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Task-Dependent Prefrontal Cortex Activation During Balance–Cognitive Dual Tasks in Ice Hockey Players: Evidence From Functional Near-Infrared Spectroscopy

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Keywords: fNIRS, prefrontal cortex, ice hockey, dual-task, postural control

Posted Date: November 5th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11283030/v1

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Additional Declarations: No competing interests reported.

Abstract

This study compared prefrontal activation in ice hockey players and non-athlete adults during balance and cognitive dual-task conditions and examined its relationship with balance performance. Seventeen male ice hockey players and 17 age-matched healthy controls completed five randomized tasks: static and dynamic balance single tasks, a cognitive single task, and static and dynamic balance–cognitive dual tasks. Functional near-infrared spectroscopy measured prefrontal oxygenated hemoglobin (HbO), while balance indices and cognitive performance were recorded. Repeated-measures analysis of variance and Pearson correlations were conducted. Players showed superior balance performance across balance tasks ($P < 0.05$), whereas cognitive performance did not differ ($P > 0.05$). A significant group × task interaction was found for left dorsolateral prefrontal cortex HbO changes ($F = 5.303$, $P = 0.002$, $q = 0.022$, $\eta^2p = 0.142$). Compared with controls, players showed greater HbO changes during the static dual task but lower changes during the dynamic dual task. During the dynamic dual task, DLPFC-L HbO changes correlated positively with balance indices in players ($r = 0.721$, $P = 0.001$) and controls ($r = 0.674$, $P = 0.003$). Ice hockey players may achieve better balance through task-dependent, efficient prefrontal resource allocation.

1. Introduction

Ice hockey is a high-intensity, contact team sport characterized by rapid directional changes, high-speed skating, and complex tactical decision-making under physical confrontation [1,2]. The unique movement demands of ice hockey place extremely high requirements on athletes' postural control and balance stability. During skating, athletes require precise postural control to maintain smooth gliding [3,4]. Studies have shown that elite ice hockey athletes possess specific postural control strategies, exhibiting low antagonist-agonist co-activation at the neck and ankle joints, a feature reflecting sport-specific neuromuscular adaptations [5].Therefore, postural control is a fundamental factor determining competitive performance in ice hockey.

In ice hockey, athletes rarely perform isolated motor tasks. Instead, they must execute complex motor skills while simultaneously processing tactical information and making rapid decisions [6]. The dual-task paradigm requires participants to perform both a motor task and a cognitive task at the same time. It is a classic method for studying the allocation of attentional resources under motor-cognitive performance [7]. The core theoretical assumption of this paradigm is that an individual's cognitive resources are limited. When the total demand of the concurrent motor and cognitive tasks exceeds the available attentional capacity, the two tasks compete for limited processing resources. This competition leads to a decline in behavioral performance in one or both tasks, a phenomenon known as motor-cognitive interference [8–10].

The prefrontal cortex (PFC) plays a critical role in executive function and postural control [11]. Previous studies have long regarded human balance regulation as an automated reflex behavior controlled by subcortical neural pathways. However, an increasing number of studies have found that the PFC is activated during postural control and requires cognitive resources. In intense and dynamic competitive

sports such as ice hockey, proper allocation of cognitive resources for postural control is fundamental to integrating surrounding information and completing motor tasks.

Long-term specialized training enables professional athletes to gradually develop a focused and efficient neural network that is highly attuned to their specific sport [12]. This network is characterized by lower cortical activation compared to non-athletes while achieving equivalent or superior performance outcomes, reflecting greater efficiency in the utilization of neural resources.This phenomenon is known as the neural efficiency hypothesis [13]. Previous studies comparing athletes with the general population have found that high-level athletes exhibit superior neural efficiency under dual-task conditions; that is, they demonstrate lower levels of cortical activation while achieving performance equivalent to or even superior to that of non-athletes [14]. The role of neural efficiency is particularly prominent in sports scenarios that require rapid perception and precise decision-making [15]. Take ice hockey as an example, while skating at high speeds and engaging in physical contact, athletes must continuously process dynamic on-ice information—including the puck's trajectory, opponents' kinematic characteristics, and teammates' positions—to make tactical judgments, thereby highly integrating technical movements with decision-making processes. Such complex motor-cognitive interactions, repeatedly reinforced during training and competition, may lead to the efficient activation of motor pathways during routine movement execution, accompanied by corresponding changes in cortical activity patterns [11].

In recent years, there has been growing interest in using functional near-infrared spectroscopy (fNIRS) to assess brain function and better understand the interaction between motor and cognitive processes. FNIRS is a noninvasive optical neuroimaging technique that quantifies hemodynamic measures associated with neural activity in the brain [16,17]. Compared to functional magnetic resonance imaging (fMRI), fNIRS offers superior temporal resolution and, crucially, allows participants to perform tasks in a natural posture without being restricted to a supine position or disturbed by scanner noise [18]. Compared to electroencephalography (EEG), fNIRS offers better spatial resolution for localizing cortical activation and is more resistant to motion artifacts, which is crucial for studies involving physical activity and postural adjustments [19].

Current fNIRS studies have mainly focused on decision-making in open-skill sports, such as soccer and table tennis, or on postural-cognitive dual tasks in older adults. However, little is known about how different subregions of the PFC are differentially recruited in ice hockey players, who must maintain dynamic balance during high-speed skating while simultaneously processing tactical information.Therefore, this study employed fNIRS to investigate task performance, changes in oxygenated hemoglobin levels in the PFC, and the relationships between these factors in ice hockey players and healthy adults under different balance tasks and cognitive dual-task conditions. These findings may provide an objective neurophysiological basis for the assessment of sport-specific abilities and neurofeedback interventions in ice hockey players.

2. Method

2.1 Ethics and safety statement

This study was conducted in accordance with the Declaration of Helsinki. The studies involving humans were approved by the Ethics Committee of Harbin Sport University (Approval No. 2025042). All procedures were conducted in accordance with the university's ethical standards, local legislation, institutional requirements, and laboratory health and safety regulations. No unusual chemical, biological, or physical hazards were involved. All participants provided written informed consent to participate in this study.

2.2 Study Participants

This study employed a mixed design involving one between-subject factor and one within-subject factor. The between-subject factor was group, comprising ice hockey players and non-athlete controls, whereas the within-subject factor was task condition, comprising five tasks: static balance single task (SB-ST), dynamic balance single task (DB-ST), cognitive single task (CST), static balance–cognitive dual task (SB-CDT), and dynamic balance–cognitive dual task (DB-CDT).

G*Power 3.1 was used to calculate the sample size. The α level for repeated-measures analysis of variance was set at 0.05, the effect size f was set at 0.3, and the target power was set at 0.80. The calculation yielded a minimum required sample size of n = 28. A total of 17 male ice hockey players and 17 age-matched healthy adult males with no ice hockey experience were recruited for this study (age: athlete group = 20.9 ± 0.9, non-athlete group = 20.2 ± 1.3, p = 0.105; BMI: athlete group = 21.47 ± 1.56, non-athlete group = 22.01 ± 1.89, p = 0.376), meeting the minimum sample size requirement. The hockey group consisted of athletes with a national athletic ranking of Level 2 or higher, while the control group consisted of college students with no specific athletic specialties. Inclusion criteria included: (1) no sports-related injuries within the past year; (2) no unhealthy habits such as smoking or alcohol consumption; (3) good physical health with no physical or mental disorders; (4) right-handedness; (5) no caffeine intake prior to testing; and (6) avoiding staying up late the night before testing to ensure a normal sleep schedule.

2.3 Experimental Procedures

Upon arrival at the laboratory, researchers provided participants with a detailed explanation of the entire experimental procedure, had them sign an informed consent form, and recorded their personal information. Participants then removed their shoes and socks and sat upright barefoot in a standard chair. Another trained researcher fitted them with the fNIRS headset. The computer connected to the fNIRS system displayed the signal quality of each light electrode in real time (red: poor signal reception; yellow: no valid signal detected; green: good signal quality). Researchers adjusted the position of the light electrodes and moved the subject's hair to ensure that the signal quality for signal-quality description.

The experiment consisted of 5 task conditions, which all participants completed in a computer-generated random order.

Before the start of each task, 20 seconds of resting-state baseline data were collected. After baseline acquisition, the researchers gave the start command, and the participant performed the corresponding task for 30 seconds. At the end of the task, the participant returned to their natural, relaxed standing posture prior to the task, rested for 40 seconds, and waited for the next task to begin. During the experiment, postural balance metrics and prefrontal cortical hemodynamic measures were simultaneously recorded. All tests were conducted in a quiet, dimly lit, standardized laboratory environment. Prior to the experiment, participants emotional states were ensured to be stable, and during testing, the fNIRS head cap was covered with a light-blocking black cloth to eliminate interference from ambient light on signal acquisition. Participants were instructed to maintain as stable a body posture as possible during the standing tasks and to avoid significant head movements. To ensure participant safety, a trained researcher was stationed directly behind each participant throughout all tests to provide protection and prevent accidents such as falls.(Fig. 1).

2.4 Outcome Measures

2.4.1 Behavioral Measures

Balance testing consists of two modes: static balance and dynamic balance, and is conducted using the Korebalance Dynamic and Static Balance Assessment and Training System (U.S.). This system consists of a balance board and a computer equipped with specialized software. When the balance board is level, the target dot on the screen is positioned exactly at the center of the circular area; if the balance board tilts, the target dot on the computer screen moves in sync with it. Participants can actively adjust their body posture to maintain balance by observing the real-time position of the target dot.

In the static balance test, participants must control the target dot to remain at the center of the circular area for as long as possible; during the dynamic balance test, a marker point appears on the screen and moves along the outer edge of the circular area, and participants must adjust their balance so that the target dot remains aligned with and tracks the moving marker at all times. The task lasts 30 seconds, with a difficulty level set to 6 (on a scale of 1–10) and a platform adjustment interval of 500 ms. Upon task completion, the system generates a dynamic posture graph based on the target dot's trajectory and automatically calculates a score; a higher score indicates poorer postural control ability.

The cognitive task uses a continuous subtraction-by-7 test. This is a classic continuous mental arithmetic task that continuously engages attention and working memory [20–22]. A starting number is randomly selected from the range of 300 to 500, and the subject is required to perform consecutive subtraction-by-7 operations. The experiment required participants to complete as many correct calculations as possible, prioritizing accuracy over speed. Researchers recorded the total number of responses and the number of correct responses for each test session.

2.4.2 Hemodynamic Measures

fNIRS data were acquired using the BS-7000 near-infrared spectroscopy system (Wuhan Zilian Hongkang Technology Co., Ltd., Wuhan, China). The system employs dual-wavelength laser diodes (690

nm and 830 nm) with a sampling frequency of 20 Hz. It is configured with 8 emitters and 8 detectors, forming 22 effective measurement channels, each consisting of a light source–detector pair positioned 3 cm apart. The arrangement of the optodes was based on the internationally accepted 10–20 system, with light source S2 corresponding to the Fpz point. The spatial coordinates of the reference points (Nz, Cz, AL, RL) and all photodes were recorded using a 3D positioning system (NirMap, Wuhan Zilian Hongkang Technology Co., Ltd., Wuhan, China). The measured brain regions primarily included eight predefined prefrontal cortical regions of interest (ROIs): the left frontopolar cortex (FPC-L), right frontopolar cortex (FPC-R), left dorsolateral prefrontal cortex (DLPFC-L), right dorsolateral prefrontal cortex (DLPFC-R), left ventrolateral prefrontal cortex (VLPFC-L), right ventrolateral prefrontal cortex (VLPFC-R), left orbitofrontal cortex (OFC-L), and right orbitofrontal cortex (OFC-R). As detailed in Table 1 and shown in Fig. 2.

Table 1
Regions of interest (ROIs) and corresponding fNIRS channels

Number	ROI Name	Channnel number
1	FPC-L	Ch 04、Ch 11
2	FPC-R	Ch 19、Ch 20、Ch 21、Ch 22
3	DLPFC-L	Ch 16、Ch 17、Ch 18
4	DLPFC-R	Ch 07、Ch 14、Ch 15
5	VLPFC-L	Ch 08、Ch 09、Ch 10
6	VLPFC-R	Ch 6、Ch 13
7	OFC-L	Ch 01、Ch 02、Ch 03
8	OFC-R	Ch 05、Ch 12、

This study selected oxygenated hemoglobin(HbO) as the hemodynamic measures because it is more sensitive to changes in cortical activity than HbR [23]. The fNIRS data were processed and analyzed using the NIRS Master software. First, bad channels were excluded and data quality control was performed; the coefficient of variation (CV) for each channel was calculated using the formula $\mathrm{CV}=\frac{\sigma}{\mu}$, and the threshold for identifying bad channels was set at 20%. Subsequently, spatial localization and MNI coordinate registration were performed, and optical density signals were converted to changes in hemoglobin concentration based on the modified Beer–Lambert law. During preprocessing, spline interpolation was used to correct motion artifacts. an IIR filter was applied to eliminate irrelevant frequency bands outside the 0.01–0.1 Hz range; and signal drift was corrected by removing the linear trend. The 20 seconds before the start of the task and were used as the baseline calibration interval, and the block-averaged HbO changes for each channel during each task phase were calculated.

The fNIRS data were analyzed using a region-of-interest (ROI)-based approach. To improve the robustness of hemodynamic measurements and reduce the influence of channel-specific noise, motion artifacts, and inter-individual anatomical variability, channels within the same anatomical ROI were averaged before statistical analysis. The mean HbO concentration changes of each ROI were calculated and used as the dependent variables in subsequent statistical analyses.

2.5 Statistical Analysis

Statistical analysis was performed using SPSS 26.0. The Shapiro-Wilk test was used to assess the normality of the data; $P > 0.05$ indicated that the data followed a normal distribution. A two-factor repeated-measures analysis of variance (ANOVA) was conducted on behavioral measures and hemodynamic measures of the PFC. The Bonferroni method was used for multiple comparisons. For the fNIRS data, the P values of the Group × Task interaction effects across the eight predefined regions of interest (ROIs) were corrected using the Benjamini–Hochberg false discovery rate (FDR) procedure. An FDR-adjusted q value < 0.05 was considered statistically significant. If the data did not satisfy the assumption of normality, the corresponding analyses were performed using appropriate non-parametric tests. Pearson correlation analysis was used to assess the correlations between balance indices, Cognitive Performance, and prefrontal hemodynamic measures. The thresholds for the correlation coefficient (r) are as follows: weak correlation ($0 \le |r| < 0.3$), moderate correlation ($0.3 \le |r| < 0.5$), strong correlation ($0.5 \le |r| < 0.8$), and very strong correlation ($0.8 \le |r| < 1.0$).

3. Results

3.1 Cognitive Performance

- As shown in Table 2, the two-way repeated measures ANOVA revealed that the interaction effects between task and group were not significant for either calculation quantity or accuracy (calculation quantity: $F = 1.581$, $P = 0.222$, $\eta^2p = 0.093$; accuracy: $F = 1.916$, $P = 0.164$, $\eta^2p = 0.110$). Main effects analysis showed that, for the calculation quantity index, the main effect of task was significant ($F = 31.183$, $P < 0.001$). Bonferroni-corrected post-hoc pairwise comparisons revealed that there was no significant difference in calculation quantity between the cognitive task alone and the static balance–cognitive dual task ($P = 1.000$), whereas the calculation quantity in the dynamic balance–cognitive dual task was significantly lower than that in both the cognitive task alone and the static balance–cognitive dual task ($P < 0.001$; $P < 0.001$). The main effect of group did not reach significance ($F = 0.056$, $P = 0.815$). For the accuracy index, neither the main effect of task ($F = 0.964$, $P = 0.392$) nor the main effect of group ($F = 0.596$, $P = 0.446$) was statistically significant.

Table 2
Cognitive task performance

Index	Group	CST	SB-CDT	DB-CDT	Main effect of task (F P)	Main effect of group(F P)	Task × group interaction(F P)
Calculated number	**Athlete**	10.76 ± 1.48	10.12 ± 1.45	8.94 ± 1.14	31.183, < 0.001	0.056, 0.815	1.581, 0.222
	Non-athlete	10.47 ± 1.28	10.71 ± 1.16	8.87 ± 1.05			
Accurcy(%)	**Athlete**	87.89 ± 8.55	90.70 ± 11.10	87.82 ± 9.68	0.964, 0.392	0.596, 0.446	1.916, 0.164
	Non-athlete	90.05 ± 8.02	86.71 ± 7.76	84.50 ± 9.56			

3.2 Balance performance

- A two-way repeated measures ANOVA of the balance index revealed a significant task × group interaction ($F = 4.007$, $P = 0.016$, $\eta p^2 = 0.172$). Subsequent simple effects analyses were conducted to further examine this interaction (Fig. 3).

3.2.1 Between-Group Comparisons

- We found that there were significant differences between the ice hockey player group and the non-athlete group in the SB-ST, DB-ST, SB-CDT, and DB-CDT ($F = 12.069$, $P = 0.001$; $F = 8.536$, $P = 0.006$; $F = 7.602$, $P = 0.010$; $F = 20.298$, $P < 0.001$).

3.2.2 Within-Group Comparisons

- Within-group pairwise comparisons for the athlete group showed that balance performance in the SB-ST was significantly better than that in the DB-ST and the DB-CDT ($P < 0.001$; $P < 0.001$), with no statistically significant difference from the SB-CDT ($P = 0.203$); balance performance in the DB-ST was significantly worse than that in the SB-CDT ($P < 0.001$), but significantly better than that in the DB-CDT ($P = 0.012$); and balance performance in the SB-CDT was also significantly better than that in the DB-CDT ($P < 0.001$).
- Within-group pairwise comparisons for the non-athlete group showed that balance performance in the DB-CDT was significantly worse than that in the SB-ST, the SB-CDT, and the DB-ST ($P < 0.001$; $P < 0.001$; $P < 0.001$); balance performance in the DB-ST was significantly worse than that in the SB-ST and the SB-CDT ($P < 0.001$; $P < 0.001$), but significantly better than that in the DB-CDT ($P < 0.001$); and balance performance in the SB-CDT was significantly worse than that in the SB-ST ($P = 0.038$).

3.3 Prefrontal Cortex Hemodynamic Measures

- We found that the HbO changes in the left DLPFC-L exhibited a significant Task × Group interaction effect (F = 5.303, P = 0.002, η^2p = 0.142). This interaction effect remained statistically significant after correction using the Benjamini–Hochberg false discovery rate (FDR) procedure (FDR q < 0.05). Subsequently, simple effects analyses were performed (Fig. 4). No significant interaction effects were observed in the remaining ROIs (P > 0.05); detailed results are provided in Table 3.

Table 3
roup × Task interaction effects for ΔHbO in all eight prefrontal cortical ROIs

ROI number	Group × Task interaction (F)	Group × Task interaction (P)	FDR (q)	η^2p
FPC-L	1.018	0.391	0.572	0.030
FPC-R	2.074	0.119	0.374	0.059
DLPFC-L	5.303	0.002	0.022	0.142
DLPFC-R	2.729	0.048	0.336	0.076
VLPFC-L	1.263	0.301	0.509	0.037
VLPFC-R	0.914	0.445	0.576	0.027
OFC-L	1.694	0.185	0.407	0.050
OFC-R	0.731	0.549	0.588	0.022

3.3.1 Between-Group Comparisons

- Across the four balance tasks, significant differences in HbO changes within the DLPFC-L were observed between the athlete and non-athlete groups (P < 0.05). Specifically, during the SB-ST and SB-CDT conditions, the athlete group exhibited significantly greater HbO changes in the DLPFC-L compared with the non-athlete group (SB-ST, P < 0.001; SB-CDT, P < 0.001). In contrast, during the DB-ST and DB-CDT conditions, the athlete group showed significantly lower HbO changes in the DLPFC-L than the non-athlete group (DB-ST, P = 0.002; DB-CDT, P = 0.012).

3.3.2 Within-Group Comparisons

- In the athlete group, pairwise comparisons of HbO changes in the DLPFC-L revealed that SB-CDT (0.120 ± 0.007 μmol/L) was significantly greater than both SB-ST (0.016 ± 0.006 μmol/L; P < 0.001) and DB-ST (0.006 ± 0.008 μmol/L; P < 0.001). No significant differences were observed among the remaining task comparisons (P > 0.05).
- In the non-athlete group, pairwise comparisons of HbO changes revealed that DB-CDT (0.150 ± 0.024 μmol/L) was significantly greater than SB-ST (− 0.016 ± 0.007 μmol/L; P < 0.001), DB-ST (0.050 ± 0.009 μmol/L; P = 0.002), and SB-CDT (0.019 ± 0.009 μmol/L; P < 0.001). Furthermore, SB-CDT was significantly greater than SB-ST (P = 0.006), and DB-ST was significantly greater than SB-ST (P < 0.001). No other task comparisons reached statistical significance (P > 0.05).

3.4 Correlation Analysis

- Only ROIs showing significant Task × Group interaction effects ($P < 0.05$) were included in the correlation analyses. Pearson correlation analyses were performed to examine the relationships between DLPFC-L HbO changes and the balance index. As shown in Fig. 6, in the non-athlete group, DLPFC-L HbO changes during the DB-CDT condition were significantly positively correlated with the balance index ($r = 0.674$, $P = 0.003$). Similarly, in the athlete group, DLPFC-L HbO changes during the DB-CDT condition showed a significant positive correlation with the balance index ($r = 0.721$, $P = 0.001$)(Fig. 5).
- In addition, under the SB-CDT and DB-CDT conditions, no significant correlations were observed between cognitive performance measures (total responses and accuracy) and either the balance index or DLPFC-L HbO changes ($P > 0.05$).

4. Discussion

4.1 Behavioral Performance During Balance–Cognitive Dual-Task in Ice Hockey Players

- The results of this study indicate that ice hockey players demonstrated significantly better balance performance than the non-athlete group across all balance tasks (SB-ST, DB-ST,SB-CDT, and DB-CDT). Ice hockey players also exhibited a smaller decline in balance performance under dual-task conditions compared to the non-athlete group. Within-group comparisons further revealed that, although ice hockey players performed significantly worse in the DB-CDT than in other tasks, no significant difference was observed between the SB-CDT and the SB-ST. In contrast, the non-athlete group already showed a significant decline in balance performance in the SB-CDT.
- Regarding cognitive task performance, both groups exhibited consistent performance characteristics. The number of calculations in the DB-CDT was significantly lower than that in the CST and the SB-CDT, whereas no statistically significant difference was found between the SB-CDT and the CST. Accuracy did not show significant fluctuations across all task conditions. Between-group comparisons showed that neither the number of calculations nor accuracy exhibited a significant main effect of group, indicating that ice hockey players and non-athletes had comparable overall cognitive output levels in dual-task scenarios. Taken together with the between-group differences in balance performance, these findings suggest that athletes maintained superior postural control without sacrificing cognitive task performance, reflecting more efficient attentional resource allocation strategies during motor–cognitive parallel processing.
- The uniqueness of ice hockey lies in its demands for dynamic balance during high-speed skating. Athletes must continuously adjust their center of gravity to maintain stability on the ice while simultaneously processing complex information from opponents, teammates, and the puck. This training environment may facilitate the development of more efficient postural control strategies in

athletes. In the present study, the advantage of ice hockey players in dynamic balance tasks was particularly pronounced, which may reflect their adaptive capacity to unstable support surfaces developed through long-term training.

4.2 Patterns of Prefrontal Cortex Activation

- In this study, we found that ice hockey players exhibited lower PFC activation levels than the non-athlete group during the DB-CDT. This result supports the neural efficiency hypothesis, which posits that expert athletes demonstrate lower cortical activation levels while achieving equivalent or superior task performance.
- The neural efficiency hypothesis originated from the seminal work of Haier et al. (1988), suggesting that high-ability individuals exhibit more efficient neural organization during cognitive task execution [24]. In the sports domain, numerous studies have confirmed this hypothesis. Babiloni et al. found that karate experts showed lower cortical activation than amateurs during action judgment tasks [13]; Del Percio et al. reported that athletes exhibited lower alpha event-related desynchronization than non-athletes during shooting [25]. The present study extends this hypothesis to the balance–cognitive dual-task domain in ice hockey players, demonstrating that expert athletes can utilize prefrontal resources more economically when facing dynamic balance challenges with high cognitive demands.
- However, the manifestation of neural efficiency may vary depending on task characteristics. Sultanov et al. proposed that in open-skill sports such as soccer, neural efficiency should not be simply understood as a global reduction in activation, but rather as neural optimization—strategically recruiting specific executive networks and enhancing functional connectivity [26]. The reduced PFC activation observed in ice hockey players during the dynamic dual task in this study may represent precisely this form of neural optimization. Through more precise resource allocation, they avoid unnecessary neural energy expenditure while maintaining excellent task performance.

4.3 Differences in Prefrontal Activation Between the Static and Dynamic Dual-Task Conditions

- The present study revealed distinct prefrontal cortical activation patterns in ice hockey athletes during the SB-CDT and DB-CDT conditions. During SB-CDT, ice hockey athletes exhibited significantly greater HbO responses in the DLPFC-L compared with the non-athlete group. In contrast, during DB-CDT, HbO responses in this region were significantly lower in athletes than in non-athletes. These bidirectional differences suggest that professional athletes employ task-dependent prefrontal cortical recruitment strategies.
- Under SB-CDT, ice hockey players may need to actively invest more cognitive resources to maintain postural stability. This result may reflect that, compared with dynamic postural control frequently encountered in their long-term training, static standing is not a primary motor context of their sport-

specific training, thus requiring greater prefrontal resource involvement in postural control and cognitive resource allocation. The FPA plays a key role in managing competing goals by continuously monitoring the relative value of alternative goals and determining whether to reallocate cognitive resources away from ongoing behavior [27–29]. The reduced activation in the DLPFC-L during the DB-CDT is particularly noteworthy. The DLPFC is one of the critical regions for working memory and executive control and plays a central role in dual-task interference [30,31]. The decreased DLPFC-L activation in ice hockey players during the DB-CDT may indicate that training has facilitated the integration of resources between postural control and cognitive regulation, leading to the automatization of certain cognitive–motor coordination processes.

4.4 Positive Associations Between Prefrontal Cortex Activation and Balance Performance

- The correlation results in the present study were observed only under the balance–cognitive dual-task conditions, whereas no significant correlations were found during the single-task conditions. This finding suggests that the coupling between left prefrontal hemodynamic responses and postural performance is task-specific and becomes evident only when motor and cognitive demands compete for limited attentional resources.
- It is noteworthy that a lower balance index represents better postural control performance in the present study. Therefore, the positive correlations between PFC activation and balance index indicate that individuals with higher PFC activation generally showed higher balance indices, suggesting that they may have faced greater postural control demands. This positive relationship may reflect the increased recruitment of prefrontal cognitive resources to cope with greater postural control demands during dual-task conditions. When the complexity of postural control or cognitive tasks increases, maintaining body stability requires greater attentional resources, which may result in increased prefrontal cortical activity [32–34].

4.5 Selective Left Prefrontal Cortex Activation

- In the present study, DLPFC-L showed significant group differences, whereas the corresponding right-sided channel did not exhibit an equivalent effect. This left-sided advantage forms an interesting contrast with findings from orienteering athletes. Liu et al. reported that orienteering experts showed significant activation differences in the left ventrolateral prefrontal cortex (L-VLPFC) during cognitive tasks, which the researchers attributed to the map-perception spatial cognitive training specific to orienteering [35]. Different sports may shape distinct PFC activation patterns. Ice hockey and orienteering may strengthen the left PFC's functions in multi-target management and spatial working memory, whereas sports such as table tennis, which rely more on rapid visuospatial processing, exhibit right-hemisphere dominance [36].
- Correlation analyses further support the critical role of the left PFC in postural control among ice hockey players. In ice hockey players during the dynamic dual task, activation in the DLPFC-L was

significantly positively correlated with balance indices (r = 0.721, P = 0.001). The existence of this positive correlation suggests that the PFC retains a certain regulatory function in dynamic balance, rather than being completely replaced by automated pathways.

- Notably, the left-sided advantage observed in this study differs from the findings reported by Yu et al. in ice hockey players. The latter found that elite ice hockey athletes exhibited right-hemisphere dominance during executive control attention network tasks [37]. This discrepancy may stem from differences in task characteristics. Yu et al. employed a lateralized attention network task, focusing on the orienting and shifting of spatial attention, whereas the present study used a balance–cognitive dual task, emphasizing multi-target management and working memory operations. Different cognitive components may be dominated by different hemispheres, and the complexity of ice hockey lies precisely in its simultaneous demand for these functions.

4.6 Limitations

- This study has several limitations. Only male ice hockey players were recruited, and all participants were drawn from the same age group and competitive level. Female athletes and athletes of different ages may exhibit distinct neural adaptation patterns. Although the sample size met the minimum requirement calculated by G*Power, it was still relatively small; a larger sample would help improve statistical power. Therefore, the findings of this study have certain limitations, and future research should expand the sampling sources and include athletes of different genders and competitive levels for validation.
- This study employed a cross-sectional design, making it impossible to determine whether the observed group differences were entirely attributable to training or whether selection effects due to innate factors were present. Longitudinal tracking studies would help clarify causal relationships.
- This study only measured the PFC and did not cover other brain regions involved in postural control, such as the parietal lobe, cerebellum, and basal ganglia. Future studies could adopt whole-brain fNIRS arrays or combine fMRI techniques to obtain more comprehensive neuroimaging data.

5. Conclusion

- This study used fNIRS to examine behavioral performance and prefrontal cortical activation in ice hockey players and non-athlete controls during single-task and balance–cognitive dual-task conditions. Ice hockey players demonstrated better balance performance than controls during static and dynamic balance tasks and during both balance–cognitive dual-task conditions. Although calculation accuracy did not differ significantly between groups, the number of calculations decreased during the dynamic balance–cognitive dual task, indicating greater cognitive demands under dynamic postural control.
- A significant Group × Task interaction was observed in DLPFC-L HbO responses. Compared with controls, ice hockey players exhibited lower DLPFC-L activation during the dynamic balance–cognitive dual task while maintaining better balance performance, a pattern consistent with more

efficient allocation of prefrontal resources. In contrast, higher DLPFC-L activation was observed in athletes during the static balance–cognitive dual task, suggesting that prefrontal recruitment varied according to task demands rather than reflecting a uniform reduction in cortical activity.

- DLPFC-L activation during the dynamic balance–cognitive dual task was positively correlated with the balance index in both groups. Because a higher balance index represented poorer postural control, this association may reflect greater compensatory prefrontal recruitment in individuals experiencing greater balance demands. Overall, the findings indicate that ice hockey players exhibit task-dependent differences in DLPFC-L engagement during balance–cognitive interactions. However, given the cross-sectional design, these findings should be interpreted as group-related neural differences that are consistent with, but do not establish, training-induced neuroplasticity.

Declarations

Conflicts of Interest:

The authors declare no conflicts of interest.

Funding Statement

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Author Contribution

W.W.: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft. Z.Y.: Investigation, Data curation, Formal analysis. C.J.: Investigation, Data curation. J.Y.: Investigation, Data curation. Z.S.: Investigation, Data curation. X.Q.: Methodology, Validation, Formal analysis. W.L.: Conceptualization, Methodology, Supervision, Writing – review & editing. F.W.: Conceptualization, Supervision, Project administration, Writing – review & editing.

Data Availability

The data that support the findings of this study are available from the corresponding author on reasonable request. Data are not publicly available due to privacy reasons.

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Figures

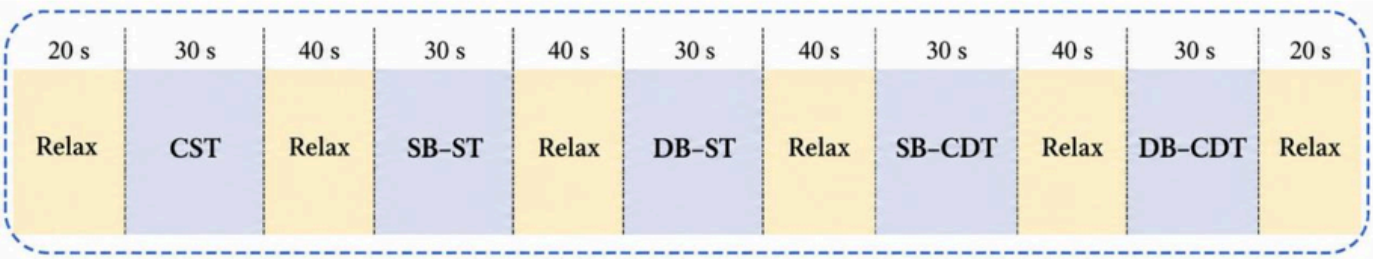


Figure 1. Experimental task procedure（The order of task conditions was presented in a randomized order to minimize potential order effects. The sequence illustrated in the figure is representative only.）

Figure 1

See image above for figure legend



Figure 2. Spatial distribution of the 22 fNIRS channels over the prefrontal cortex.

Figure 2

See image above for figure legend

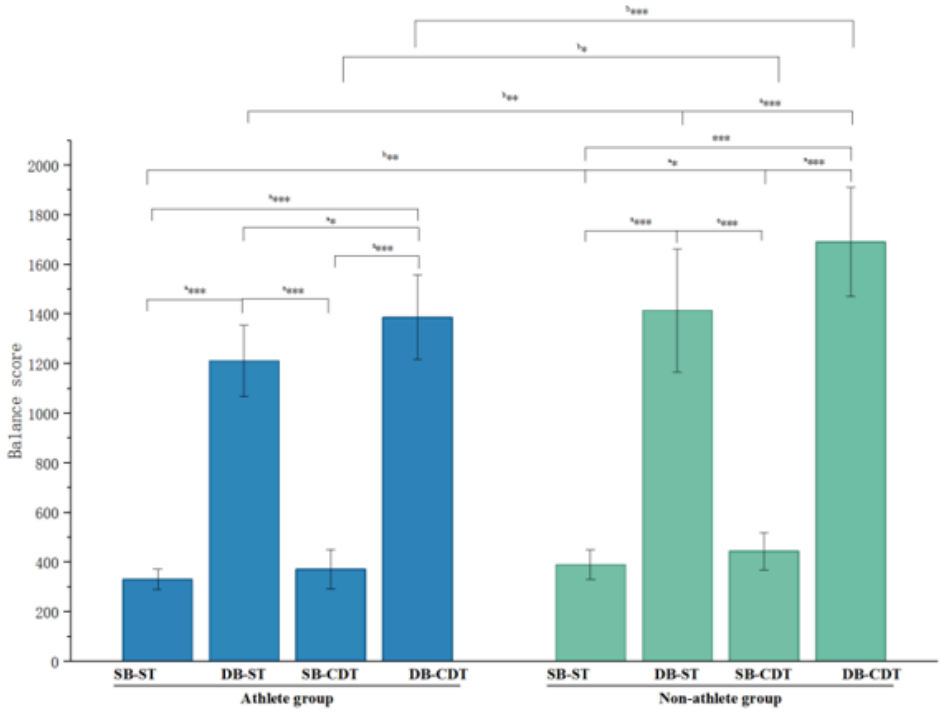


Figure3. Comparison of the balance index under different task conditions.（a, Within-group comparisons; b, Between-group comparisons）

Figure 3

See image above for figure legend

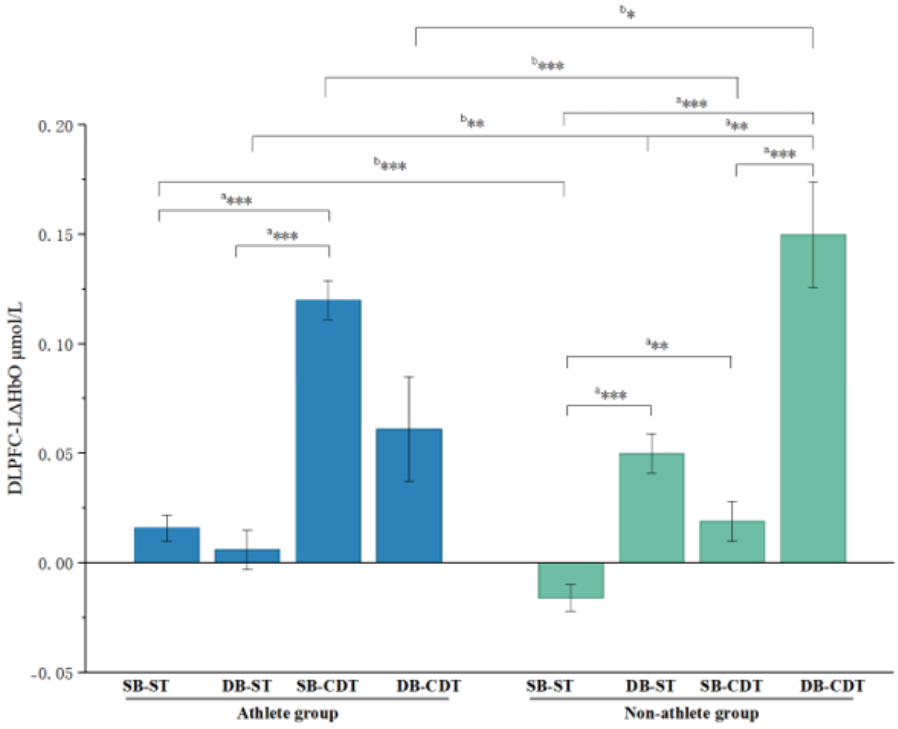


Figure4. Comparison of ΔHbO in DLPFC-L under different task conditions.（a, Within-group comparisons; b, Between-group comparisons）

Figure 4

See image above for figure legend

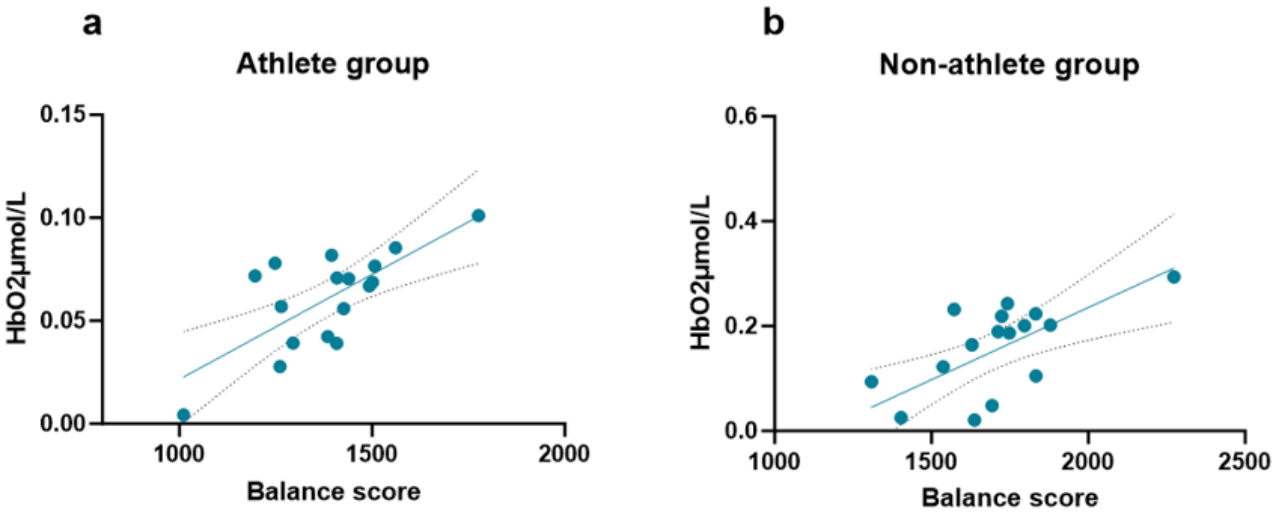


Figure 5. Correlations under balance–cognitive dual-task conditions.(a) DLPFC-L ΔHbO and balance index in non-athletes during DB-CDT. (b) DLPFC-L ΔHbO and balance index in athletes during DB-CDT.

Figure 5

See image above for figure legend