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Original research

Effects of an eight-week neuro-athletic training program on passing accuracy, shooting precision, flexibility, and isokinetic knee strength in male soccer players: A randomized controlled trial

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ABSTRACT

Objectives: To investigate the effects of an eight-week neuro-athletic training (NAT) program, in addition to usual football training, on passing accuracy, shooting precision, flexibility, and isokinetic knee strength in competitive male soccer players.
Design: Parallel-group, assessor-blinded randomized controlled trial with pre-test/post-test measurements.
Setting: Outdoor synthetic football pitch in Balıkesir, Türkiye, during the 2023–2024 Turkish Regional Amateur League season.
Methods: Fifty-six male soccer players (mean age 20.7 ± 1.8 years) competing in the Turkish Regional Amateur League were randomly allocated to a NAT group ($n = 26$) or a control group ($n = 30$) using computer-generated block randomization with concealed allocation (sealed opaque envelopes). Both groups continued their regular team training; the NAT group additionally performed three NAT sessions per week for eight weeks. Primary outcomes were passing accuracy and shooting precision, assessed with standardized field tests (Mor-Christian passing and shooting tests). Secondary outcomes were hamstring–lumbar flexibility (sit-and-reach test) and concentric isokinetic knee strength of the quadriceps and hamstrings at 60°/s and 180°/s, including hamstring-to-quadriceps ratios, measured with an isokinetic dynamometer and normalized to body mass (Nm/kg). All assessments were performed at baseline and after eight weeks by an assessor blinded to group allocation.
Results: Groups were comparable at baseline for age, anthropometric characteristics, training experience, and all performance measures (all $p > 0.05$). After eight weeks, the neuro-athletic training (NAT) group demonstrated significantly greater improvements than the control group in passing accuracy (9.25 ± 1.52 vs. 8.15 ± 1.69 points; $\Delta\Delta = +0.75$; $p = 0.037$; Cohen's $d = 0.57$; 95% CI [0.05, 1.45]), shooting precision (36.85 ± 8.24 vs. 29.77 ± 11.62 points; $\Delta\Delta = +6.07$; $p = 0.007$; $d = 0.75$; 95% CI [1.73, 10.41]), and sit-and-reach flexibility (30.12 ± 3.21 vs. 22.50 ± 2.12 cm; $\Delta\Delta = +7.64$; $p < 0.001$; $d = 2.15$; 95% CI [5.73, 9.55]). Isokinetic strength outcomes also favored the NAT group, with larger gains in quadriceps and hamstring peak torque at 60°/s (quadriceps $\Delta\Delta = +40.18$ N·m; $p < 0.001$; $d = 1.75$; 95% CI [28.21, 52.15]; hamstrings $\Delta\Delta = +24.39$ N·m; $p < 0.001$; $d = 1.05$; 95% CI [12.01, 36.77]) and in hamstring strength at 180°/s ($\Delta\Delta = +5.18$ N·m; $p = 0.045$; $d = 0.55$; 95% CI [0.12, 10.24]). Favorable changes were also observed in hamstring-to-quadriceps ratios at both velocities (60°/s: $\Delta\Delta = +0.08$; $p = 0.025$; 95% CI [0.01, 0.16]; 180°/s: $\Delta\Delta = +0.09$; $p = 0.003$; 95% CI [0.03, 0.14]).
Conclusions: An eight-week neuro-athletic training program, added to regular football training, produced greater improvements in passing accuracy, shooting precision, flexibility, and isokinetic knee strength than standard training alone in competitive male soccer players. These findings support the integration of structured neuro-athletic training into in-season performance programs.

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Practical implications

From an applied and clinical standpoint, the present results provide several concrete messages for coaches, strength and conditioning professionals, and sport medicine practitioners:

- Feasibility and safety in elite environments: The NAT protocol was successfully integrated into in-season microcycles as three sessions per week of approximately 35–45 min, performed on the pitch immediately before regular team training. The tools used (for example, Brock strings, pinhole glasses, vision sticks, BOSU platforms, digital visual stimuli) are relatively low-cost and portable, and no serious adverse events related to NAT were observed. This suggests that similar programs can be implemented in professional or semi-professional contexts without major disruption of existing training structures or elevated risk.
- Meaningful technical performance gains: Improvements of about 33% in passing accuracy and 28% in shooting precision represent more than just statistically significant effects; they correspond to tangible enhancements in skills directly linked to ball retention, chance creation, and goal scoring. In practical terms, this supports the integration of NAT-based drills such as visually constrained rondos, saccade-based shooting tasks, and dual-task passing exercises into warmups or technical-tactical blocks, particularly for midfielders and forwards who must repeatedly make fast, accurate decisions under pressure.
- Favorable neuromuscular adaptations and joint protection: The roughly 27% increase in quadriceps torque at 60°/s, together with clear gains in normalized hamstring strength and stable or slightly improved H:Q ratios, indicates that NAT can contribute to improved force production without creating unfavorable muscle imbalances. For practitioners, this means that sensorimotor-based drills can be used alongside conventional strength training to support explosive actions (sprinting, cutting, jumping, kicking) while remaining aligned with injury-prevention principles for the knee and hamstrings. Periodic isokinetic or field-based strength assessments may be used to monitor these adaptations over the season.
- Integration with existing training and return-to-play pathways: Because NAT targets visual, vestibular, and proprioceptive systems, it can be flexibly combined with technical, tactical, and physical conditioning work. Coaches can periodize NAT content across the week (for example, more complex dual-task drills on lower-load days; simpler visual tasks on match-eve sessions) and tailor exercises by position group. In rehabilitation and return-to-play settings, selected NAT elements (such as controlled visual-vestibular tasks on stable or progressively unstable surfaces) may be used to restore sensorimotor integration and neuromuscular control before full return to chaotic match demands, in line with contemporary views on functional joint stability and neuromuscular control.
- Guidance for future applied practice and research: Practitioners who adopt NAT should consider systematic monitoring of key indicators (passing and shooting tests, flexibility, strength or H:Q ratios, and if possible, match-derived metrics such as successful passes and shots on target) to track individual responses and refine exercise selection. At the same time, the present findings highlight the value of closer collaboration between applied staff and researchers to further explore how NAT can be optimized for different age groups, competition levels, and injury histories, building on emerging evidence around multisensory control of motor behavior and sport vision training.

Overall, the current trial suggests that a structured NAT program can be a practical and impactful addition to high-performance football environments, offering a way to link brain-centered training concepts directly to measurable improvements in on-field performance and neuromuscular robustness.

1. Introduction

Performance optimization in football necessitates a multifaceted approach extending beyond muscular strength, endurance, and technical skill, and increasingly emphasizes neurocognitive and sensory–perceptual determinants of game performance.[1–5] Crucially, it relies on finely tuned neuromuscular coordination, proprioceptive acuity, and the rapid integration of perceptual information into motor responses. The athlete's capacity to interpret dynamic visual cues (e.g., ball trajectory, opponent movement), make instantaneous postural adjustments, and react effectively to unpredictable environmental changes is critically dependent on the processing efficiency of the central nervous system (CNS).[1–4] Contemporary training science increasingly recognizes the CNS as a fundamental determinant of athletic performance,[1,3–5] with expert–novice differences in attentional control, perceptual decision-making, and cortical efficiency now regarded as key mechanisms underlying superior performance.[3,5]

Neuro-athletic training (NAT) represents an integrative methodology designed to optimize the brain–body connection by specifically targeting the visual, vestibular, and proprioceptive sensory systems. Through structured sensorimotor stimulation and neurocognitive engagement, NAT aims to enhance neuromuscular control, movement precision, and reactive capabilities.[6–8] This approach is fundamentally grounded in the principles of neuroplasticity, which demonstrate that targeted sensory input can modulate and strengthen neural pathways, thereby improving cortical regulation of both voluntary and reflexive movements.[9] Within this framework, NAT can be conceptualized as a sport-specific extension of sport vision and perceptual–cognitive training paradigms that seek to systematically challenge sensory channels and their integration with motor output in ecologically relevant contexts.[6–10]

From a performance perspective, several potential merits of NAT and related sport vision training approaches have been proposed for athletes: (i) enhancement of visuomotor reaction speed and anticipation through more efficient visual motion processing and visuomotor transformation,[3,8,10–13] (ii) improved postural control and joint stabilization via refined proprioceptive weighting and spinal–supraspinal adaptations,[5–7,11,14,15] and (iii) superior exploitation of sport-specific visual cues that may translate into higher technical efficiency and tactical decision-making under time pressure.[1,10,16–20] Recent experimental work in high-performance populations supports these merits by demonstrating that targeted visual and sensorimotor training can improve sensory station outcomes, visuomotor reaction time, and sport-specific skills in disciplines such as ice hockey, racquet sports, and shooting.[8,10–13,20]

Conversely, recent critical and systematic reviews highlight important demerits and limitations that justify cautious interpretation and further investigation. These include small and heterogeneous samples, inconsistent and sometimes poorly described training protocols, short intervention and follow-up periods, and a relative paucity of randomized, placebo-controlled designs directly linking NAT or sport vision training to objective game performance metrics.[10,21,22] Moreover, observational data indicate that many athletes perform at a high level despite suboptimal basic visual function, and that certain football tasks, such as penalty kicks, may be relatively robust even to substantial visual degradation.[23,24] Such findings suggest that the performance relevance of intensive NAT programs may be task- and context-specific and that their added value over high-quality football-specific practice remains insufficiently established, particularly in elite cohorts.[10,21–24]

Football performance places exceptional demands on real-time sensorimotor integration. Players must continuously adapt to a flux of internal (e.g., body position) and external cues (e.g., ball dynamics, spatial relationships with opponents and teammates) within a complex tactical environment.[1,16] Effective execution under these conditions requires not only musculoskeletal capacity but also highly efficient processing of afferent feedback and the generation of anticipatory neural activity to pre-empt play developments.[3,4] Optimizing these neurocognitive processes holds significant potential for enhancing critical skills such as passing accuracy, shooting precision, and tactical decision-making under competitive duress,[1,16] and makes football a particularly suitable model for evaluating the real-world impact, merits, and limitations of NAT interventions in elite team-sport athletes.

Empirical support for sensorimotor-based training comes from studies across various high-performance sports. Notably, a recent randomized controlled trial (RCT) with elite volleyball players demonstrated that an eight-week NAT intervention significantly improved serve speed, upper limb coordination, and flexibility, providing evidence for the transfer of neurocognitive adaptations to functional athletic performance.[8] Complementary electrophysiological and behavioral studies in racquet and precision sports have shown that specialized visual and visuomotor training can accelerate cortical motion processing in area MT, reduce visuomotor reaction time, and improve sport-specific outcomes such as hit distance or shooting accuracy in elite youth and adult athletes.[10–13,17,20,25] Furthermore, targeted proprioceptive and visual training programs have documented benefits in enhancing postural control, joint stabilization, and reducing reflex latency, contributing to both performance enhancement and injury risk mitigation.[6,7,14,15] Recent systematic reviews of sport vision training converge on the conclusion that such interventions can reliably improve trained visual and visuomotor tasks and, under more sport-specific and naturalistic conditions, may also yield meaningful improvements in competition-related performance indices.[10,21,22] However, these reviews also underscore that evidence remains uneven across sports, outcome domains, and study designs, with football being notably underrepresented.[10,21,22]

Despite its growing theoretical appeal and practical adoption, the application of NAT specifically within football training remains comparatively limited and underexplored in rigorous scientific literature.[26] Conventional football training regimens often prioritize physiological capacities (strength, endurance) and overt technical skills, while the underlying neural substrates of movement control and sensory processing receive less systematic attention.[26] This paucity of high-quality experimental research examining NAT in football constitutes a significant gap in evidence-based sport science practice. Previous reviews and models have explicitly called for training interventions that more effectively integrate principles of motor learning and sensory processing to enhance game-specific functionality.[25,27] Importantly, most existing studies on sport vision and NAT-like interventions involve youth or sub-elite samples, use laboratory-based visuomotor outcomes rather than football-specific technical skills, and rarely employ randomized controlled designs in elite players.[8,10–13,17,20–22] Thus, there is a clear need for well-controlled trials that determine whether an additional NAT component yields measurable gains in core football performance outcomes—such as passing accuracy and shooting precision—beyond those achieved through standard high-level training alone, and that also explore potential trade-offs such as added cognitive load or interference with existing periodization.[10,21,22]

The conceptual rationale for NAT in football is reinforced by established theoretical frameworks underscoring the critical importance of visual tracking, vestibular regulation, and proprioceptive sensitivity for sport-specific decision-making accuracy and motor execution precision.[17–19] Within this context, NAT offers a promising, multidisciplinary strategy to bridge the cognitive-perceptual and physical dimensions of training and competitive performance, but requires sport- and context-specific evidence before it can be routinely implemented as a core component of football conditioning programs.[10,17–19,21,22,26]

The present study therefore aims to experimentally evaluate the effects of an eight-week neuro-athletic training program on selected motor and skill-related performance outcomes in male football players. Primary outcome measures will assess pass accuracy and shot precision. Secondary outcomes will evaluate flexibility and isokinetic knee strength. It is hypothesized that participants receiving the neuro-athletic training intervention will demonstrate significantly greater improvements across all measured outcomes compared to a control group adhering to standard training protocols. By employing a randomized controlled design and integrating football-specific technical skills with neuromuscular performance indices, this study addresses current gaps in the literature and provides novel evidence on the potential benefits and limitations of neuro-athletic training (NAT) as an adjunct to conventional football training programs.

2. Materials and methods

2.1. Study design

This study was a parallel-group randomized controlled trial (RCT) with a pre-test/post-test design, comparing an eight-week neuro-athletic training (NAT) program plus conventional football training to conventional football training alone in male football players (allocation ratio 1:1). The trial was conducted outdoors on a synthetic pitch under standardized environmental conditions. All assessments and intervention sessions were scheduled during regular evening training hours to minimize disruption to the competitive schedule and reduce diurnal variability.

The RCT was designed, conducted, and reported in accordance with the CONSORT 2010 guidelines for parallel-group randomized trials. Ethical approval was obtained from the Balıkesir University Interventional Clinical Research Ethics Committee (Decision No: 2024/71, dated 21/05/2024). All participants provided written informed consent before enrolment, and the trial was prospectively registered at ClinicalTrials.gov (ID: NCT07092735).

Outcome measures were collected at two time points:

- Baseline (T0): within seven days before initiation of the intervention,
- Post-intervention (T1): within seven days after completion of the eight-week training period.

No additional follow-up assessments were planned.

2.2. Participants

The football players aged 18–23 years competing in the Turkish Football Federation's Regional Amateur Leagues during the 2023–2024 season were eligible for the study.

Players were recruited from three different clubs competing at the same league level. Within each club, all eligible players were informed about the study during a team meeting and invited to participate. Those who met the inclusion criteria and provided written consent underwent baseline assessments prior to randomization. Randomization was performed within clubs, not by club, so that both the NAT and control groups included players from each participating club. This individual-level allocation within clubs was chosen specifically to reduce potential “cluster” effects and to minimize systematic differences in coaching, tactical approaches, and training culture between groups.

To further limit the risk of contamination between groups, NAT sessions were delivered in small subgroups at each club on a separate area of the pitch immediately before regular training, under the supervision of the research physiotherapist. Coaches were explicitly instructed not to integrate any NAT drills into the standard training of the control players during the intervention, and players in the NAT group were asked not to practice NAT exercises informally with teammates from the control group outside supervised sessions.

Inclusion criteria were:

1. Male football players aged 18–23 years,
2. Active registration in the Turkish Regional Amateur League during the 2023–2024 season,
3. ≥5 consecutive years of systematic football training experience,

4. Regular participation in ≥4 team-based football training sessions per week,
5. No self-reported history of neuromuscular or visual impairment that could affect performance testing,
6. Ability and willingness to attend all evaluation and training sessions, and
7. Provision of written informed consent.

Exclusion criteria were:

1. History of orthopedic or neurological surgery within the past year,
2. Acute or chronic musculoskeletal injury at baseline that limited full participation in training or testing,
3. Uncorrected visual impairment,
4. Use of medications known to influence neuromuscular function, balance, or attention,
5. Previous or concurrent participation in structured neuromuscular, neuro-athletic, or sport vision training programs,
6. Irregular training attendance (missing >20% of scheduled football training sessions in the preceding three months),
7. Diagnosed vestibular, neurological, or cardiopulmonary conditions, or other medical conditions judged by the team physician to compromise safe participation, and
8. Inability to comply with study instructions.

A total of 60 players from the three clubs met the eligibility criteria and were enrolled. After randomization, 30 players were allocated to the NAT group and 30 to the control group. During the trial, 2 players in the NAT group sustained serious musculoskeletal injuries unrelated to the intervention that prevented further participation, and 2 players in the NAT group did not meet the predefined adherence threshold (attendance <80% of NAT sessions and/or team training) and did not attend post-intervention testing. Thus, 26 players in the NAT group and all 30 players in the control group completed the trial, resulting in 56 players included in the primary analyses.

To evaluate potential attrition bias, baseline characteristics (age, anthropometrics, playing experience, and all primary and secondary outcome measures) of the four players who withdrew were compared with those of the players who completed the study. No statistically significant differences were found (all $p > 0.05$), suggesting that dropouts were unlikely to bias the results.

2.3. Sample size justification and power analysis

An a priori power analysis was conducted using G*Power software (version 3.1.9.7)[10] to determine the required sample size for detecting between-group differences in the primary outcome (change in Mor-Christian Passing Accuracy score). Based on pilot data from 20 players (10 per group), an effect size of Cohen's $d = 0.65$ was estimated. For a two-tailed independent sample t-test with $\alpha = 0.05$ and power $(1 - \beta) = 0.80$, the required total sample size was $n = 52$ (26 participants per group).

To account for potential dropouts and non-compliance, we planned to oversample by approximately 15%, aiming to recruit 60 players. This strategy was intended to ensure that at least the calculated minimum of 52 participants, and ideally 56, would complete both pre- and post-intervention measurements while maintaining the planned 1:1 allocation ratio. Ultimately, 60 players were enrolled and randomized, and 56 provided complete data for the primary analysis.

2.4. Randomization procedure and blinding

Randomization was conducted at the individual level, with stratification by club to ensure that both intervention and control groups included players from each of the three participating clubs. Within each club, a computer-generated randomization list was created using Microsoft Excel, employing block randomization with randomly permuted blocks of four and six to maintain balanced group sizes during recruitment (allocation ratio 1:1).

Allocation concealment was ensured by using sequentially numbered, opaque, sealed envelopes prepared by a research team member who had no role in recruitment, baseline testing, or intervention delivery. After baseline (T0) assessments were completed, the enrolling researcher opened the next envelope in sequence to reveal the participant's assigned group.

Because of the nature of the intervention, participants and the physiotherapists delivering the NAT could not be blinded. However, two levels of blinding were implemented:

- The physiotherapist who conducted all performance assessments at T0 and T1 was blinded to group allocation and instructed not to ask about the type of training the players were receiving.
- The statistician who performed data cleaning and analyses was blinded to group allocation, with the groups coded as “Group A” and “Group B” until all primary analyses were completed.

No independent assessor was involved in delivering the intervention; instead, treatment fidelity was monitored by standardized written protocols, session logs, and progression checklists.

2.5. Performance measurements

All performance assessments were conducted at T0 and T1 on the same synthetic pitch used for regular training. To reduce day-to-day variability, testing sessions for each player were scheduled at approximately the same time of day (±1 h) at both time points. Participants were instructed to refrain from strenuous exercise and caffeine intake for at least 24 h before each testing session.

The following outcome measures were used:

- Primary outcomes
  - o Mor-Christian Passing Accuracy Test
  - o Mor-Christian Shooting Accuracy Test

- Secondary outcomes
  - o Sit-and-reach test (flexibility)
  - o Isokinetic knee strength (quadriceps and hamstring peak torque at 60°/s and 180°/s; H:Q ratio)

All tests were administered by the same experienced physiotherapist who was blinded to group allocation and followed standardized instructions and familiarization procedures. The selection of tests was based on their established use in football-specific performance testing and documented validity and reliability: the Mor-Christian tests for passing and shooting have demonstrated good construct validity and test-retest reliability in competitive players[21]; the sit-and-reach test shows excellent reliability for hamstring flexibility in athletes[22]; and isokinetic testing of knee extensors and flexors yields highly reliable indices of neuromuscular performance (ICC 0.87–0.97).[11] Detailed test protocols are described in the previous section (Performance measurements) and were applied identically at T0 and T1.

2.6. Mor-Christian Passing Accuracy Test

This test evaluates short passing precision, control, and targeting accuracy under game-like constraints. Players completed 12 passes from three distances (7, 8.5, and 10 m) toward a 0.75 m × 1.5 m mini goal. Each pass targeting the central zone received maximum points. The final score, ranging up to 120, reflects the player's technical precision. This test demonstrates high discriminant validity for technical proficiency in footballers, with established test-retest reliability (ICC = 0.88; 95% CI: 0.82–0.93) as documented.[21]

2.7. Mor-Christian Shooting Accuracy Test

This assessment involves 16 shots from 14.5 m toward four circular targets (45 cm diameter) fixed on a goal wall. Each shot was scored based on target difficulty, with total scores reaching a maximum of 80 points. The test's construct validity for finishing accuracy is well-established, showing ICC = 0.85 (95% CI: 0.78–0.90) in competitive populations.[21]

2.8. Sit-and-reach test

To assess flexibility of the hamstrings and lower back, players performed the sit-and-reach test using a standard box. They were instructed to reach forward as far as possible while seated with knees extended, and the best of three trials was recorded. The sit-and-reach test is a valid tool for estimating hamstring extensibility with excellent reliability in athletes (ICC = 0.91–0.93).[22]

2.9. Isokinetic strength test

Concentric peak torque of the quadriceps and hamstrings was measured using the ISOMED 2000 dynamometer at angular velocities of 60°/s and 180°/s in concentric–concentric mode. For each test, athletes performed five maximal repetitions at 60°/s and fifteen maximal repetitions at 180°/s following a standardized warmup and familiarization protocol. The highest peak torque values (Nm) were recorded, and peak torque was normalized to body mass (Nm/kg). Additionally, the hamstring-to-quadriceps (H:Q) ratio was calculated for each leg to assess muscular balance (ICC = 0.87–0.97).[11]

2.10. Neuro-athletic training protocol

Both the NAT and control groups continued their conventional in-season team training throughout the eight-week intervention. This typically comprised four on-field sessions per week, including technical drills, tactical instruction, aerobic and anaerobic conditioning, and small-sided games. Providing the same conventional training to both groups was considered essential to preserve ecological validity and to specifically isolate the additional effect of the NAT program, rather than replacing usual practice with an experimentally artificial regimen.

For players in the NAT group, the NAT sessions were integrated into the weekly schedule as an additional component performed immediately before the first three regular training sessions of each week (e.g., Monday, Wednesday, Friday). NAT sessions were conducted on a separate area of the pitch at each club and supervised by the research physiotherapist. Each NAT session lasted approximately 35–45 min and followed a standardized structure, while allowing for progressive increases in difficulty over time:

1. Dynamic football-specific warmup (≈8 min)
2. Visual recovery and preparation (palming, eye massage; 5–7 min)
3. Passing development stations with visual and proprioceptive challenges (≈15–18 min)
4. Shooting development stations with saccadic and pursuit-based visual drills (≈15–18 min)

The content of the passing and shooting development stations (Vision Stick Paired Passing, Pinhole Rondo, Eye Patch Rondo, Reaction Pass, Letter Saccade Shooting, Anti-Saccade Shooting, Smart Optometry Shooting, Brock String Shooting, Star Chart Tracking) has been described in detail in the main text.

Progression across the eight weeks involved:

- Increasing task complexity (e.g., adding decision-making and dual-task components such as mental arithmetic or color naming),
- Increasing ball speed and defender pressure,
- Reducing stimulus exposure time or increasing the number of stimuli per series,
- Increasing visual constraints (more frequent use of pinhole glasses or monocular occlusion),
- Varying distances and angles of passing and shooting.

Table 1 provides a week-by-week summary of the NAT program, including the primary focus (e.g., oculomotor control, depth perception, peripheral awareness) and the main drills emphasized in that week. However, because the full session-by-session structure (3 sessions per week × 8 weeks) is too detailed for the main manuscript, a comprehensive session plan, including the exact sequence of exercises, sets, repetitions, and work–rest intervals for each of the 24 NAT sessions, is provided in Supplementary File 1. This supplementary material includes schematic diagrams and/or photographs for each key drill to facilitate replication in future studies.

The control group did not receive any NAT or sport vision training but maintained their standard club training. Both groups were asked to avoid starting any new neuromuscular or visual training programs during the study period.

2.10.1. Compliance, adherence, and adverse events

Attendance at each NAT session and each team training session was recorded. Adherence to the NAT program was defined a priori as attending ≥80% of NAT sessions; adherence to conventional training was defined as attending ≥80% of team sessions during the intervention period. The treatment compliance rate (proportion of planned sessions attended) and the overall adherence rate are reported in the Results section. Two musculoskeletal injuries occurred in the NAT group, leading to withdrawal; no serious adverse events directly attributable to the NAT drills (e.g., visual discomfort, dizziness) were observed, although transient mild eyestrain and fatigue were occasionally reported and resolved spontaneously.

The specific content of each exercise is described below:

A- Passing Development Stations

Players performed progressive passing drills designed to integrate visual–perceptual challenges. Vision Stick Paired Passing required players to use a beaded stick held at nose level to promote binocular coordination (convergence–divergence) while exchanging passes, supporting accuracy in long balls (Fig. 1a). In Pinhole Rondo, attackers wore pinhole glasses that limited peripheral vision during small-sided games, enhancing reliance on central vision and anticipation under pressure (Fig. 1b). Eye Patch Rondo involved covering one eye to simulate obstructed fields of view, improving monocular spatial judgment and body positioning during possession (Fig. 1d). Finally, in Reaction Pass, players redirected the ball instantly in response to coach-provided color cues while evading defenders, sharpening split-second decision-making and peripheral processing applicable to breaking presses or switching play (Fig. 1c).

B- Shooting Development Stations

Players engaged in advanced shooting drills designed to integrate visual–perceptual demands with technical execution. *Letter Saccade Shooting* required athletes to alternate their gaze between letter cards to elicit rapid saccadic eye movements before immediately striking served balls, thereby coupling accelerated visual scanning with finishing precision—an ability essential for identifying shooting lanes in congested penalty areas (Fig. 2d). In *Anti-Saccade Shooting*, players

Table 1
Eight-week NAT progression overview.

Week	Goals	NAT exercises	Training features	Duration
1	Foundational visual control and convergence	Palming, Vision Stick (Convergence–Divergence)	Visual focus, low cognitive load	3 sets × 1 min
2	Depth perception and central visual processing	Brock String Drill, Pinhole Rondo Passing	Central fixation, spatial awareness	3 sets × 1 min
3	Monocular training and peripheral awareness	Eye Patch Rondo, Letter Identification While Moving	Monocular dominance, balance integration	3 sets × 1.5 min
4	Dual-task coordination and reaction-based movement	Reactive Color Passing, Number Recognition with Direction Change	Decision-making under cognitive load	3–4 sets × 2 min
5	Executive function and ocular-motor inhibition	Anti-Saccade Drill, Delayed Response Shooting	Inhibitory control, executive motor planning	3 sets × 2 min
6	Postural-visual integration on unstable surfaces	Smart Optometry Tracking, BOSU Passing with Visual Fixation	Core stability, visual-proprioceptive synchronization	3 sets × 2 min
7	Multisensory conflict resolution	Light Cue Reaction, Auditory Mismatch with Reactive Dribbling	Audio-visual integration, response timing under pressure	4–5 sets × 2.5 min
8	Integrated neuromotor control under fatigue	Mixed-Stimulus Fatigue Circuits (Reaction + Sprint + Skill Drills)	Multitasking under fatigue, stress tolerance	5 sets × 3 min

intentionally directed their gaze counter to presented visual cues prior to receiving passes, cultivating inhibitory control to suppress deceptive defensive movements and exploit shooting opportunities under conditions of perceptual conflict (Fig. 2e). *Smart Optometry Shooting* involved continuous tracking of moving on-screen stimuli while simultaneously responding to color-based commands, fostering dynamic attentional shifts and divided-focus processing, with immediate shooting actions

Fig. 1. Passing development drills with visual–perceptual constraints: (a) *Vision Stick Paired Passing* using a beaded stick to enhance binocular coordination during exchanges; (b) *Pinhole Rondo* with restricted peripheral vision to promote central vision focus and anticipation; (c) *Reaction Pass* requiring instant redirection based on coach-provided color cues; and (d) *Eye Patch Rondo* simulating obstructed fields of view to improve monocular spatial judgment and positioning.

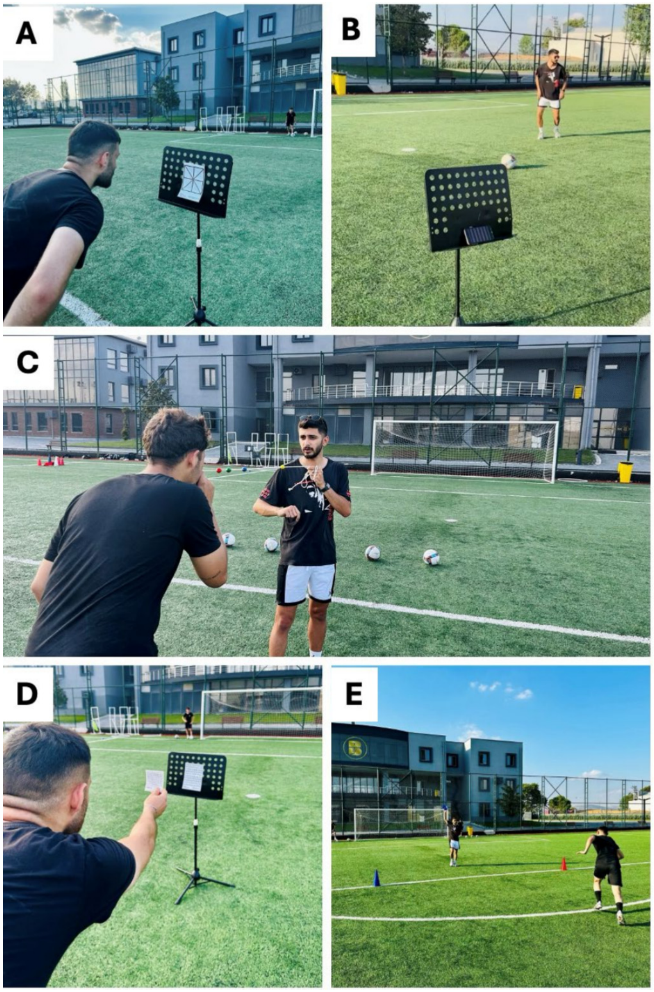

Fig. 2. Shooting development drills with integrated visual–perceptual constraints: (a) *Star Chart Tracking*—ocular pursuit training with subsequent pressured volleys; (b) *Smart Optometry Shooting*—dynamic target tracking with immediate finishing; (c) *Brock String Shooting*—binocular fusion and depth-perception training for long-range accuracy; (d) *Letter Saccade Shooting*—rapid saccadic shifts linked to finishing precision; and (e) *Anti-Saccade Shooting*—inhibitory control drills to counter defensive deception.

simulating in-game scenarios of defender monitoring and rebound positioning (Fig. 2b). *Brock String Shooting* emphasized alignment of beads to achieve binocular fusion through the formation of a clear visual “X,” refining depth perception and ensuring accurate distance judgment for executing long-range power shots (Fig. 2c). Finally, *Star Chart Tracking* tasked players with smoothly tracing star-shaped diagonal trajectories while maintaining head fixation, reinforcing ocular pursuit stability, before transitioning into pressured shooting sequences to replicate the demands of tracking crosses or reacting to deflections prior to volley execution (Fig. 2a).

2.11. Statistical analysis

All statistical analyses were performed using IBM SPSS Statistics for Windows, version 26.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics are presented as mean ± standard deviation for continuous variables and as frequencies and percentages for categorical variables. The normality of continuous variables was assessed using the Shapiro–Wilk test in combination with visual inspection of histograms and Q–Q plots.

Baseline comparability between the neuro-athletic training (NAT) and control groups for demographic characteristics (age, height, body mass, training experience, playing position) and all outcome variables (passing accuracy, shooting accuracy, sit-and-reach flexibility, and isokinetic strength parameters) was evaluated descriptively and confirmed statistically within the mixed-model framework. No significant Group effects at baseline were identified (all $p > 0.05$), indicating successful randomization. As baseline equivalence was achieved, no covariate adjustment was applied in subsequent analyses.

Primary and secondary intervention effects were examined using a 2 (Group: NAT vs. Control) × 2 (Time: Pre vs. Post) mixed-design analysis of variance (ANOVA) for each outcome variable. The primary effect of interest was the Group × Time interaction, which reflects differential changes over time between the intervention and control groups. For all outcomes, F statistics, corresponding p values, and partial eta-squared (η^2) values were reported as measures of effect size.

To facilitate clinical interpretation, between-group differences in change scores ($\Delta\Delta$) were calculated from model-estimated marginal means, and effect sizes were expressed as Cohen's d. Ninety-five percent confidence intervals (95% CI) for between-group differences in change scores were also reported. Statistical significance was set a priori at $p < 0.05$ for all analyses.

Isokinetic strength variables were analyzed separately for each angular velocity (60°/s and 180°/s) and for absolute (N·m) and body mass–normalized (N·m/kg) torque values. Hamstring-to-quadriceps (H:Q) ratios were analyzed using the same mixed-model approach.

Intention-to-treat (ITT) considerations were addressed descriptively. Of the 60 randomized participants, 56 (93.3%) completed both baseline (T0) and post-intervention (T1) assessments. Four participants (6.7%) withdrew before post-intervention testing (two due to injury and two due to non-compliance). As post-intervention outcome data were unavailable for these participants, formal ITT analyses using multiple imputation were not feasible. Therefore, the primary analyses were conducted on a per-protocol basis.

As a sensitivity check, a conservative scenario assuming no change from baseline for missing cases was explored. This approach did not alter the direction or statistical significance of the main Group × Time effects, supporting the robustness of the reported findings.

3. Results

3.1. Participant characteristics

The demographic and training background characteristics of the participants are presented in this section. The NAT and control groups were similar at baseline with no statistically significant differences in age, height, body mass, or football experience ($p > 0.05$) (Table 2).

3.2. Baseline group comparisons

At baseline, no statistically significant differences were observed between the neuro-athletic training (NAT) and control groups across any of the assessed variables, including passing accuracy, shooting performance, flexibility, and all isokinetic strength measures (all $p > 0.05$). Specifically, baseline comparisons for passing accuracy ($p = 0.458$), shooting performance ($p = 0.699$), sit-and-reach flexibility ($p = 0.987$), and isokinetic quadriceps and hamstring strength outcomes (all $p > 0.17$) confirmed group equivalence. These findings, illustrated in Figs. 3 and 4, provide a robust baseline for attributing subsequent changes to the intervention effects.

3.3. Passing performance (PAS score)

At pre-intervention, passing accuracy did not differ between groups (NAT: 6.96 ± 1.80 vs. control: 6.61 ± 1.70 points; $t(54) = -0.75$, $p = 0.458$). Following the intervention, the NAT group demonstrated significantly greater improvement than the control group (9.25 ± 1.52 vs. 8.15 ± 1.69 points), corresponding to a significant between-group difference ($t(54) = -2.71$, $p = 0.009$; Cohen's $d = 0.73$; 95% CI [0.28, 1.92]). Analysis of change scores confirmed a significant Group × Time interaction ($\Delta\Delta = +0.75$ points; $t(54) = 2.14$, $p = 0.037$; $d = 0.57$; 95% CI [0.05, 1.45]), as summarized in Table 3 and depicted in Fig. 4.

3.4. Shooting performance (shot test)

Baseline shooting scores were comparable between groups (NAT: 28.73 ± 10.88 vs. control: 27.72 ± 8.78 points; $p = 0.699$). Post-intervention, shooting performance increased significantly more in the NAT group (36.85 ± 8.24 points) than in the control group (29.77 ± 11.62 points), yielding a significant between-group difference ($t(54) = -2.65$, $p = 0.011$; $d = 0.71$; 95% CI [1.71, 12.45]). Change-score analysis further confirmed a significant Group × Time interaction ($\Delta\Delta = +6.07$ points; $t(54) = 2.80$, $p = 0.007$; $d = 0.75$; 95% CI [1.73, 10.41]) (Fig. 4, Table 3).

3.5. Flexibility (sit-and-reach test)

No baseline difference in flexibility was observed between groups (NAT: 21.16 ± 6.27 cm vs. control: 21.18 ± 3.13 cm; $p = 0.987$). After the intervention, the NAT group exhibited substantially greater flexibility (30.12 ± 3.21 cm) compared with the control group (22.50 ± 2.12 cm), representing a highly significant between-group difference ($t(54) = -10.85$, $p < 0.001$; $d = 2.91$; 95% CI [6.19, 9.05]). The Group × Time interaction was also significant ($\Delta\Delta = +7.64$ cm; $t(54) = 8.03$, $p < 0.001$; $d = 2.15$; 95% CI [5.73, 9.55]) (Fig. 4, Table 3).

3.6. Isokinetic strength outcomes

3.6.1. 60°/s angular velocity

For quadriceps strength at 60°/s, the NAT group showed a substantial post-intervention increase of +44.79 N·m, compared to only +4.61 N·m in the control group. This resulted in a significant between-group difference ($\Delta\Delta = +40.18$ N·m, $t(54) = 6.52$, $p <$

Table 2
Baseline characteristics of NAT and control groups.

Characteristic	NAT group (n = 26)	Control group (n = 30)	p-Value
Age (years)	20.4 ± 1.9	20.9 ± 1.7	0.312
Height (cm)	179.6 ± 6.2	181.1 ± 5.8	0.287
Body mass (kg)	74.3 ± 5.6	75.8 ± 6.1	0.334
Training experience (y)	7.2 ± 1.4	7.5 ± 1.6	0.421
Weekly training (h)	12.4 ± 1.8	11.9 ± 2.1	0.339

NAT = neuro-athletic training; n = sample size; y = years; h = hours; cm = centimeters; kg = kilograms; p-value = probability value (significance threshold = 0.05).

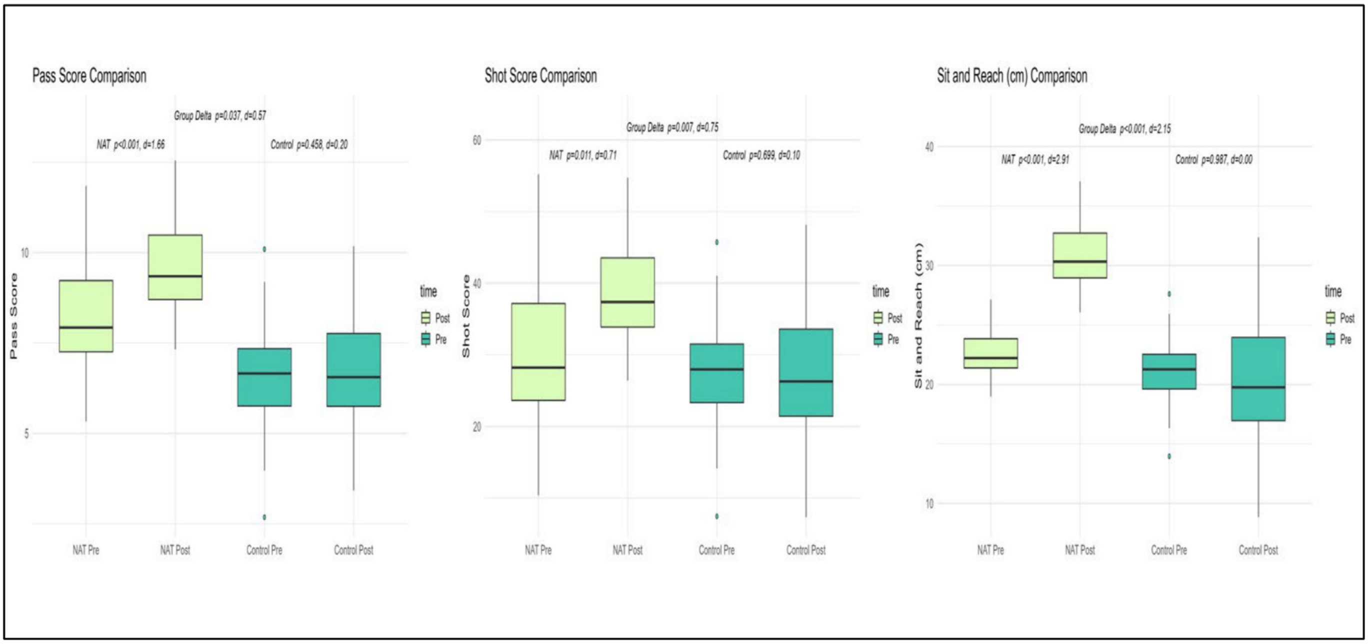

Fig. 3. Comparison of performance metrics across groups and time points. (A) Pass Score Comparison, (B) Shot Score Comparison, and (C) Sit and Reach (cm) Comparison. Data are presented as mean ± SD. NAT = neuro-athletic training group; Control = control group; Pre = pre-intervention; Post = post-intervention.

0.001, d = 1.75). Final torque values further supported this outcome (NAT: 212.40 ± 22.15 N·m vs. control: 170.21 ± 25.42 N·m; $t(54) = -6.78$, $p < 0.001$). A similar trend was observed in hamstring strength, with the NAT group gaining +29.45 N·m compared to +5.06 N·m in the control group ($\Delta\Delta = +24.39$ N·m, $t(54) = 3.92$, $p < 0.001$, $d = 1.05$).

In terms of body mass–normalized quadriceps torque (N·m/kg), the NAT group demonstrated a large and significant increase (+1.05 N·m/kg vs. +0.11 N·m/kg), corresponding to a ΔΔ of +0.94 ($t(54) = 9.12$, $p < 0.001$, $d = 2.44$). Comparable improvements were observed for normalized hamstring torque at 60°/s, again favoring the NAT group (Fig. 4 and Table 3).

3.6.2. 180°/s angular velocity

At 180°/s, hamstring peak torque increased significantly more in the NAT group than in the control group, yielding a modest but significant Group × Time interaction ($\Delta\Delta = +5.18$ N·m; $t(54) = 2.05$, $p = 0.045$; $d = 0.55$; 95% CI [0.12, 10.24]). Normalized hamstring torque showed a larger effect ($\Delta\Delta = +0.32$ N·m/kg; $t(54) = 7.12$, $p < 0.001$; $d = 1.91$; 95% CI [0.23, 0.41]) (Fig. 4, Table 3).

3.7. Hamstring-to-quadriceps (H:Q) ratio

At 60°/s, the NAT group maintained the H:Q ratio, whereas the control group demonstrated a decline, resulting in a significant Group × Time interaction ($\Delta\Delta = +0.08$; $p = 0.025$; $d = 0.60$; 95% CI [0.01, 0.16]). Similarly, at 180°/s, the NAT group exhibited relative preservation of the H:Q ratio compared with a marked reduction in the control group ($\Delta\Delta = +0.09$; $p = 0.003$; $d = 0.82$; 95% CI [0.03, 0.14]) (Fig. 4, Table 3).

3.8. Mixed ANOVA summary (Group × Time interaction)

To provide an ANOVA-style overview of the intervention effects, a 2 (Group: NAT vs. Control) × 2 (Time: Pre vs. Post) mixed design was evaluated for each primary and secondary outcome using change scores. For df = 1,54, the F statistics correspond to the squared t values for the between-group differences in change scores, and partial η^2 values quantify the magnitude of the Group × Time interaction. As summarized in Table 3, significant Group × Time interactions were found for all primary outcomes (passing and shooting accuracy) and key secondary outcomes (flexibility and isokinetic strength variables), with effect sizes ranging from medium to very large (partial $\eta^2 = 0.07$–0.61).

4. Discussion

This randomized controlled trial (RCT) demonstrated that an eight-week neuro-athletic training (NAT) program, implemented alongside regular in-season training, was associated with significantly greater improvements in passing accuracy, shooting precision, flexibility, and body mass–normalized isokinetic knee strength in male football players, compared with standard training alone. Importantly, hamstring-to-quadriceps (H:Q) ratios were maintained or slightly improved in the NAT group, whereas they tended to deteriorate in the control group. In this section, we compare our findings with previous studies, discuss potential mechanisms, critically appraise the strengths and limitations of the trial (including adverse events and field constraints), and outline clinical implications.

4.1. Passing accuracy

In the NAT group, passing scores improved from 6.96 ± 1.80 to 9.25 ± 1.52, corresponding to an absolute gain of 2.29 points and a relative increase of about 32.9%. In contrast, the control group improved from 6.61 ± 1.70 to 8.15 ± 1.69 (absolute gain 1.54 points; relative increase about 23.3%). The between-group post-intervention difference was significant ($p = 0.009$, $d = 0.73$), and the between-group change (ΔΔ) favored NAT by 0.75 points ($p = 0.037$, $d = 0.57$).

These findings are consistent with literature indicating that visual search strategy, selective attention, and perceptual expertise are central to high-level football performance.[1,16,18,28,29] More highly trained football players typically deploy more efficient gaze patterns and extract critical tactical information from fewer, more informative fixations.[1,16,18,28,30,31] Recent critical and systematic reviews of sport vision and perceptual–cognitive training further emphasize that visual abilities such as dynamic visual acuity, depth perception,

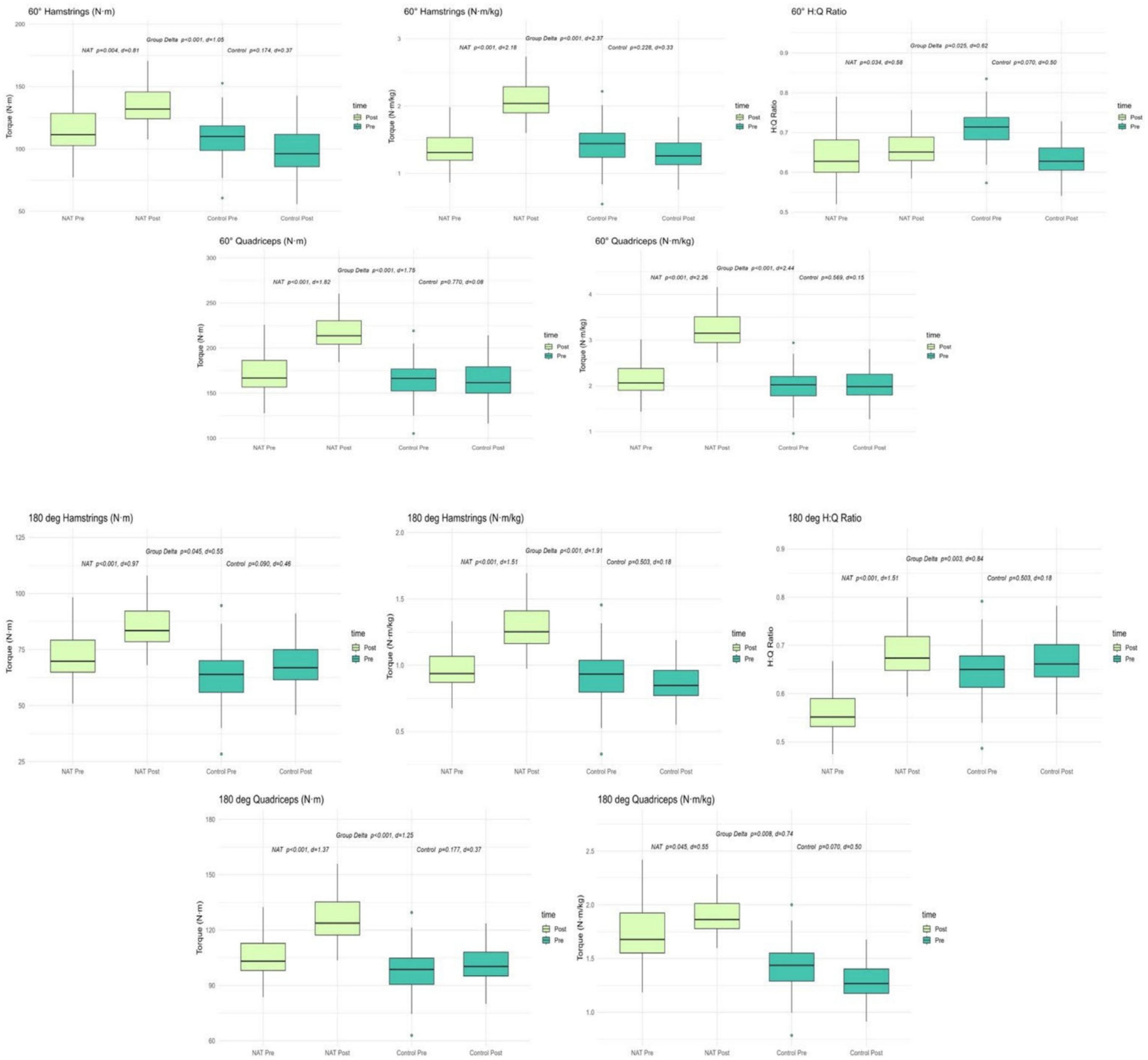

Fig. 4. Comparison of performance metrics across groups and time points: 60° Hamstrings (N/m), 60° Hamstring Torque, 60° H:Q Ratio, 60° Quadriceps (N/m), 60° Quadriceps Torque, 180° Hamstrings (N/m), 180° Hamstring Torque, 180° H:Q Ratio, 180° Quadriceps (N/m), and 180° Quadriceps Torque. Data are presented as mean ± SD. NAT = neuro-athletic training group; Control = control group; Pre = pre-intervention; Post = post-intervention.

Table 3
Mixed Group × Time ANOVA summary for primary and secondary outcomes.

Outcome (Group × Time)	df (effect, error)	F value	p value	Partial η^2	Cohen's d (between-group ΔΔ)	95% CI (ΔΔ)
Pass score (Mor-Christian Passing Test)	1,54	4.58	0.037	0.078	0.57	[0.05, 1.45]
Shot score (Mor-Christian Shooting Test)	1,54	7.84	0.007	0.127	0.75	[1.73, 10.41]
Sit-and-reach (cm)	1,54	64.48	<0.001	0.544	2.15	[5.73, 9.55]
60° quadriceps torque (N·m)	1,54	42.51	<0.001	0.440	1.75	[28.21, 52.15]
60° hamstring torque (N·m)	1,54	15.37	<0.001	0.222	1.05	[12.01, 36.77]
60° quadriceps torque (N·m/kg)	1, 54	83.17	<0.001	0.606	2.44	[0.73, 1.14]
180° hamstring torque (N·m)	1,54	4.20	0.045	0.072	0.55	[0.12, 10.24]
180° hamstring torque (N·m/kg)	1,54	50.69	<0.001	0.484	1.91	[0.23, 0.41]
60° H:Q ratio	1,54	5.10	0.025	0.086	0.60	[0.01, 0.16]
180° H:Q ratio	1,54	9.20	0.003	0.145	0.82	[0.03, 0.14]

Group × Time interaction tested via independent-sample t-tests on change scores (NAT vs. Control). For df = 1,54, F = t^2; partial η^2 = F / (F + df). NAT = neuro-athletic training group; H:Q = hamstring-to-quadriceps ratio; N·m = Newton-meter; N·m/kg = Newton-meter per kilogram; ANOVA = analysis of variance; ΔΔ = between-group difference in change scores; df = degrees of freedom; SD = standard deviation.

and processing speed are meaningfully associated with on-field decision-making and technical performance, while also highlighting considerable heterogeneity in intervention design and outcome measures.[10,21,22,29,32,33] Within this context, sport vision and oculomotor training studies report improvements in dynamic visual acuity, gaze stability, and balance—often on the order of 15–30%—after 4–8 weeks of training.[20,23,24,29,32,33] For example, ocular-motor exercises have enhanced dynamic visual acuity and stability limits in female basketball and volleyball players,[23,24] and visual-stimulus training has produced double-digit percentage improvements in reaction time and cognitive performance in young soccer players.[20]

The roughly 33% improvement in passing accuracy observed here in footballers is therefore comparable to, or slightly larger than, the visual and perceptual gains reported in these sport vision trials.[20,23,24,29,32,33] Our NAT drills (Vision Stick Paired Passing, Pinhole Rondo, Eye Patch Rondo, Reaction Pass) directly targeted binocular coordination, central and peripheral vision, and rapid transformation of visual information into passing actions in ecologically valid situations. This design aligns with evidence that motor training induces experience-specific plasticity in cortico-spinal circuits[3,5,9] and with models emphasizing multisensory control of motor behavior in sport.[19,29,33,34] Taken together with observations that athletes with superior visual profiles tend to perform better in invasion games,[28,29,35,36] these data suggest that embedding structured visual–motor challenges into football passing drills can generate substantial, practically meaningful performance gains beyond those attained by standard training alone.

4.2. Shooting precision

Shooting performance also improved more in the NAT group, from 28.73 ± 10.88 to 36.85 ± 8.24 (absolute gain 8.12 points; relative increase about 28.3%), than in the control group, which changed from 27.72 ± 8.78 to 29.77 ± 11.62 (absolute gain 2.05 points; relative increase about 7.4%). The between-group difference at post-test favored NAT ($p = 0.011$, $d = 0.71$), and the between-group change ($\Delta\Delta$) in shot score was 6.07 points ($p = 0.007$, $d = 0.75$).

These effects dovetail with findings that specific visual and executive functions—such as near–far quickness, selective attention, and cognitive flexibility—are linked to decision-making and finishing quality in football.[28,29] Eye-movement studies report that expert players display faster and more efficient saccades, which supports rapid target identification and alignment in goal-oriented tasks.[30,31,37] Work in professional football and other invasion sports shows that visual function profiles (e.g., contrast sensitivity, stereopsis, motion perception) distinguish elite or near-elite athletes, and that even partial visual impairment can measurably affect penalty-kick and shooting performance.[29,35,36,38] Complementary evidence from precision sports indicates that dedicated sport vision training can improve visuomotor skills and shooting accuracy in elite skeet shooters,[39] reinforcing the notion that refining visual processing can translate into more accurate and consistent hitting or finishing actions.

In the current trial, shooting stations (Letter Saccade Shooting, Anti-Saccade Shooting, Brock String Shooting, Smart Optometry Shooting, Star Chart Tracking) were designed to couple saccadic speed, inhibitory control, binocular fusion, and gaze stabilization with football-specific finishing actions. This structure is congruent with work in racquet and precision sports showing that faster visual-motion processing speed and visuomotor reaction times distinguish high-performing athletes.[12,13,17,40,41] The approximately 28% improvement in shooting precision in the NAT group, compared with about 7% in controls, is in line with the magnitude of changes reported for visual-motor and sport vision interventions,[10,21,22,29,32,33,39–41] but here observed in a key football skill with direct impact on scoring probability and chance conversion.[12,16,20,23,28,31,32,36,38,42]

4.3. Flexibility

Sit-and-reach performance in the NAT group increased from 21.16 ± 6.27 cm to 30.12 ± 3.21 cm, reflecting an absolute gain of 8.96 cm and a relative improvement of about 42.3%. The control group improved only from 21.18 ± 3.13 cm to 22.50 ± 2.12 cm (absolute gain 1.32 cm; relative increase about 6.2%). The between-group difference at post-test was highly significant ($p < 0.001$, $d = 2.91$), and the between-group change ($\Delta\Delta$) was 7.64 cm ($p < 0.001$, $d = 2.15$).

These large flexibility gains are in line with our earlier NAT trial in elite volleyball players, where a similar neuro-athletic framework led to clear improvements in flexibility and upper-limb performance.[12] More broadly, balance and sensorimotor training has been associated with adaptations in postural function and neuromuscular control.[3,5–7,14,15] The sit-and-reach test is a well-established, valid indicator of hamstring and lumbar extensibility[22]; an improvement of approximately 40% in an already trained population suggests substantial modification of functional range of motion.

Mechanistically, several NAT components likely contributed. Tasks performed on unstable surfaces (for example, BOSU Passing with visual fixation) and visually demanding postural exercises required integrated processing of visual, vestibular, and proprioceptive inputs. This is consistent with evidence that the vestibular and sensorimotor systems play key roles in skeletal alignment and dynamic postural regulation.[5–7,14,15,19,43–45] Recent data show that combining gaze-stabilization exercises with balance training can improve static and dynamic balance in healthy adults,[43] and that vestibular dysfunction in athletes is associated with malalignment and compromised postural control.[44,45] Repeated exposure to multisensory conflict and visually constrained stability tasks, as implemented in the present NAT protocol, may therefore promote more economical alignment, reduce excessive co-contraction in the posterior chain, and increase tolerance to stretch in hamstrings and lumbar structures. Together with dynamic warmup and visual relaxation techniques, this multisensory challenge profile provides a plausible link between the observed flexibility improvement in the NAT group and previously reported adaptations in postural function and sensorimotor control.[3,5–7,12,14,15,19,22,43–45]

4.4. Isokinetic knee strength

For body mass–normalized torque at 60°/s, quadriceps strength in the NAT group increased by 1.05 N·m/kg, compared with 0.11 N·m/kg in the control group, yielding a $\Delta\Delta$ of 0.94 N·m/kg ($p < 0.001$, $d = 2.44$). Normalized hamstring torque at 60°/s showed a similar pattern, again favoring NAT. At 180°/s, normalized hamstring torque increased by 0.35 N·m/kg in the NAT group versus 0.03 N·m/kg in controls, with a $\Delta\Delta$ of 0.32 N·m/kg ($p < 0.001$, $d = 1.91$).

For absolute torque, quadriceps strength at 60°/s in the NAT group increased from 167.61 N·m to 212.40 N·m, an absolute gain of 44.79 N·m and a relative increase of about 26.7%. In contrast, the control group improved from 165.60 N·m to 170.21 N·m (gain 4.61 N·m; relative increase about 2.8%). Hamstring torque at 60°/s increased by 29.45 N·m in the NAT group versus 5.06 N·m in controls, representing roughly a sixfold difference in absolute gain. At 180°/s, hamstring torque changes were also greater in the NAT group ($\Delta\Delta = 5.18$ N·m, $p = 0.045$, $d = 0.55$).

H:Q ratios evolved in a favorable direction in the NAT group. At 60°/s, the ratio was essentially preserved (change about +0.01), while the control group showed a decline (about −0.08; $\Delta\Delta = 0.08$, $p = 0.025$). At 180°/s, the NAT group again showed minimal change (about −0.005), whereas the control group declined more markedly (about −0.09; $\Delta\Delta = 0.09$, $p = 0.003$).

These strength outcomes align with literature indicating that balance and sensorimotor training can produce spinal and supraspinal adaptations that enhance force production and joint stability.[3,5–7,9,11,14,15,19] The NAT program combined reactive drills (Light Cue Reaction, Auditory Mismatch with Reactive Dribbling), visually constrained movement tasks, and unstable-surface work, which collectively demand precise coordination of trunk and lower-limb musculature. Such training profiles fit well with models in which multisensory integration optimizes motor unit recruitment, timing between agonist and antagonist muscles, and functional joint stability.[3,5–7,9,11,14,15,19,34,43–45] Insights from sport vision and electrophysiological studies further suggest that targeted visual and perceptual training can modify cortical processing speed and visuomotor transformation efficiency,[12,29,33,34,40,41] which may indirectly contribute to more effective recruitment of force-producing units during explosive movements.

The roughly 27% increase in quadriceps torque at 60°/s in the NAT group, compared with about 3% in controls, is comparable to or greater than improvements typically reported after conventional strength or neuromuscular training blocks of similar duration in athletic populations.[11] Crucially, these strength gains were achieved without compromising H:Q balance; indeed, H:Q ratios remained stable or improved slightly in the NAT group. Given the known relationship between imbalanced H:Q ratios, hamstring strain, and knee injury risk,[11,14,15,24] this pattern suggests that NAT can help enhance force-generating capacity while supporting joint-stabilizing muscle balance, in line with contemporary concepts of neuromuscular control and injury prevention.[11,19,34,40,43–45]

4.5. Limitations and future directions

Major strengths of this trial include the randomized controlled design, concealed allocation, blinded outcome assessment and analysis, a priori power calculation, and use of validated football-specific performance tests and isokinetic dynamometry. The NAT program was implemented in a real-world elite football environment, which supports external validity.

Several limitations should also be acknowledged. The sample comprised football players aged 18–23 from a single competitive context, limiting generalizability to female players, youth athletes, and other competition levels. The intervention lasted eight weeks, and outcomes were assessed only immediately after completion, so long-term maintenance of gains and their influence on seasonal match statistics or injury incidence remain unknown. Although the observed changes and their effect sizes are consistent with mechanisms derived from prior neurophysiological and sport-science work, we did not directly measure neural, kinematic, or perceptual–cognitive variables, nor did we perform formal mediation analyses. Future studies combining performance outcomes with neurophysiological and biomechanical measures—and using mediation or structural modeling—are needed to quantify how much of the observed improvement is attributable to changes in visual processing, multisensory integration, or neuromuscular control.

Regarding safety, four of the 60 randomized players (6.7%) did not complete the trial. Two sustained acute lower-limb musculoskeletal injuries during routine club training (not during NAT sessions), and two were excluded due to repeated non-attendance. All injured players were evaluated and treated by the club's medical team according to standard protocols and were not included in post-intervention assessments. No serious adverse events related to NAT were observed. Transient symptoms such as mild eyestrain, dizziness, or fatigue occasionally occurred during visually demanding tasks; these were managed by short rest periods or temporary reductions in drill complexity or intensity and resolved completely.

Real-time field constraints also influenced the study. NAT sessions were conducted on a synthetic pitch immediately before regular team training (approximately 35–45 min), and content sometimes had to be adapted to match schedules, travel, weather conditions, and coaching priorities. Space and equipment constraints occasionally necessitated minor modifications in drill sequencing. Although NAT and control sessions were separated, some informal exchange of information between players cannot be entirely ruled out. Overall weekly training load and recovery were monitored through close communication with coaching staff rather than being strictly standardized. These factors introduce ecological variability typical of high-performance environments but should be kept in mind when interpreting the magnitude and consistency of the observed effects.

Future research should evaluate NAT across multiple teams and competition levels, including female and youth athletes; examine its impact on match-derived metrics (for example, successful passes, shots on target, high-intensity efforts) and injury incidence over full seasons; and directly compare NAT with other perceptual–cognitive and constraint-led approaches. Integrating detailed neurophysiological and biomechanical outputs, alongside appropriate mediation analyses, will be essential to fully delineate the pathways through which NAT modifies performance and neuromuscular outcomes.

5. Conclusion

This randomized controlled trial showed that an eight-week neuroathletic training (NAT) program, delivered in addition to standard in-season football training, was associated with substantial improvements in key technical and physical parameters in male players. Specifically, passing accuracy increased by about 33%, shooting precision by about 28%, flexibility by about 42%, and quadriceps torque at 60°/s by about 27%, while H:Q ratios were preserved or slightly improved. These adaptations were observed despite both groups maintaining comparable club-based training loads, indicating that the added NAT stimulus provided a meaningful incremental benefit over usual practice.

Taken together, these findings are concordant with and extend prior work highlighting the relevance of visual search behavior, postural plasticity, sensorimotor integration, and sport vision interventions in athletic performance. The present study adds to this literature by demonstrating that a structured, football-specific NAT program can simultaneously enhance technical skills (passing and shooting), flexibility, and lower-limb strength, while preserving favorable H:Q balance in an elite population under real-world competitive conditions. Within this context, NAT emerges as a promising, field-compatible adjunct to traditional technical, tactical, and strength-conditioning programs in football, with potential relevance for both performance enhancement and injury-risk reduction.

CRediT authorship contribution statement

Ali Polat Cakici: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft. **Numan Alpay:** Conceptualization, Methodology, Resources, Supervision, Writing – review & editing. **Caglar Soylu:** Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration.

Clinical trial registration

This trial was registered at ClinicalTrials.gov (ID: NCT07092735).

Confirmation of ethical compliance

Ethical approval was obtained from the Balıkesir University Non-Interventional Clinical Research Ethics Committee (Decision No: 2024/71, dated 21/05/2024).

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No material from other sources requiring permission was reproduced in this manuscript.

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Declaration of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsams.2026.01.013.

Data availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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