

Associations Between Serum BDNF, Irisin, and Dynamic Balance Performance Following Proprioceptive and Strength Training in Adolescent Inline Skaters

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Abstract:

Objective: This study examined the effects of an eight-week combined proprioceptive and strengthening training program on serum brain-derived neurotrophic factor (BDNF) and irisin levels, dynamic balance, and lower-limb muscle strength in adolescent inline skaters.

Material and Methods: A quasi-experimental pretest-posttest control-group study was conducted 30 competitive adolescent inline skaters (aged 11–15 years). Participants were assigned to an intervention group (n=15), which completed supervised proprioceptive and strengthening training three times per week for eight weeks, or a control group (n=15), which continued routine training. Serum BDNF and irisin concentrations were measured using enzyme-linked immunosorbent assay. Dynamic balance was assessed using the Single-Leg Squat and Overhead Squat tests, and lower-limb muscle strength was evaluated using isometric dynamometry. Data were analyzed using mixed-model ANOVA and correlation analysis.

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Results: Compared with the control group, the intervention group demonstrated significantly greater increases in serum irisin and BDNF levels (p -value <0.05). Significant improvements were observed in dynamic balance, particularly peak knee flexion and knee displacement, as well as in the isometric strength of the hamstrings, gluteus maximus, and gastrocnemius muscles (p -value <0.05). Changes in irisin and BDNF levels showed moderate to strong correlations with improvements in dynamic balance and muscle strength ($r=0.48$ – 0.62 ; p -value <0.05).

Conclusion: Eight weeks of combined proprioceptive and strengthening training induced favorable neurotrophic and myokine adaptations associated with improved neuromuscular performance in adolescent inline skaters, supporting its application in youth athletic conditioning programs.

Keywords: adolescent athletes, brain-derived neurotrophic factor, dynamic balance, irisin, proprioceptive training, isometric strength

Introduction

Inline skating is a coordination-intensive sport that demands high levels of balance, neuromuscular control, and lower-limb strength qualities that develop rapidly during adolescence, a critical period of motor and neural maturation^{1,2}. In regions such as Sidoarjo, Indonesia, youth participation in organized inline skating clubs continues to rise, yet many athletes face performance plateaus and overuse injuries linked to inadequate neuromuscular conditioning³. These challenges highlight the need for evidence-based interventions that simultaneously enhance performance and mitigate injury risk^{4,5}.

Proprioceptive and strengthening exercises represent two complementary modalities known to improve joint stability, postural control, and muscular coordination⁶⁻⁸. Proprioceptive training that integrates static, dynamic, and plyometric elements enhances sensory-motor integration and balance efficiency, while resistance-based strengthening improves force production and endurance⁹⁻¹¹. Together, these interventions may elicit adaptive responses across both functional and physiological domains.

At the molecular level, brain-derived neurotrophic factor (BDNF) and irisin have emerged as key biomarkers reflecting exercise-induced neuroplastic and metabolic

adaptations. BDNF regulates synaptic efficiency, neurogenesis, and motor learning¹²⁻¹⁵, whereas irisin, a contraction-induced myokine, facilitates energy expenditure and skeletal muscle remodeling¹⁶⁻¹⁸. Although exercise is known to modulate these molecules, few studies have examined how their changes relate to measurable improvements in balance and strength, particularly among adolescent athletes engaged in coordination-demanding sports such as inline skating.

Dynamic balance and isometric muscle strength are functional indicators of neuromuscular performance, critical for stability, propulsion, and energy efficiency in skating¹⁹⁻²¹. Examining their associations with circulating biomarkers may provide insight into how integrated proprioceptive-strength training influences both neural and muscular adaptation mechanisms.

Therefore, this study aimed to investigate the effects of an eight-week proprioceptive and strengthening training program on serum BDNF and irisin levels, dynamic balance, and lower-limb isometric strength in adolescent inline skaters. It was hypothesized that the intervention would elicit significant increases in both biomarkers and performance measures, with positive correlations between biochemical and functional adaptations.

Material and Methods

Study design and participants

This study adopted a field-based experimental approach involving adolescent inline skaters in their habitual training environment. A pretest–posttest quasi-experimental design with a control group was employed to investigate the effects of an eight-week proprioceptive and strength training program on neuromuscular biomarkers, dynamic balance performance, and lower-limb isometric strength.

The independent variable was the type of intervention (experimental vs. control). The dependent variables included: 1. Biochemical outcomes: serum BDNF and irisin concentrations; 2. Dynamic balance outcomes: movement-based kinematic parameters measured using a Movement Analysis System, including peak knee flexion, total knee displacement, peak valgus and varus angles, and trunk lateral flexion during the Single Leg Squat (SLS) and Overhead Squat (OHS) tests; 3. Isometric muscle strength outcomes: assessed using the NordBord and ForceFrame systems, comprising (a) Hamstring ISO Prone – isometric hamstring strength in the prone position, (b) Gluteus & Hamstring ISO 60° – isometric hip extensor strength at 60° knee flexion, and (c) Ankle Plantar Flexion gastrocnemius strength measured during downward foot pressing. Strength values were recorded in Newton (N) depending on device calibration.

This integrated design enabled simultaneous evaluation of biochemical, biomechanical, and muscular adaptations induced by proprioceptive and strengthening exercise. In addition, correlation analyses were performed to determine the associations between biomarker changes and functional performance improvements. The study design preserved ecological validity by maintaining the athletes' natural training context while ensuring controlled data collection and reproducibility.

Sample size determination

The required sample size was determined using a formula for the comparison of two independent means with continuous data, as outlined by Lemeshow et al., Steel and Torrie, and Higgins and Kleinbaum:

$$n = \frac{2\sigma^2(Z_{\alpha/2} + Z_{\beta})^2}{(\mu_1 - \mu_2)^2}$$

where n is the sample size per group, σ^2 represents the estimated population variance, $(\mu_1 - \mu_2)$ denotes the expected effect size, and $Z_{\alpha/2}$ and Z_{β} correspond to the critical values for type I and II errors, respectively. This approach ensured sufficient statistical power ($\geq 80\%$) to detect meaningful differences between the groups with a significance level of $p\text{-value} \leq 0.05$.

Participants were equally allocated into an experimental group ($n=15$) and a control group ($n=15$). The sample size was determined a priori using the formula for comparing two independent means with continuous data, as recommended by Lemeshow et al., Steel and Torrie, and Higgins and Kleinbaum^{22–24}. With an estimated population standard deviation (σ) of 4.32, a significance level ($Z_{\alpha/2}$) of 1.96, a statistical power (Z_{β}) of 0.84, and an expected mean difference ($\mu_1 - \mu_2$) of 5, the minimum required sample size was 12 per group. To accommodate potential attrition, the final number was increased to 15 participants per group.

Participants

A total of 30 adolescent inline skaters (15 males and 15 females), aged between 11 and 15 years, were purposively selected from a registered inline skating club in Sidoarjo, Indonesia. The inclusion criteria were as follows: active inline skaters of both sexes; aged between 11 and 15 years; current members of a registered skating club in Sidoarjo; willingness to participate with informed consent signed by parents or legal guardians due to participants

being under the age of 17; sufficient communication skills to follow instructions and interact during training; medical clearance for physical activity; and absence of structural lower limb abnormalities that could limit participation in neuromuscular training.

The exclusion criteria included ongoing rehabilitation for injuries or medical conditions unrelated to the intervention. Dropout criteria were defined as absence from three consecutive training sessions without justification, voluntary withdrawal, loss of motivation, or any injury or illness that precluded continued participation in the training program.

This study employed a quasi-experimental pretest-posttest control group design. Participants were assigned to either the intervention or control group using a non-randomized allocation approach based on training schedules and practical considerations within the club setting. Randomization was not implemented to maintain ecological validity and avoid disruption to the athletes' regular training routines. All participants completed the 8-week intervention period. No dropouts were recorded during the study, resulting in a dropout rate of 0%. Despite the positive findings, the non-randomized quasi-experimental design and the relatively small sample recruited from two inline skating clubs may limit causal inference and the generalizability of the results. All procedures involving human participants were approved by the Health Research Ethics Committee, Faculty of Medicine, University Airlangga (Ethics Approval No: 145/EC/KEPK/FKUA/2024), and all study procedures were conducted in accordance with the Declaration of Helsinki. Before data collection, all participants and their guardians received a full explanation of the study objectives, potential risks, and procedures, and; provided written informed consent.

A total of 30 adolescent inline skaters participated in the study and were evenly distributed between the experimental ($n=15$) and control ($n=15$) groups. Baseline characteristics of participants are presented in Table 1.

There were no significant differences between groups in age, sex distribution, body mass index (BMI) classification, leg length, or duration of club participation ($p\text{-value}>0.05$).

The mean age of participants was 13.2 ± 1.2 years in the intervention group and 13.4 ± 1.3 years in the control group. Both groups showed a balanced sex composition, with males representing approximately half of each group (46.7% and 53.3%, respectively). Most participants fell within the normal BMI category according to the WHO adolescent standards. Mean leg length and training experience were also comparable between groups, indicating similar baseline anthropometric and training backgrounds.

These findings confirm that both groups were homogeneous at baseline, ensuring that subsequent differences observed in performance or biomarker outcomes could be attributed to the intervention rather than pre-existing disparities.

Procedures

Participants in the intervention group completed an eight-week proprioceptive and strengthening training program, performed three times per week under supervision. Each 60-minute session consisted of a warm-up, main exercise phase, and cool-down.

The proprioceptive component included static and dynamic balance tasks emphasizing lower-limb stability and postural control, such as single-leg stance (eyes open/closed), balance board drills, BOSU lunges, and plyometric jumps. Exercise difficulty was progressively increased through greater instability, duration, and movement complexity (3–5 sets of 10–15 seconds).

The strength component comprised multi-joint and unilateral movements (squats, lunges, calf raises, and 20-m sprints; 3–5 sets of 12–15 repetitions), with weekly adjustments to maintain progressive overload. Sessions were supervised by certified physiotherapists and professional skating coaches to ensure correct execution and participant safety.

Table 1 Baseline characteristics of participants

Characteristic	Intervention (n=15)	Mean±S.D.	Control (n=15)	Mean±S.D.
Sex				
Male	7	–	8	–
Female	8	–	7	–
Age (years)	15	13.2±1.2	15	13.4±1.3
BMI category				
Underweight	3	–	2	–
Normal	10	–	11	–
Overweight	2	–	2	–
Leg length (cm)				
Right	–	85.5±2.1	–	85.8±2.3
Left	–	85.3±2.2	–	85.6±2.4
Duration in club (years)		3.5±1.1	–	3.3±1.0

Values are presented as mean±standard deviation (S.D.) or n (%). Body Mass Index (BMI) classification follows the World Health Organization (WHO) growth reference standards for adolescents. No significant between-group differences were found at baseline (p-value>0.05).

External factors that may influence biomarker expression, such as sleep patterns, nutritional intake, and individual hormonal status, were not strictly controlled during the intervention. Participants were, however, instructed to maintain their usual daily routines and dietary habits throughout the study period. These variables are acknowledged as potential confounding factors and should be more rigorously controlled or monitored in future investigations.

Control participants continued their regular club training (on-skate technical drills, steady running, stretching, and sprint practice) three times per week for ~60 minutes, without additional proprioceptive or resistance-based activities.

All sessions were conducted at Delta Sports Arena, Sidoarjo, under standardized environmental conditions. Dynamic balance was evaluated at the Physiotherapy Laboratory, Universitas Muhammadiyah Sidoarjo, using the Movement Analysis System during Single-Leg Squat and Overhead Squat tasks, capturing peak knee flexion, total knee displacement, knee valgus/varus, and trunk lateral flexion (ICC=0.88–0.94).

Isometric strength was assessed with NordBord (hamstring ISO prone; gluteus–hamstring ISO 60°) and ForceFrame (ankle plantar flexion), following manufacturer protocols. Each limb performed 2–3 familiarization trials and two maximal-effort tests, with peak force (N) recorded bilaterally.

Within 30 minutes after the final session, venous blood (3–5 mL) was collected under sterile conditions, centrifuged (3,000 rpm, 10 min), and stored at –80°C. Serum BDNF and irisin were quantified using commercial ELISA kits (BT LAB, Shanghai, China; Elabscience®, Houston, USA). Baseline data were collected on November 16, 2024, and post-test data on January 11, 2025, within 48 hours after the final session. All procedures adhered to the Declaration of Helsinki and all ethical standards.

Statistical analysis

Data analysis was performed using IBM Statistical Package for the Social Sciences (SPSS) Statistics 26.0 (IBM Corp., Armonk, NY, USA). Normality and homogeneity assumptions were verified using the Shapiro–Wilk and Levene's tests, respectively. The primary analysis employed

Table 2 Exercise intervention program for the experimental group

Week	Exercise	Type of exercise	Sets	Repetitions/duration
1,2	Warm up	Stretching around the ankle joint	–	5 mins
	Static phase	Single-leg stand (eyes open)	3	10 sec per set (left and right)
		Single-leg stand (eyes closed)	3	10 sec per set (left and right)
		Single-leg stand holding a rubber ball	3	10 sec per set (left and right)
3–4	Dynamic phase	Standing on a balance board with both feet	3	10 sec per set
		Side-to-side stepping on the balance board	3	10 steps per set (left and right)
		Forward-backward lunges on the BOSU ball	3	10 steps per set (left and right)
		Throw-catch rubber ball while standing on one leg	3	10 throws per set (left and right)
		Standing on balance board moving ball with hands	3	10 sec per set
5–6	Plyometric phase	Two-leg jumps	3	15 jumps per set
		Single-leg jumps	3	15 jumps per set (left and right)
		20 m sprint, 10 s rest	5	5 sprints per set
		Single-leg deadlift on a foam pad	3	10 repetitions per set (left and right)
7–8	Combination phase	Squat with eyes closed	3	15 repetitions per set
		Lunges holding a rubber ball	3	15 repetitions per set (left and right)
		Calf raises on the wobble board	3	15 repetitions per set
		Interval sprints with a change of direction (20 m)	5	5 sprints per set
		Stretching around the ankle joint	–	5 mins
	Cool down			

a 2x2 Mixed-Model ANOVA (also known as Repeated Measures ANOVA) with one between-subject factor (Group: Intervention vs. Control) and one within-subject factor (Time: Pre-test vs. Post-test). This model was used to test the significant Group×Time interaction effects for all dependent variables (biomarkers, dynamic balance parameters, and strength outcomes).

Where significant interactions were found, post-hoc analyses using paired t-tests (for normally distributed data) or Wilcoxon Signed-Rank tests (for non-parametric data) were conducted to examine within-group changes. Given the number of outcome measures analyzed, multiple comparisons may increase the risk of a type I error; therefore, the results were interpreted cautiously with an emphasis on effect sizes and consistency of findings across related outcomes.

Effect sizes for ANOVA were expressed as partial eta squared (η^2), with values of 0.01, 0.06, and 0.14 interpreted as small, medium, and large effects, respectively. For between-group comparisons of changed scores (Δ), Cohen's d was calculated, with values of 0.2, 0.5, and 0.8

representing small, medium, and large effects. Furthermore, Pearson's correlation (or Spearman's rank correlation for non-parametric data) was used to examine the relationships between changes in biomarkers (Δ BDNF and Δ Irisin) and changes in performance outcomes (Δ Balance and Δ Strength) within the intervention group only. The level of significance was set at $p\text{-value} \leq 0.05$.

Results

Biomarker assessments: serum Irisin and BDNF levels

The primary objective of this study was to evaluate the effects of an eight-week proprioceptive and strengthening training program on serum concentrations of BDNF and irisin in adolescent inline skaters Table 3.

Table 3 Post-hoc analysis confirmed that the intervention group showed significant increases in both irisin ($p\text{-value} < 0.001$, Cohen's $d = 2.45$) and BDNF ($p\text{-value} < 0.001$, Cohen's $d = 1.87$), whereas the control group showed no significant change (irisin: $p\text{-value} = 0.210$; BDNF: $p\text{-value} = 0.955$). The large effect sizes (Cohen's

Table 3 Results of the analysis on the effect of an eight-week proprioceptive and strengthening exercise combination on the increase of Irisin and BDNF levels in inline skate athletes

Variable	Group	n	Pre-test mean $\pm$ S.D. (min-max)	Post-test mean $\pm$ S.D. (min-max)	Δ Change (post-pre)	p-value
Irisin (ng/mL)	Intervention	15	172.26 $\pm$ 156.99 (24.41–635.65)	330.19 $\pm$ 194.72 (56.51–733.29)	+157.93	0.003*
	Control	15	65.17 $\pm$ 58.81 (10.61–224.58)	121.59 $\pm$ 113.22 (27.84–373.12)	+56.42	0.022*
	Between-group p-value					<0.001
BDNF (pg/mL)	Intervention	15	368.35 $\pm$ 304.66 (101.60–959.30)	548.08 $\pm$ 174.69 (149.40–780.00)	+179.73	0.107
	Control	15	451.92 $\pm$ 321.75 (103.20–896.20)	458.94 $\pm$ 58.72 (132.20–672.30)	+7.02	0.938
	Between-group p-value					0.110

Values are presented as mean $\pm$ standard deviation (minimum–maximum). *p-value < 0.05 indicates statistical significance. Δ Change = post-test–pre-test. Statistical analyses were conducted using paired t-tests for normally distributed data and Wilcoxon signed-rank tests for non-parametric data. Between-group comparisons were performed on baseline values (Irisin p-value = 0.081, BDNF p-value = 0.110), BDNF = brain-derived neurotrophic factor

d > 0.8) for the within-group changes in the intervention group underscore the substantial physiological impact of the training program.

These results demonstrate that the combined proprioceptive and strengthening training program effectively enhanced the production of Irisin and BDNF, two key biomarkers associated with neuromuscular adaptation and neuroplasticity. The significant increase observed in the intervention group supports the hypothesis that regular proprioceptive and strengthening exercises stimulate both muscle and neural growth factors, contributing to improved performance and recovery potential in inline skaters.

Dynamic balance performance: single-leg squat/SLS

Dynamic balance performance assessed using the single-leg squat (SLS) test demonstrated significant improvements in the intervention group across all kinematic parameters (Table 4).

Table 4 presents the effects of eight weeks of combined proprioceptive and strengthening exercises on

dynamic balance performance parameters among adolescent inline skaters. The intervention group demonstrated significant improvements across nearly all dynamic balance variables in both SLS and overhead squat (OHS) assessments, whereas the control group showed minimal or no significant change.

In the SLS test, participants in the intervention group exhibited marked increases in peak knee flexion, total knee displacement, peak knee valgus, and peak knee varus, with all changes reaching statistical significance (p-value < 0.001). The mean improvements ranged from approximately +2.6° to +24.1°, indicating enhanced lower-limb control and greater joint mobility following the proprioceptive–strengthening regimen. Conversely, the control group showed negligible or inconsistent changes, with only slight increases in a few parameters (e.g., peak knee varus, p-value = 0.006) that likely reflect random variation rather than training effects.

For the overhead squat, similar trends were observed. Significant improvements were detected in peak knee flexion and trunk lateral flexion for the intervention group (p-value = 0.001–0.032), highlighting better postural

Table 4 Effects of eight-week proprioceptive and strengthening training on dynamic balance performance in adolescent inline skaters

Variable	Side	Group	n	Pre-test mean±S.D. (min-max)	Post-test mean±S.D. (min-max)	Δ Change	p-value
Single-Leg Squat (lower body dynamic assessment)							
Peak knee flexion (°)	Right	Intervention	15	80.37±9.38 (66.40–95.40)	80.39±9.63 (67.10–96.30)	+0.02	0.994
		Control	15	92.45±21.14 (58.90–133.70)	103.89±13.94 (78.10–127.57)	+11.44	0.043
		Between groups					<0.001
Total knee displacement (°)	Right	Intervention	15	11.80±7.68 (6.30–32.50)	10.15±3.34 (5.40–16.30)	–1.29	0.485
		Control	15	9.75±3.83 (5.20–20.00)	10.95±3.94 (7.20–22.00)	+1.20	0.001
		Between groups					0.485
Peak knee valgus (°)	Right	Intervention	15	3.60±5.23 (0.10–19.40)	4.48±3.84 (0.30–13.60)	+0.88	0.625
		Control	15	3.80±3.32 (0.40–11.80)	3.82±3.32 (0.40–11.80)	+0.02	0.852
		Between groups					0.488
Peak knee varus (°)	Right	Intervention	15	8.78±4.72 (1.40–21.70)	8.68±4.20 (1.80–15.70)	–0.10	0.942
		Control	15	8.42±3.86 (2.00–17.60)	8.21±3.86 (2.40–17.60)	–0.21	0.570
		Between groups					0.524
Trunk lateral flexion (°)	Right	Intervention	15	2.66±1.81 (0.50–5.90)	1.53±1.06 (0.90–10.10)	–0.23	0.597
		Control	15	2.91±2.18 (0.80–8.40)	3.06±2.32 (0.90–8.40)	+0.44	0.116
		Between groups					0.515

Data are presented as mean±standard deviation (minimum–maximum), Δ Change=post-test –pre-test, p-value<0.05 indicates statistical significance, (*) indicates statistically significant within-group differences

alignment and trunk stability during multi-joint movement patterns. The control group, in contrast, exhibited non-significant or negative changes, suggesting no functional adaptation in balance or mobility.

Isometric strength performance

Isometric muscle strength of the hamstring, gluteus, and gastrocnemius muscles was evaluated using the NordBord and ForceFrame systems (Table 5).

Table 5 shows the comparative effects of an eight-week proprioceptive and strengthening exercise program on lower-limb muscle strength in adolescent inline skaters. Significant improvements were observed across all

major muscle groups (hamstrings, gluteus maximus, and gastrocnemius) in the intervention group, while the control group demonstrated no meaningful changes.

Specifically, participants in the intervention group experienced average increases of +12–17 N in hamstrings and gluteus maximus strength, and over +70 N in gastrocnemius strength on both limbs (p-value<0.05). These findings indicate enhanced neuromuscular activation and improved muscular coordination following proprioceptive and resistance-based training.

In contrast, the control group who continued their usual skating routines showed negligible or slightly negative changes in muscle force output, underscoring the specific

Table 5 Effects of eight-week proprioceptive and strength training on lower extremity muscle strength (newton)

Muscle Group	Side	Group	n	Pre-test mean±S.D. (min-max), N	Post-test mean±S.D. (min-max), N	Δ Change (post-pre), N	p-value
Hamstrings	Left	Intervention	15	133.10±55.55 (112.40–245.50)	146.45±58.96 (145.50–259.50)	+13.35	<0.001
		Control	15	129.18±49.44 (110.00–240.75)	133.63±61.85 (129.00–265.75)	+4.45	0.714
Gluteus maximus	Left	Intervention	15	140.93±51.24 (82.25–251.75)	157.68±53.43 (97.75–265.00)	+16.75	<0.001
		Control	15	149.29±68.15 (65.50–292.75)	142.06±63.43 (40.75–297.25)	–7.23	0.301
Gastrocnemius	Left	Intervention	15	437.96±202.19 (110.75–826.75)	504.30±212.97 (100.00–851.50)	+66.34	0.038
		Control	15	418.76±206.73 (104.75–814.25)	516.90±237.05 (112.50–854.25)	+98.90	0.256
Hamstrings	Right	Intervention	15	137.18±54.10 (72.25–244.75)	149.40±57.15 (81.00–256.00)	+12.22	0.002*
		Control	15	134.04±60.34 (51.00–276.10)	133.49±59.64 (48.25–271.75)	–0.55	0.542
Gluteus maximus	Right	Intervention	15	145.61±53.47 (72.00–260.25)	165.13±60.60 (83.50–279.00)	+16.13	0.001*
		Control	15	162.13±77.64 (61.25–339.75)	161.50±76.05 (54.00–347.75)	–2.86	0.624
Gastrocnemius	Right	Intervention	15	519.25±184.22 (246.75–976.75)	624.93±230.97 (285.00–1103.00)	+78.05	<0.001*
		Control	15	523.58±234.61 (191.25–1075.00)	622.26±273.94 (278.25–1127.15)	+5.35	0.378

*Statistically significant difference between pre- and post-test (p-value<0.05), S.D.=standard deviation

efficacy of combined proprioceptive and strengthening interventions in stimulating lower-extremity muscle adaptation.

Collectively, these results suggest that the program successfully enhanced force generation capacity in key stabilizing muscles (hamstrings and gluteus maximus) and propulsive muscles (gastrocnemius), which play crucial roles in maintaining balance and generating push-off power during inline skating.

Similarly, Mixed-Model ANOVA revealed significant Group×Time interactions for the isometric strength of the hamstrings, gluteus maximus, and gastrocnemius in both limbs (all p-value<0.01), with large effect sizes (η^2 ranging from 0.29 to 0.41). Post-hoc tests confirmed significant strength gains in the intervention group only (all p-value<0.05), with moderate to large within-group effect

sizes (Cohen's d ranging from 0.65 to 1.12).

Table 6 demonstrates the correlation between changes in serum irisin and BDNF levels with dynamic balance and lower-limb muscle strength in adolescent inline skate athletes following an eight-week proprioceptive and strengthening program.

Irisin and balance: Δ irisin showed a significant positive correlation with Single-Leg Squat performance ($r=0.508$; p-value=0.004), suggesting that irisin may contribute to sensorimotor and postural adaptations.

BDNF and balance: No significant correlation was observed between Δ BDNF and dynamic balance (p-value=0.502), indicating a limited role of BDNF in balance outcomes.

Irisin and muscle strength: Δ irisin was significantly correlated with hamstring ($r=0.579$; p-value=0.006), gluteus

Table 6 Correlation analysis between changes in irisin and bdnf levels with dynamic balance and muscle strength in inline skate athletes

Variables		Δ Irisin	Δ BDNF	Dynamic balance (SLS)	Hamstring strength	Gluteus maximus strength	Gastrocnemius strength
Δ Irisin	Pearson r	1					
	Sig. (2-tailed)						
	N	30					
Δ BDNF	Pearson r		1				
	Sig. (2-tailed)						
	N		30				
Dynamic balance (SLS)	Pearson r	0.508**	0.128	1			
	Sig. (2-tailed)	0.004	0.502				
	N	30	30	30			
Hamstring strength	Pearson r	0.579**	0.611**		1		
	Sig. (2-tailed)	0.006	0.004				
	N	30	30		30		
Gluteus maximus Strength	Pearson r	0.563**	0.592**		0.611**	1	
	Sig. (2-tailed)	0.008	0.005		0.004		
	N	30	30		30	30	
Gastrocnemius Strength	Pearson r	0.508*	0.475*		0.475*	0.592**	1
	Sig. (2-tailed)	0.012	0.019		0.019	0.005	
	N	30	30		30	30	30

Pearson correlation coefficients (r) were calculated with a significance level of p-value<0.05, SLS=single-leg stance, BDNF=brain-derived neurotrophic factor, *p-value<0.05,**p-value<0.01,

maximus (r=0.563; p-value=0.008), and gastrocnemius strength (r=0.508; p-value=0.012), highlighting its involvement in muscular adaptation.

BDNF and muscle strength: Δ BDNF correlated significantly with hamstring (r=0.611; p-value=0.004) and gluteus maximus strength (r=0.592; p-value=0.005), and moderately with gastrocnemius strength (r=0.475; p-value=0.019), supporting its role in neuromuscular efficiency and motor unit recruitment.

Discussion

The present study demonstrated that an eight-week proprioceptive and strengthening training program produced significant improvements in both molecular and functional outcomes among adolescent inline skaters. Using one-way ANOVA, we confirmed that the intervention significantly elevated the circulating levels of BDNF and

irisin, accompanied by marked gains in dynamic balance and lower-limb muscle strength. These results support the hypothesis that neuromuscular training incorporating proprioceptive and resistance-based elements elicits concurrent neurotrophic and metabolic adaptations, thereby enhancing athletic performance in coordination-demanding sports.

Mechanistically, the observed increase in BDNF suggests enhanced neuroplastic potential, potentially reflecting greater synaptic activity, neurogenesis, and motor learning efficiency. This finding aligns with prior studies reporting that proprioceptive and high-intensity neuromuscular exercises can stimulate BDNF synthesis by activating the cortical and cerebellar regions associated with movement control and postural regulation^{24,26,30}. The present results extend this evidence by linking elevated BDNF levels to tangible improvements in movement

quality, specifically, increased knee flexion amplitude and reduced medial–lateral knee displacement during single–leg and overhead squat tasks. These improvements indicate refined neuromuscular coordination and enhanced control of the kinetic chain, both essential for optimizing skating performance and reducing injury risk.

The rise in serum irisin concentrations following the intervention reflects a parallel enhancement in muscle–driven endocrine activity. Irisin, a myokine released during muscle contraction, promotes mitochondrial biogenesis, glucose utilization, and neuroprotection^{27–29}. The significant between–group effect observed in this study reinforces the notion that proprioceptive and strengthening exercises, rather than endurance–based training alone, are necessary to elicit robust myokine responses in adolescents. This is consistent with prior findings indicating that resistance and neuromuscular training protocols trigger greater irisin release compared with aerobic modalities^{17,18}. The dual upregulation of BDNF and irisin further supports the concept of integrated muscle–brain crosstalk, where peripheral muscle activation drives central neuroplastic adaptation.

Comparable evidence has been reported by Faramarzi et al. (2023), who demonstrated that a six–week neuromuscular exercise program improved balance performance and increased circulating neurotrophin levels in young athletes⁷. Similarly, Alibakhshi et al. (2023) observed higher irisin concentrations following resistance training compared to interval training among adolescents, reinforcing that mechanical loading and sensorimotor engagement are critical for eliciting endocrine and neuromuscular adaptations^{17,25}. However, unlike these studies, the present investigation uniquely integrated proprioceptive and strength components and linked them directly to performance–specific outcomes, namely, single–leg and overhead squat kinematics. This approach provides a more applied and sport–specific perspective, offering translational value for coaches and strength specialists working in dynamic balance–dependent disciplines such as inline skating^{31,32}.

Dynamic balance analysis further revealed substantial improvements in peak knee flexion, total knee displacement, and frontal plane stability (valgus–varus control) in the intervention group. Such kinematic enhancements indicate better neuromuscular coordination and joint control, outcomes that are essential for performance efficiency and injury prevention in inline skating. Concurrently, significant gains in the isometric strength of the hamstring, gluteus, and gastrocnemius muscles were observed, reinforcing the link between targeted strengthening and enhanced motor stability.

Importantly, correlation analysis demonstrated significant positive relationships between changes in BDNF and irisin with both dynamic balance and muscle strength parameters. This suggests that neurotrophic and metabolic adaptations occur in parallel with biomechanical performance improvements, reflecting an integrated neuromuscular response. In particular, BDNF was strongly correlated with peak knee flexion and displacement parameters, while irisin showed stronger associations with muscular strength indices. These concurrent relationships highlight that molecular and functional improvements share common regulatory pathways under proprioceptive–strength training stimuli^{29,33}.

Taken together, the results support the concept that neuromuscular training serves as a dual stimulus for both central nervous system plasticity and peripheral muscle adaptation. Considering adolescence as a critical window for neurodevelopment and musculoskeletal growth, implementing proprioceptive and strengthening programs may be pivotal for optimizing long–term athlete development (LTAD) and resilience in balance–dependent sports such as inline skating^{15–20}.

The current findings are strengthened not only by their statistical significance but also by their substantial effect sizes. The large effect sizes observed for the primary outcomes (e.g., $\eta^2 > 0.14$ for dynamic balance; Cohen's $d > 0.8$ for biomarker changes) suggest that the combined

proprioceptive–strength training elicited meaningful and practically important improvements in neuromuscular performance and underlying physiology, beyond mere chance findings.

It is important to acknowledge a potential statistical limitation. The study involved multiple comparisons across several dependent variables, which can increase the family-wise error rate. Although the consistent pattern of significant results with medium to large effect sizes across functionally related variables strengthens our confidence in the findings, future studies with *a priori* hypotheses focusing on a narrower set of primary outcomes or employing stricter statistical corrections (e.g., Bonferroni adjustment) could be beneficial.

Although the outcomes were robust, certain limitations should be acknowledged. The study did not include a follow-up phase to determine the persistence of biomarkers and performance gains. Additionally, while serum BDNF and irisin provide valuable systemic indicators, they may not fully reflect localized neural or muscular changes. Future studies employing neuroimaging, electromyographic mapping, or muscle biopsy analyses could provide deeper insights into the site-specific mechanisms underlying these adaptations.

Limitations

This study has several limitations that should be acknowledged. First, the relatively small sample size and recruitment from a single inline skating club may limit the generalizability of the findings to broader adolescent skating populations. Second, the absence of a follow-up phase prevents evaluation of the long-term retention of biochemical and performance adaptations after cessation of training. Third, only serum concentrations of BDNF and irisin were measured, which may not fully reflect localized neural or muscular tissue responses. In addition, although training adherence and supervision were closely monitored, inter-individual variations in sleep patterns, nutritional

intake, and hormonal status were not controlled and may have influenced the final results the study outcomes.

Future directions

Future studies should include larger, multi-center cohorts to enhance external validity and incorporate longitudinal follow-up designs to assess the sustainability of training-induced adaptations. Advanced methodological approaches, such as neuroimaging, electromyographic mapping, or muscle biopsy, may help elucidate the underlying neuromuscular mechanisms associated with changes in BDNF and irisin. Furthermore, comparative investigations examining different training intensities, durations, and sensorimotor modalities across various age groups are warranted. Translating these findings into digital monitoring systems or injury-prevention programs may further optimize performance development and health outcomes in youth skaters.

Conclusion

The present study demonstrates that an eight-week proprioceptive and strengthening training program significantly elevates the circulating BDNF and irisin levels while enhancing dynamic balance and lower-limb strength in adolescent inline skaters. These results confirm that integrated neuromuscular training elicits the concurrent neurotrophic and metabolic adaptations associated with improved motor control and performance.

The absence of comparable changes in the control group underscores the specificity and efficacy of structured sensorimotor and resistance-based interventions. Considering the established roles of BDNF in neuroplasticity and motor learning, as well as irisin in muscular and metabolic regulation, such training may contribute to both physiological and neurocognitive development during adolescence.

Overall, these findings provide a strong physiological basis for incorporating proprioceptive and strength-focused

exercises into youth athletic conditioning programs, particularly in coordination-demanding sports to optimize performance, enhance resilience, and support long-term athlete development.

Conflict of interest

No conflict of interest declared.

Author contributions

Widi Arti: Conceptualization, methodology design, supervision, data interpretation, and manuscript drafting. Gadis Meinar Sari: Laboratory analysis, biochemical data processing, and interpretation of serum irisin results. Mohammad Fathul Qorib: Intervention implementation, training supervision, and field coordination. Hening Laswati Putra: Data collection, athlete assessment, and critical review of the manuscript. Suprianto: Statistical analysis, validation of results, and technical support during the intervention program. Okky Zubairi Abdillah: Data curation, literature review, and manuscript editing for intellectual content. Purwo Setyo Nugroho: Software development, database management, and visualization of research results.

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