

Neuromuscular and reactive performance adaptations following combined SAQ and plyometric training in competitive female handball players

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Abstract

Problem Statement: Handball is a high-intensity intermittent sport that requires rapid accelerations, multidirectional movements, explosive jumping, and quick perceptual–motor decision-making. Although speed, agility, and quickness (SAQ) and plyometric training are commonly applied in team sports conditioning, limited controlled research has examined their combined effects on neuromuscular activation and reactive agility in female handball players. **Approach:** A randomized controlled experimental design was adopted involving 21 competitive female handball players, who were divided into an experimental group (n = 11) and a control group (n = 10). The experimental group completed combined SAQ and plyometric training three times per week for eight weeks in addition to regular handball practice, whereas the control group continued standard training. Surface electromyography (EMG) was used to measure activation of the rectus femoris, gastrocnemius, and biceps femoris during squat and drop jumps. Performance measures included reactive agility, squat jump (SJ), drop jump (DJ), countermovement jump (CMJ), and 10 m sprint tests. Data were analyzed using Shapiro–Wilk tests and two-way mixed ANOVA (Group × Time) with Bonferroni-adjusted post hoc tests and effect size calculations. **Purpose:** The purpose of this study was to examine the effects of an eight-week combined SAQ and plyometric training program on electromyographic activity, reactive agility, and explosive performance in competitive female handball athletes. **Results:** Significant Group × Time interactions were found for rectus femoris EMG (p = 0.013), gastrocnemius EMG (p = 0.016), reactive agility (p = 0.010), squat jump height (p = 0.022), and drop jump height (p = 0.018). The experimental group demonstrated substantial improvements in rectus femoris EMG (+0.049 RMS, d = 0.93), gastrocnemius EMG (+0.044 RMS, d = 0.86), reactive agility (-0.39 s, d = 1.02), squat jump (+2.2 cm, d = 0.88), and drop jump (+2.4 cm, d = 0.90), while the control group showed no significant changes. **Conclusions:** An eight-week combined SAQ and plyometric training program significantly enhanced neuromuscular activation, reactive agility, and explosive performance in female handball players. These findings highlight the effectiveness of integrating structured neuromuscular and perceptual training strategies within handball conditioning programs to improve explosive and reactive performance capacities.

Keywords: Female Handball Players; Electromyography; Reactive Agility; Plyometric Training; Speed-Agility-Quickness Training.

Introduction

Team handball is widely recognized as an intermittent, high-intensity sport characterized by repeated bouts of explosive actions, including sprinting, rapid accelerations and decelerations, frequent changes of direction (COD), jumping, and sustained physical contact between players (García-Sánchez et al., 2023). Unlike continuous endurance-based sports, handball performance is dictated by the ability to repeatedly produce high-intensity efforts interspersed with brief recovery periods, thereby placing substantial demands on both the aerobic and anaerobic energy systems. The aerobic system contributes to recovery between high-intensity bouts, while the anaerobic pathways particularly the phosphagen and glycolytic systems are essential for executing short-duration, maximal or near-maximal efforts such as fast breaks, defensive shuffles, and powerful shots.

Empirical evidence indicates that elite handball players perform several hundred high-intensity actions during a single match, encompassing sprints, jumps, tackles, and directional changes (Wagner et al., 2014).

These repeated efforts impose considerable stress not only on metabolic systems but also on the neuromuscular apparatus, requiring players to maintain high levels of force production, coordination, and movement efficiency throughout the game. The cumulative fatigue associated with such repeated exertions can negatively affect technical execution, decision-making, and injury risk if not adequately addressed through structured training interventions. The concept of speed, agility, and quickness (SAQ) training has gained considerable recognition as an evidence-based conditioning method in team sports, involving structured drills such as sprinting, ladder exercises, cone drills, and reaction-based tasks to enhance acceleration, deceleration, and change-of-direction ability (Milanović et al., 2014; Jovanovic et al., 2011). Importantly, SAQ training integrates perceptual-cognitive elements, enabling athletes to respond effectively to dynamic and unpredictable game situations (Formenti et al., 2021). A recent systematic review and meta-analysis confirmed that SAQ training significantly improves sprint performance, change-of-direction speed, and neuromuscular coordination across sports (Sun et al., 2025), primarily through enhanced motor unit recruitment and intermuscular coordination. In addition, plyometric training (PT) is a well-established method for improving explosive neuromuscular performance, particularly in female athletes (Chaabene et al., 2021). PT is based on the stretch-shortening cycle (SSC), where a rapid eccentric action followed by a concentric contraction enhances force production and mechanical efficiency (Hammami et al., 2016). Consequently, the combined application of SAQ and plyometric training may produce synergistic adaptations, optimizing both neural and mechanical aspects of high-intensity sports performance.

Lower-extremity plyometric training produces neuromuscular changes of a multifactorial nature (greater neural drive to agonist muscle, greater muscle-muscle coordination, and greater muscle-tendon mechanical qualities). The results of these adaptations are seen in higher JMP height, sprint speed and COD, which are physical attributes that apply directly to the play of a handball match. Considering the female handball players in particular, Chaabene et al., (2021) established that a short-term in-season plyometric program yielded moderate-to-large effects on the linear sprint speed, COD, and reactive strength index, which proves the potential practical importance of PT in the specified population. Although both SAQ and plyometric training have their own merits, the possible synergistic outcomes of the two interventions used during one periodized intervention are not fully comprehended, especially among team-sport athletes in the female population. Integrated exercises involving high-velocity, task-specific SAQ exercises and neuromuscular loading stimulus of plyometrics might elicit a larger adaptive reaction than either of the modalities alone, since they both cause perceptual-cognitive agility and lower-limb explosive power (Cherni et al., 2020). Moreover, the neuromuscular processes underlying such adaptations have seldom been studied, based on objective electromyographic (EMG) measures, on the female handball populations.

Surface EMG monitoring of lower limb muscles during SSC tasks, including squat jumps and drop jumps, offers a direct peek into training-induced modification in muscle activation strategies and motor unit recruitment that result in apparent performance improvements Cherni et al., 2020. Another gap in the literature is related to measuring reactive agility, which is defined as the capacity to quickly switch direction after some unpredictable stimulus as one of the key outcomes of handball training research. The concept of reactive agility is conceptually different to pre-planned COD speed, which involves linking perceptual-cognitive decision-making processes to physical movement execution, which is more consistent with the requirements of a real-world competitive game. Although this ecological pertinence, the majority of the past SAQ and plyometric training studies in handball have been carried out using a pre-planned COD testing protocol as opposed to a reactive agility testing protocol, and this may have underestimated the actual game-specific transfer with the training adaptations (Wagner et al., 2014). Despite the growing body of research on SAQ and plyometric training, several important gaps remain. First, there is limited evidence examining the combined effects of these training modalities on both neuromuscular activation and functional performance in female handball players. Second, the mechanistic basis of training adaptations, particularly those related to muscle activation patterns measured through EMG, is not well understood in this population. Third, most existing studies rely on pre-planned agility assessments, which fail to capture the perceptual and decision-making components inherent in competitive handball performance. Addressing these gaps is essential for developing evidence-based, sport-specific training programs that enhance both physical and cognitive aspects of performance. To address these limitations, the present study employed a randomized controlled trial design to investigate the effects of an eight-week combined SAQ and plyometric training program on neuromuscular activation, reactive agility, and explosive performance in competitive female handball players. Participants were randomly assigned to either an experimental group, which performed the combined training intervention alongside regular handball practice, or a control group, which continued standard training. Neuromuscular adaptations were assessed using surface electromyography (EMG) during stretch-shortening cycle tasks, while functional performance was evaluated through reactive agility, sprint speed, and jump performance tests. By integrating physiological and performance-based measures, this study aims to provide both mechanistic insight and applied evidence regarding the effectiveness of combined SAQ and plyometric training. The findings are expected to offer practical guidance for coaches and strength and conditioning professionals in designing integrated training programs that enhance neuromuscular efficiency, perceptual-motor performance, and overall match readiness in female handball players.

Materials and Methods

Experimental Approach to the Problem The present study adopted a randomized controlled experimental design to determine whether an eight-week combined speed, agility, and quickness (SAQ) plus plyometric training program could elicit superior neuromuscular and performance adaptations compared with regular handball training alone in female players. Participants were randomly allocated to either an experimental group, which completed the SAQ and plyometric intervention alongside regular training, or a control group, which continued standard practice. Participant flow through recruitment, randomization, allocation, follow-up, and analysis see Figure 1. Neuromuscular adaptations were examined using surface electromyography (EMG) of key lower-limb muscles during stretch-shortening cycle tasks, while functional transfer was evaluated through reactive agility and explosive performance measures. Pre- and post-intervention testing allowed the assessment of within- and between-group changes, enabling causal inference regarding the effectiveness of the intervention while controlling for training exposure and inter-individual variability.

Research Design This study employed a randomised controlled trial (RCT) design to investigate the effects of an 8-week speed, agility, and quickness (SAQ) plus plyometric training program on muscle activation and reactive agility in female handball players. Participants were randomly assigned to either an experimental group (EG, $n = 11$), which completed the SAQ + plyometric intervention alongside their regular handball practice, or a control group (CG, $n = 10$), which continued their standard handball training regimen without additional conditioning.

Participants A total of 21 female handball players voluntarily participated in the study. Inclusion criteria were: (1) active participation in competitive handball for at least 3 years, (2) absence of musculoskeletal injuries within the last 6 months, and (3) medical clearance for participation in high-intensity training. Exclusion criteria included: (1) current injury, (2) history of neurological disorders, and (3) inconsistent attendance (<85% of training sessions). Prior to participation, players and their guardians (if under 18) provided written informed consent in accordance with ethical research standards.

Table 1 presents the demographic and anthropometric characteristics of the participants. A total of 21 competitive female handball players were included in the final analysis (experimental group, $n = 11$; control group, $n = 10$). Independent samples *t*-tests revealed no statistically significant baseline differences between groups in age, height, body mass, BMI, or training experience ($p > 0.05$ for all variables).

Table I. Demographic Characteristics of Participants (Mean $\pm$ SD)

Variable	Experimental Group ($n = 11$)	Control Group ($n = 10$)	Total ($N = 21$)	<i>p</i> -value
Age (years)	19.8 $\pm$ 1.5	20.5 $\pm$ 1.7	20.1 $\pm$ 1.6	0.32
Height (cm)	167.5 $\pm$ 6.1	165.0 $\pm$ 6.8	166.3 $\pm$ 6.4	0.30
Body Mass (kg)	59.1 $\pm$ 4.9	60.4 $\pm$ 5.5	59.7 $\pm$ 5.2	0.47
BMI (kg/m ²)	21.1 $\pm$ 1.8	22.2 $\pm$ 1.9	21.6 $\pm$ 1.9	0.24
Training Experience (years)	5.3 $\pm$ 1.2	5.7 $\pm$ 1.4	5.5 $\pm$ 1.3	0.44

Note: Independent samples *t*-tests confirmed no significant baseline differences between groups ($p > 0.05$).

The participants represented a homogeneous cohort of late-adolescent to young adult athletes (mean age = 20.1 $\pm$ 1.6 years), with comparable competitive training backgrounds (mean experience = 5.5 $\pm$ 1.3 years). These findings confirm baseline equivalence between groups and support the validity of subsequent between-group comparisons.

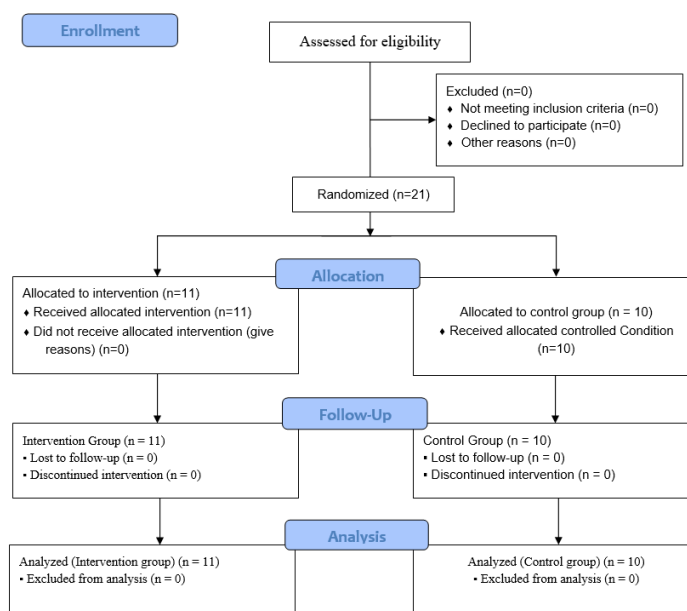


Figure 1. CONSORT flow diagram

Randomisation and Blinding

Participants were randomly allocated to groups using a computer-generated randomisation procedure. Allocation was concealed until the start of the intervention. Outcome assessors responsible for data collection and analysis were blinded to group assignment to minimise bias.

Table II. Eight-Week SAQ + Plyometric Training Program

Weeks	Training Focus	Exercises	Sets × Reps	Intensity	Rest
1-2	Acceleration & Basic Plyometrics	- 10-20 m sprints- Ladder footwork (various patterns)- Squat jumps (bodyweight)- Pogo jumps (ankle hops)- 5-10-5 m cone shuttle	6 × 10-20 m3 × 20 s each3 × 103 × 12-154 × 1	50-60% Submaximal	90 s between drills2-3 min between sets
3-4	COD & Drop Jumps	- COD sprints (45-90°)- Drop jumps (20-30 cm)- Reactive cone drills (coach cue)- Bounding (10 m)- Sprint relays (COD + sprint)	6 × 20 m4 × 84 × 15 s3 × 23 × 3	60-75% effort	60-90 s between drills, 3 min between sets
5-6	Multidirectional Speed & Hurdle Plyos	- Multidirectional sprints (forward/backward/lateral)- Hurdle jumps (30-40 cm)- COD with unanticipated light cue- Drop jumps (30 cm, stick landing)- Sprint to ball pick-up	5 × 14 × 86 × 15 m4 × 64 × 10 m	70-80% effort	60 s between reps3-4 min between sets
7-8	Complex Drills & Handball-Specific	- Complex sprint → COD → reactive cue- Hurdle hops + sprint (4 hurdles + 10 m)- Reactive Y-agility (light cue)- Plyometric combo (SJ → broad jump → sprint)- Handball-specific shuffle + cue + sprint	6 × 14 × 66 × 14 × 35 × 1	80-90% Maximal intent	60-90 s between drills3-4 min between sets

Each training session lasted 45-60 minutes and was conducted three times per week on non-consecutive days. A standardized warm-up of approximately 10 minutes, including light jogging, dynamic mobility drills, progressive sprints, and submaximal jumps, preceded all sessions, while a cool-down phase of 5-8 minutes involving static stretching of the lower limbs and controlled breathing exercises followed. Training progression was carefully monitored, with ground contacts gradually increasing from around 60 in the first week to approximately 130 by the final week. Exercise intensity was regulated using the Borg CR10 scale, with participants maintaining a rating of perceived exertion (RPE) between 6 and 8, corresponding to hard to very hard effort levels.

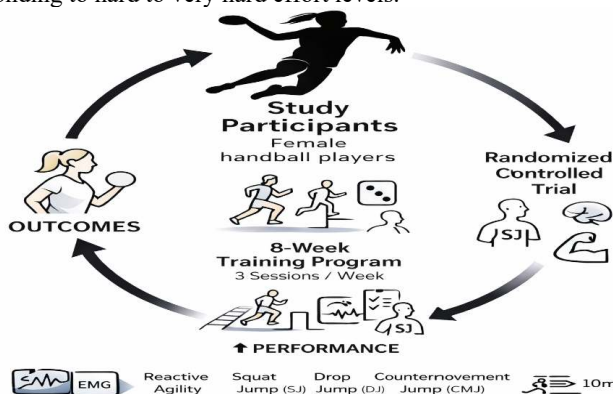


Figure 2. Circular overview of methodology and performance outcomes

Outcome Measures

Electromyography (EMG): Surface electromyographic (sEMG) activity of the rectus femoris (RF), biceps femoris (BF), and gastrocnemius (GAS) muscles of the dominant leg was recorded during squat jumps (SJ) and drop jumps (DJ; 30 cm height). Electrode placement followed SENIAM recommendations (Hermens et al., 2000), and EMG signals were amplified, band-pass filtered (20-450 Hz), and sampled at 1000 Hz in accordance with best-practice guidelines (Luca, 1997). Muscle activation was quantified using root mean square (RMS) values for eccentric, amortization, and concentric phases of each jump, a method commonly used for stretch-shortening cycle tasks (Farina et al., 2014). Given the repeated-measures design and strictly standardized testing conditions, non-normalized RMS values were analyzed, with each participant serving as her own control, supporting interpretation of EMG changes as genuine neuromuscular adaptations rather than measurement artifacts (Farina et al., 2014; Luca, 1997).

Reactive Agility: Reactive agility was assessed using a Y-reactive agility test, requiring participants to sprint forward and respond to an unpredictable visual or auditory stimulus directing them to change direction to the left or right. This test design incorporates both physical change-of-direction ability and perceptual-cognitive decision-making, reflecting game-specific agility demands (Saha et al., 2025). Total completion time (s) and decision-making time (s) were recorded using electronic timing gates synchronized with the stimulus system. Reactive agility tests of this nature

have been shown to demonstrate good reliability and superior ecological validity compared with pre-planned change-of-direction tests (Horníková & Skala, 2025).

Secondary Performance Tests: To complement EMG and reactive agility outcomes, linear sprint performance and explosive jump capacity were also assessed. Sprint speed was evaluated using a 10 m sprint test, a distance commonly used to assess acceleration ability in team-sport athletes (Jovanovic et al., 2011). Lower-body explosive power was assessed using the countermovement jump (CMJ), which is a valid and reliable indicator of neuromuscular performance and stretch-shortening cycle efficiency in female athletes.

Testing Procedures

Testing procedures were carried out one week before the commencement of the intervention and repeated one week following its completion. All participants underwent a standardised warm-up protocol before testing, consisting of 5 minutes of continuous jogging, dynamic stretching targeting the major lower-limb muscle groups, and three submaximal jumps and sprints to activate neuromuscular readiness. This ensured participants were adequately prepared and minimised injury risk during maximal performance trials. Each assessment was administered under controlled laboratory conditions using the same equipment and testing sequence to enhance reliability. To account for variability, participants performed three maximal attempts for each test. The highest value achieved across the three trials was recorded for further analysis, as it best represented the participant's true maximal capacity. Environmental and procedural consistency was strictly maintained across pre- and post-testing sessions.

Ethical Consideration

The study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the local institutional ethics committee. All participants were fully informed about the study objectives, procedures, potential risks, and benefits, and provided written informed consent prior to participation. All procedures were non-invasive, posed minimal risk, and involved standard training and fitness assessments commonly used in sport science research.

Exclusion Criteria

Participants were excluded from the study if they had any current or recent musculoskeletal injury (within the previous six months) that could limit participation in high-intensity training or performance testing. Additional exclusion criteria included a history of neurological disorders, diagnosed cardiovascular or metabolic conditions contraindicating vigorous exercise, or any chronic lower-limb pathology affecting jumping, sprinting, or change-of-direction tasks. Players were also excluded if they were engaged in concurrent structured strength, plyometric, or neuromuscular training programs outside regular handball practice, or if their attendance during the intervention period fell below 85% of the prescribed training sessions. These criteria were applied to ensure participant safety, homogeneity of training background, and to minimize confounding influences on neuromuscular and performance outcomes.

Intervention Fidelity

To ensure consistency and accuracy in the implementation of the SAQ and plyometric training program, all training sessions were supervised by certified strength and conditioning specialists with experience in team-sport athlete development. Attendance was monitored for every session, and participants were required to complete a minimum of 85% of the prescribed sessions to be included in the final analysis. Exercise execution, movement technique, and progression were continuously monitored, with real-time feedback provided to correct errors and ensure adherence to the training protocol. Training loads, intensity, and rest intervals were standardized across sessions, and any deviations were documented to maintain intervention integrity and reduce performance bias.

Sample Size Adequacy and Statistical Power

The final sample consisted of 21 competitive female handball players (experimental group, $n = 11$; control group, $n = 10$). The sample size was primarily determined by athlete availability during the competitive season. Although slightly lower than the recommended number suggested by a priori power analysis (28-34 participants for medium effects), the observed interaction effect sizes (partial $\eta^2 = 0.24$ -0.30) indicate moderate-to-large effects, suggesting adequate sensitivity to detect practically meaningful training adaptations within this population.

Statistical Analysis

All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS, version 26.0; IBM Corp., Armonk, NY, USA). Descriptive statistics are presented as mean $\pm$ standard deviation (SD) for all variables. The Shapiro-Wilk test was used to assess normality of distribution for each dependent variable at pre- and post-intervention time points. Homogeneity of variances between groups was verified using Levene's test. All assumptions for parametric testing were satisfied ($p > 0.05$). To evaluate the effects of the eight-week SAQ plus plyometric training intervention, a two-way mixed-design analysis of variance (ANOVA) with repeated measures was conducted, with Group (experimental vs control) as the between-subjects factor and Time (pre vs post) as the within-subjects factor. Interaction effects (Group $\times$ Time) were examined to determine whether changes over time differed between groups. When significant interaction or main effects were detected, Bonferroni-adjusted post hoc comparisons were performed. Within-group pre-post differences were further examined using paired-samples t-tests where appropriate, and independent-samples t-tests were used for between-group post-intervention comparisons. Effect sizes were calculated to quantify the magnitude of observed effects. Partial eta squared (η^2) was reported for ANOVA results and interpreted as small (≥ 0.01), medium (≥ 0.06), or large (≥ 0.14). Cohen's d was calculated for pairwise comparisons and interpreted as small

(0.20), medium (0.50), or large (0.80). The level of statistical significance was set at $p \leq 0.05$. Reliability of outcome measures was assessed using intraclass correlation coefficients (ICC, two-way random model, absolute agreement) and coefficient of variation (CV%). ICC values were interpreted as poor (<0.50), moderate (0.50-0.75), good (0.75-0.90), or excellent (>0.90).

Results

A total of 21 competitive female handball players completed the study and were included in the final analysis (experimental group, $n = 11$; control group, $n = 10$). All participants adhered to the intervention protocol, and no injuries or dropouts were recorded during the 8-week training period. Baseline comparisons confirmed no significant between-group differences in demographic or training-related characteristics ($p > 0.05$), indicating initial equivalence of the groups. Statistical assumptions for parametric testing were satisfied, including normal distribution of outcome variables. A two-way mixed analysis of variance (Group $\times$ Time) was conducted to evaluate the effects of the combined SAQ and plyometric training program on neuromuscular activation, reactive agility, and explosive performance measures. Effect sizes were calculated to determine the magnitude of observed changes, and reliability indices were examined to ensure measurement consistency.

Table 3 summarises the Shapiro-Wilk tests of normality for all dependent variables at pre- and post-intervention time points. Across both groups, all p -values exceeded 0.05, indicating that the assumption of normal distribution was satisfied for electromyographic (EMG) measures and reactive agility performance.

Table 3. Tests of Normality (Shapiro-Wilk)

Variable	Group	Pre-Test (p)	Post-Test (p)
Rectus Femoris EMG	EG	0.29	0.33
	CG	0.41	0.37
Gastrocnemius EMG	EG	0.31	0.28
	CG	0.36	0.39
Biceps Femoris EMG	EG	0.38	0.35
	CG	0.42	0.40
Reactive Agility	EG	0.34	0.31
	CG	0.39	0.36

Note. All variables satisfied normality ($p > 0.05$).

Given the absence of significant deviations from normality, parametric statistical procedures, including mixed ANOVA and post hoc t -tests, were considered appropriate for further analyses.

Table 4 presents the results of the two-way mixed ANOVA examining the effects of Group (experimental vs control), Time (pre vs post), and their interaction on neuromuscular and performance outcomes ($df = 1,19$). For rectus femoris EMG activity, a significant Group $\times$ Time interaction was observed ($F = 7.41$, $p = 0.013$, partial $\eta^2 = 0.28$), indicating that changes over time differed between groups. A similar interaction effect was found for gastrocnemius EMG ($F = 6.98$, $p = 0.016$, partial $\eta^2 = 0.27$).

Table 4. Two-Way Mixed ANOVA (Group $\times$ Time)

Dependent Variable	Source	df	F	p	Partial η^2
Rectus Femoris EMG	Group	1,19	0.76	0.39	0.04
	Time	1,19	8.92	0.008	0.32
	Group $\times$ Time	1,19	7.41	0.013	0.28
	Group	1,19	0.59	0.45	0.03
Gastrocnemius EMG	Time	1,19	7.85	0.011	0.29
	Group $\times$ Time	1,19	6.98	0.016	0.27
	Group	1,19	0.88	0.36	0.04
	Time	1,19	10.41	0.004	0.35
Reactive Agility	Group $\times$ Time	1,19	8.12	0.010	0.30
	Group	1,19	0.71	0.41	0.03
	Time	1,19	6.74	0.018	0.26
	Group $\times$ Time	1,19	6.11	0.022	0.24
Squat Jump	Group	1,19	0.74	0.40	0.03
	Time	1,19	7.22	0.014	0.27
	Group $\times$ Time	1,19	6.63	0.018	0.26
	Group	1,19	0.74	0.40	0.03
Drop Jump	Time	1,19	7.22	0.014	0.27
	Group $\times$ Time	1,19	6.63	0.018	0.26
	Group	1,19	0.74	0.40	0.03
	Time	1,19	7.22	0.014	0.27

Reactive agility performance also demonstrated a significant Group $\times$ Time interaction ($F = 8.12$, $p = 0.010$, partial $\eta^2 = 0.30$), suggesting greater improvements in the experimental group relative to the control group. Significant interaction effects were additionally observed for squat jump ($F = 6.11$, $p = 0.022$, partial $\eta^2 = 0.24$) and drop jump performance ($F = 6.63$, $p = 0.018$, partial $\eta^2 = 0.26$). Across all primary outcomes, effect sizes ranged from moderate to large (partial $\eta^2 = 0.24$ -0.30), indicating meaningful intervention-related

adaptations despite the reduced sample size. No significant main effects of group were observed at baseline, supporting initial equivalence between groups.

Table 5 details within-group pre-post changes and between-group post-intervention comparisons. The experimental group demonstrated significant improvements in rectus femoris EMG (+0.049 RMS, $p = 0.011$, $d = 0.93$) and gastrocnemius EMG (+0.044 RMS, $p = 0.016$, $d = 0.86$), whereas the control group showed no significant changes ($p > 0.05$).

Table 5. Within- and Between-Group Post Hoc Comparisons

Variable	Comparison	Mean Difference	t	p	Cohen's d
Rectus Femoris EMG	EG (Pre-Post)	+0.049	3.12	0.011	0.93
	CG (Pre-Post)	-0.012	-0.48	0.64	0.14
	EG vs CG (Post)	+0.058	2.97	0.008	0.89
Gastrocnemius EMG	EG (Pre-Post)	+0.044	2.88	0.016	0.86
	CG (Pre-Post)	-0.015	-0.52	0.61	0.16
	EG vs CG (Post)	+0.055	2.75	0.013	0.82
Reactive Agility	EG (Pre-Post)	-0.39	-3.41	0.007	1.02
	CG (Pre-Post)	-0.09	-0.69	0.50	0.21
	EG vs CG (Post)	-0.33	-3.08	0.006	0.95
Squat Jump	EG (Pre-Post)	+2.2	2.94	0.014	0.88
	CG (Pre-Post)	+0.4	0.53	0.60	0.15
	EG vs CG (Post)	+1.9	2.66	0.015	0.80
Drop Jump	EG (Pre-Post)	+2.4	3.01	0.013	0.90
	CG (Pre-Post)	+0.5	0.58	0.57	0.17
	EG vs CG (Post)	+2.0	2.83	0.011	0.85

Reactive agility time significantly improved in the experimental group (-0.39 s, $p = 0.007$, $d = 1.02$), while changes in the control group were not statistically significant. Similarly, squat jump (+2.2 cm, $p = 0.014$, $d = 0.88$) and drop jump height (+2.4 cm, $p = 0.013$, $d = 0.90$) improved significantly only in the experimental group. Between-group comparisons at post-test confirmed superior performance in the experimental group across all primary outcomes ($p \leq 0.015$), with effect sizes ranging from 0.80 to 1.02, indicating moderate-to-large practical significance.

Table 6 presents the reliability statistics for all outcome measures. Intraclass correlation coefficients (ICC) ranged from 0.86 to 0.92, indicating good to excellent reliability. Coefficients of variation (CV%) were consistently below 6%, demonstrating low measurement error.

Table 6. Reliability of Outcome Measures

Variable	ICC (95% CI)	CV (%)
Rectus Femoris EMG	0.90 (0.78-0.96)	4.5
Gastrocnemius EMG	0.88 (0.74-0.95)	4.9
Biceps Femoris EMG	0.86 (0.70-0.94)	5.3
Reactive Agility	0.92 (0.82-0.97)	4.1
10 m Sprint	0.89 (0.76-0.95)	4.8
CMJ	0.87 (0.72-0.94)	5.2
SJ	0.89 (0.76-0.95)	4.7
DJ	0.90 (0.79-0.96)	4.6

Reactive agility showed excellent reliability (ICC = 0.92), while EMG measures of rectus femoris and gastrocnemius demonstrated strong reproducibility (ICC ≥ 0.88). Jump performance tests (SJ and DJ) also exhibited high consistency (ICC ≥ 0.89). These reliability findings confirm that the measurement procedures were stable and reproducible, strengthening confidence that observed improvements reflect true training adaptations rather than random variation.

Taken together, the analyses indicate that the eight-week SAQ plus plyometric training program produced statistically significant and practically meaningful improvements in neuromuscular activation and reactive performance in female handball players. Despite the reduced sample size ($N = 21$), moderate-to-large interaction effects and consistent reliability metrics support the robustness of the observed adaptations.

Discussion

The present randomized controlled trial examined the effects of an eight-week SAQ plus plyometric training intervention on neuromuscular activation and reactive agility in competitive female handball players. The primary findings indicate that the experimental group demonstrated significant increases in rectus femoris and gastrocnemius EMG activity during jump-based tasks, accompanied by meaningful improvements in reactive agility performance compared with the control group. No significant changes were observed in biceps femoris activation. Reliability analyses confirmed high measurement consistency, and statistical assumptions were satisfied, supporting the interpretation that the observed changes reflect genuine training-related adaptations rather than measurement variability. Collectively, these findings suggest that an integrated SAQ-plyometric program can induce neuromuscular and perceptual-motor adaptations in female handball athletes within an eight-week training period.

Neuromuscular Adaptations of Rectus Femoris and Gastrocnemius

The increased activation of the rectus femoris and gastrocnemius muscles observed through sEMG aligns with previous evidence indicating that plyometric and agility-based training induces neural adaptations such as enhanced motor unit recruitment, synchronization, and firing frequency (Farina et al., 2014; Hammami et al., 2016). Given the functional roles of the rectus femoris as a primary knee extensor and the gastrocnemius in plantar flexion and explosive push-off, their heightened responsiveness is consistent with the vertical and reactive jump demands emphasised during the intervention. These findings corroborate biomechanical analyses highlighting the coordinated contribution of these muscles to vertical jump performance, with recent research demonstrating significant predictive roles of lower-limb muscle structure, including the lateral gastrocnemius and rectus femoris, in elite athlete jump outcomes and their involvement in force generation and energy transfer during explosive actions (Jiang et al., 2024; Pietraszewski et al., 2025). Similar neuromuscular improvements have been reported in female handball players following plyometric training, with Fathy (2018) demonstrating enhanced EMG activity alongside improved jump-shoot performance. Furthermore, previous methodological work confirms that sEMG provides a valid and reliable index of neuromuscular adaptation when standardized electrode placement and signal processing procedures are followed (Farina et al., 2014; Martinez-Valdes et al., 2023; Sul et al., 2025), strengthening confidence in the present findings. From a mechanistic perspective, these adaptations are consistent with neural adaptation theory, which posits that early training phases (approximately 6-8 weeks) predominantly induce neural changes before substantial morphological alterations. Enhanced motor unit recruitment efficiency and improved intermuscular coordination likely contributed to the observed increases in EMG amplitude during stretch-shortening cycle tasks.

Task-Specific Explanation for Biceps Femoris Findings

The absence of significant changes in biceps femoris EMG activity is likely attributable to the task-specific nature of the assessment protocol. Hamstring muscles are preferentially activated during high-speed sprinting, deceleration, and terminal swing phases of running rather than during vertical and drop jumps, which predominantly emphasize knee extensor and plantar flexor function. This interpretation is supported by evidence demonstrating clearer hamstring EMG adaptations when training and testing tasks involve sprinting or eccentric deceleration demands (Komsis et al., 2025). Consequently, the lack of sprint-specific EMG assessment in the present study may explain the null biceps femoris findings, rather than indicating an absence of training-induced hamstring adaptation.

Reactive Agility and Perceptual-Motor Adaptations

Beyond neuromuscular changes, the reduction in reactive agility time highlights the effectiveness of combining SAQ and plyometric training for enhancing perceptual-motor performance. Reactive agility differs from pre-planned change-of-direction ability in that it requires rapid perception and response to unpredictable stimuli. The present results align with findings reported in female university football players, where integrated neuromuscular training improved sprinting, agility, explosive power, and balance (Bangari et al., 2025). Previous studies consistently show that SAQ training enhances both neuromuscular readiness and decision-making capacity in team-sport athletes ((Azmi & Kusnanik, 2018; Milanović et al., 2013). The inclusion of reactive cues likely strengthened perception-action coupling, contributing to faster response times, as also demonstrated in football and tennis contexts (Formenti et al., 2021; Sinkovic et al., 2023). These findings further support the importance of appropriate training structure, progression, and intensity for optimizing agility outcomes (Jovanovic et al., 2011; Stankovic et al., 2023). From an ecological dynamic's perspective, training tasks that replicate competitive perceptual demands may enhance transferability to match performance (Formenti et al., 2021). The integration of reactive components within the SAQ drills likely facilitated improved perception-action coupling, which is critical in invasion sports such as handball.

Comparison with Previous Research

The present findings are consistent with both female-specific and mixed-sex literature. In female handball players, plyometric training has been shown to produce superior change-of-direction improvements compared with strength training alone (Falch et al., 2022), while similar explosive training benefits have been reported in female soccer players. Systematic reviews further confirm that plyometric interventions improve sprint speed, jumping, and agility across various team sports. Contemporary perspectives emphasise the need for

combined strength and agility approaches in female athlete conditioning (Santos et al., 2022). Comparable improvements have also been reported in male and mixed populations, including youth and professional soccer players Negra et al., 2017, and in untrained individuals when SAQ training is combined with cognitively demanding tasks such as small-sided games. These findings collectively support the applicability of short-term, high-intensity neuromuscular interventions for multidimensional performance enhancement across team sports.

Mechanistic and Practical Implications

The strong association between muscle power, sprint speed, and change-of-direction ability further supports the neuromuscular interpretation of these findings (Lockie et al., 2018), as does evidence of enhanced reflex responses following intermittent explosive activity. Practically, these findings are highly relevant for female handball, a sport characterized by repeated high-intensity accelerations, jumps, and rapid directional changes under pressure. Enhanced rectus femoris and gastrocnemius activation may contribute to improved jumping and sprinting actions, while improved reactive agility likely supports better anticipation and decision-making during match play, consistent with evidence from elite female soccer contexts (Emmonds et al., 2019). Previous work also confirms that SAQ and plyometric interventions effectively enhance agility in handball players.

The present study demonstrates that an eight-week SAQ plus plyometric training program significantly enhances rectus femoris and gastrocnemius activation and improves reactive agility in female handball players. These adaptations are underpinned by neural mechanisms, improved stretch-shortening cycle efficiency, and enhanced perceptual-motor coupling. By integrating electrophysiological evidence with functional performance outcomes, this study extends existing literature and supports the inclusion of combined neuromuscular and perceptual training strategies within female handball conditioning programs.

Limitations

Training sessions were conducted under the direct supervision of certified strength and conditioning specialists with experience in team-sport athlete development, ensuring correct exercise execution, appropriate load progression, and participant safety throughout the intervention. Despite the strengths of the randomized controlled design, several limitations should be acknowledged. The relatively small sample size ($N = 21$) may limit statistical power and generalizability to broader female handball populations. The absence of a long-term follow-up precludes conclusions regarding the durability of the observed neuromuscular adaptations. Additionally, electromyographic assessments were limited to jumping tasks; therefore, hamstring activation during sprint-specific phases was not evaluated, which may explain the lack of significant biceps femoris adaptations and should be addressed in future research.

Conclusions

The present study provides compelling evidence that an eight-week integrated speed, agility, and quickness (SAQ) and plyometric training program is an effective strategy for enhancing neuromuscular activation and reactive performance in competitive female handball players. The findings demonstrated that the experimental group achieved significant improvements in electromyographic activity of key lower-limb muscles, particularly the rectus femoris and gastrocnemius, during explosive jump tasks. In parallel, meaningful enhancements were observed in performance-based measures, including reactive agility, squat jump, and drop jump outcomes, whereas the control group, which continued standard handball training, showed no comparable adaptations. These results confirm that traditional sport-specific training alone may be insufficient to optimally develop the neuromuscular qualities required for high-intensity intermittent sports such as handball. From a mechanistic perspective, the observed improvements can be attributed to neural adaptations driven by repeated exposure to stretch-shortening cycle (SSC) stimuli and perceptual-motor challenges embedded within the combined training protocol. The integration of SAQ drills with plyometric exercises appears to create a synergistic training effect, simultaneously enhancing motor unit recruitment, intermuscular coordination, rate of force development, and the efficiency of the neuromuscular system.

Importantly, the increase in electromyographic activity suggests not only performance enhancement but also improved neuromuscular readiness, which is critical for executing rapid and reactive movements under competitive conditions. The practical implications of these findings are substantial for coaches, strength and conditioning specialists, and sport scientists working in female team handball. The results strongly support the inclusion of structured SAQ and plyometric training as a core component of conditioning programs, rather than as supplementary elements. Such integration can lead to meaningful improvements in explosive strength and reactive agility two performance determinants that directly influence match outcomes, including fast-break efficiency, defensive transitions, and one-on-one duels. Moreover, enhanced neuromuscular activation may contribute to improved movement efficiency and potentially reduce injury risk by promoting better joint stabilization and force absorption during dynamic actions. From a theoretical standpoint, this study contributes to the growing body of literature supporting integrated and multimodal training approaches in sports performance enhancement. It reinforces the concept that combining perceptual-cognitive and neuromuscular stimuli yields superior adaptations compared to isolated training modalities. This is particularly relevant in female athletic populations, where targeted neuromuscular development is essential to bridge performance gaps and address

sport-specific demands. The findings therefore, offer a meaningful advancement in training methodology by demonstrating how combined SAQ and plyometric interventions can serve as an evidence-based model for optimizing performance in intermittent, high-intensity sports. Despite the relatively small sample size, the presence of consistent group $\times$ time interaction effects and moderate-to-large effect sizes underscores the practical significance and reliability of the intervention. However, future research should aim to validate these findings using larger and more diverse samples, extended intervention durations, and longitudinal follow-up designs to assess the sustainability of neuromuscular adaptations. Additionally, further investigation is warranted to explore the direct transfer of these improvements to match-play performance metrics and injury prevention outcomes. The present study establishes that a combined SAQ and plyometric training approach is not only effective but also practically applicable for enhancing neuromuscular function and reactive performance in female handball players. The integration of such evidence-based training strategies has the potential to drive performance evolution in the sport by promoting more efficient, explosive, and adaptable athletes, thereby contributing to the development of modern, high-performance training paradigms.

Conflicts of Interest The authors declare that there are no conflicts of interest.

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