target may differ by task demands (discrete *vs.* continuous). Practically, incorporating synergy-informed metrics may help clinicians detect meaningful functional adaptations even when standard kinematic outcomes show limited sensitivity or when improvements manifest differently across movement contexts.

Several limitations of this study warrant consideration, including the short intervention window, and the restriction to adult male club members. Additionally, joint hypermobility was not formally assessed in this study. Because joint hypermobility may influence available range of motion, passive joint stability, and movement coordination strategies, the lack of hypermobility screening limits the ability to fully separate coordination-based adaptations from individual structural joint characteristics. Future studies should incorporate standardized hypermobility assessments to better account for individual variability in joint laxity and its potential influence on motor performance. Future work should examine longer-term retention, include pain/function scales and sport-specific strokes, and test whether synergy/DOF changes predict injury risk reduction in real play.

5. Conclusions

This study demonstrates that sequencing pelvic–lumbar coordination training before conventional shoulder stabilization leads to superior recovery of dominant shoulder function in adult male recreational racket-sport participants. Importantly, the benefits of this sequencing were task-specific: improvements during discrete movements were primarily associated with increased dynamical degrees of freedom, whereas improvements during continuous movements were linked to earlier expansion of biomechanical degrees of freedom. These findings indicate that effective shoulder rehabilitation involves reorganization of coordination structures, rather than isolated joint-level changes alone. By integrating kinetic chain–based intervention with synergy-informed outcome measures, the present approach provides a more comprehensive framework for evaluating functional recovery. Collectively, the results suggest that prioritizing proximal coordination training may enhance the effectiveness of shoulder rehabilitation, particularly in sports characterized by both discrete and continuous movement demands. The present framework represents a proof-of-concept derived from a homogeneous sample of individuals with mild shoulder discomfort and provides a foundation for future rehabilitation approaches that incorporate stratification based on functional or biomechanical profiles. Nevertheless, given the short inter-session interval and immediate post-test assessments, the present findings primarily reflect acute training-order effects, and future studies incorporating longer washout periods and delayed retention tests are warranted to confirm longer-term rehabilitation outcomes.

AVAILABILITY OF DATA AND MATERIALS

The datasets generated during and/or analyzed in the current study are available from the corresponding author on reasonable request.

AUTHOR CONTRIBUTIONS

EJ and DS—designed the research study; wrote the manuscript collaboratively. EJ—conducted the experiments and collected the data. DS—performed the data analysis and interpretation. Both authors contributed to editorial revisions, read, and approved the final version of the manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This study was conducted in accordance with the Declaration of Helsinki and was approved by the Institutional Review Board of Jeonbuk National University (approval no. 2025-02-021-001). All participants were informed about the purpose and procedures of the study, and written informed consent was obtained from all individuals prior to participation. In addition, the participant provided explicit consent for the publication of identifiable images included in this manuscript.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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