

Interventions and fNIRS Brain Activity for Preventing Cognitive Frailty: A Systematic Review

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INTRODUCTION

Cognitive frailty is a reversible pre-dementia stage, but traditional tests fail to track real-time brain dynamics or distinguish true neural efficiency from exhausting compensatory hyperactivation. Functional Near-Infrared Spectroscopy (fNIRS) overcomes this by monitoring prefrontal cortex oxygenated hemoglobin and hemodynamic changes during active movement. This systematic review analyzes fNIRS-based prefrontal changes during interventions to provide an objective, neuroscientific basis for tailored clinical rehabilitation.

METHODS

Following PRISMA guidelines and the PICO framework, we systematically reviewed the effects of preventive interventions on cognitive frailty and associated fNIRS brain activity changes. A comprehensive literature search was conducted across Scopus, Embase, PubMed, EBSCO, and PsycINFO using keywords related to aging, cognitive frailty, fNIRS, and clinical interventions. Based on rigorous inclusion criteria—targeting older adults without neurological disorders and using fNIRS hemodynamic metrics—6 studies were finally selected and analyzed for data synthesis.

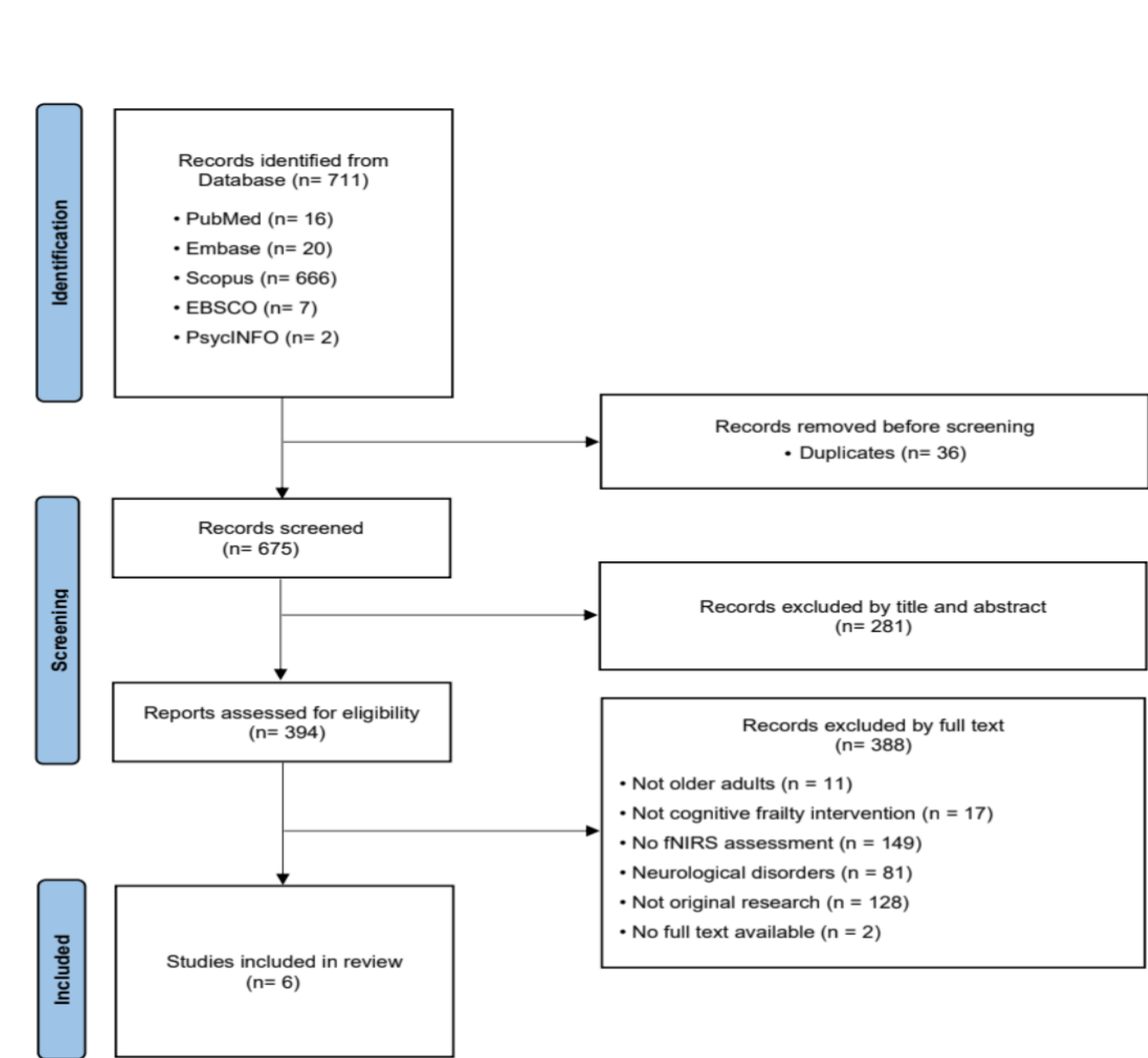


Figure 1. PRISMA flow diagram

<Table 1> Characteristics of Included Studies and Technical Specifications						
No.	Study (Author, Year)	Study Design	Total Participants (N)	Population and Age (Mean±SD)	fNIRS Device (Number of Channels)	Region of Interest (ROI) and Placement
1	Holtzer et al. (2019)	Burst measurement design (repeated measures)	83	Community-dwelling non-demented older adults; 78.05±6.37 years	fNIRS Imager 1100 (16 channels)	Prefrontal Cortex (PFC) / International 10-20 system
2	Izzetoglu & Holtzer (2025)	Device comparison and validity verification (cross-over study)	15	Healthy older adults; 67.4±6.49 years	fNIR Imager 1100 & NIRSport 2 (16 channels)	Prefrontal Cortex (PFC) / International 10-20 system
3	Liao et al. (2021)	Randomized Controlled Trial (RCT)	46	Frail older adults; 79.6±9.0 years	OEG-16 (16 channels)	Bilateral Prefrontal Cortex (PFC) / 10-20 system
4	Wagshul et al. (2019)	Multimodal neuroimaging study (MRI + fNIRS)	55	Community-dwelling non-demented healthy older adults; 74.8±5.0 years	fNIRS Imager 1100 (16 channels)	Bilateral Prefrontal Cortex (PFC) / 10-20 system
5	Wang et al. (2025)	Cross-sectional study	50	Cognitively frail older adults and healthy controls; 78.4±5.9 years	NIRSport2 (14 channels)	PFC, SMA, PMC / International 10-5 system
6	Yao et al. (2022)	Randomized Controlled Trial (RCT)	72	Community-dwelling older adults; 66.92±4.77 years	NirxSmart (19 channels)	Prefrontal Cortex (PFC) / International 10-20 system

<Table 2> Summary of Task/Intervention Protocols and fNIRS Outcomes						
No.	Study (Author, Year)	Task and Intervention Details	Duration and Frequency	Hemodynamic Indices	Primary Outcome Measures	Key fNIRS Results (Brain Activation Changes)
1	Holtzer et al. (2019)	Dual-Task Walking (DTW: walking + alphabet)	3 repetitions within 1 session	HbO ₂ , Hb	Walking speed, alphabet generation rate, PFC HbO ₂	Decrease in PFC HbO ₂ during repeated performance (improved brain efficiency)
2	Izzetoglu & Holtzer (2025)	Dual-Task Walking (DTW: walking + subtracting 3)	1 visit	HbO, HbR	PFC HbO, walking speed, heart rate	Significant increase in PFC activity during DTW; proven to be actual neural activity
3	Liao et al. (2021)	Exergaming vs. combined physical exercise	12 weeks, 3 times/week, 60 min/session	HbO	Global cognition (MoCA), executive function, attention	Decrease in PFC activation during cognitive tasks after training (enhanced brain efficiency)
4	Wagshul et al. (2019)	Dual-Task Walking (DTW: walking + alphabet)	2 sessions (MRI/fNIRS)	HbO ₂	Prefrontal Gray Matter Volume (GMV), PFC HbO ₂	Smaller GMV associated with increased HbO ₂ during DTW (neural inefficiency)
5	Wang et al. (2025)	Square-Stepping Exercise (SSE: cognitive-motor task)	Single assessment	HbO	SSE performance, brain activation (HbO), executive function	Observed capacity limitation and neural inefficiency in the cognitively frail group
6	Yao et al. (2022)	Baduanjin exercise vs. motor imagery training vs. control	Single session, 15 min	HbO	Executive function (Stroop), brain activation	Significant increase in left PFC (DLPFC) HbO during Stroop task performance Significant increase in right IFG HbO (imagery group only)

DLPFC = dorsolateral prefrontal cortex; DTW = dual-task walking; fNIRS = functional near-infrared spectroscopy; GMV = gray matter volume; HbHbR = deoxygenated hemoglobin; HbO/HbO2 = oxygenated hemoglobin; IFG = inferior frontal gyrus; min = minutes; MoCA = Montreal Cognitive Assessment; MRI = magnetic resonance imaging; PFC = prefrontal cortex; SSE = Square-Stepping Exercise.

RESULTS

Across the 6 selected studies involving 321 older adults, fNIRS consistently tracked prefrontal cortex hemodynamic responses during various cognitive-motor and physical interventions. Older adults with cognitive frailty initially demonstrated neural inefficiency, showing excessive prefrontal compensatory hyperactivation during high-load dual-tasks to sustain performance. However, when cognitive or motor difficulty exceeded a certain threshold, a capacity limitation occurred where prefrontal activation dropped sharply, leading to a decline in task performance.

Conversely, structured multi-domain interventions—such as 12-week exergaming or combined physical exercise—significantly decreased prefrontal oxygenated hemoglobin concentration while improving cognitive test scores. This reduction reflects a training-induced neural efficiency pattern and successful brain automation. Additionally, even a single 15-minute session of physical or motor imagery exercise immediately enhanced localized prefrontal activation, providing clear neuroscientific evidence that targeted non-pharmacological strategies induce neuroplastic changes.

CONCLUSIONS

Non-pharmacological interventions effectively prevent cognitive frailty, with fNIRS-measured prefrontal hemodynamic changes providing a robust neuroscientific basis for their clinical efficacy. The findings demonstrate that structured training successfully shifts brain activity from costly compensatory hyperactivation to optimized neural efficiency.

These results suggest that brain-imaging-based objective evaluations are essential for developing tailored brain health programs and precision intervention strategies in clinical rehabilitation. Ultimately, fNIRS holds substantial potential as a sensitive biomarker for evaluating early-stage dementia prevention strategies in the aging population.

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