*Original Article*

PTRS Physical Therapy Rehabilitation Science

https://doi.org/10.14474/ptrs.2024.13.2.213
eISSN 2287-7584
pISSN 2287-7576

Phys Ther Rehabil Sci
2024, 13(2), 213-222
www.jptrs.org

# A Systematic Review of Cortical Excitability during Dual-Task in Post-Stroke Patients

**Soyi Jung**[a], **Chang-Sik An**[b*]

[a]Department of physical therapy, Uijeongbu eulji university hospital, Republic of Korea
[b]Department of Physical Therapy, College of Health Science, Eulji University, Republic of Korea

**Objective:** Stroke is a leading cause of disability worldwide, often leaving survivors with significant cognitive and motor impairments. Dual-task (DT), which involves performing cognitive and motor tasks simultaneously, can influence brain activation patterns and functional recovery in stroke patients.

**Design:** A systematic review

**Methods:** Following PRISMA guidelines, databases including MEDLINE, CINAHL, Embase, and Web of Science were searched for studies assessing cortical activation via functional near-infrared spectroscopy (fNIRS) during DT performance in stroke patients. Studies were selected based on predefined eligibility criteria, focusing on changes in hemodynamic responses and their correlation with task performance.

**Results:** Eight studies met the inclusion criteria. Findings indicate that DT leads to increased activation in the prefrontal cortex (PFC), premotor cortex (PMC), and posterior parietal cortex (PPC), suggesting an integrated cortical response to managing concurrent cognitive and motor demands. However, increased activation did not consistently translate to improved functional outcomes, highlighting the complex relationship between brain activation and rehabilitation success.

**Conclusions:** DT interventions may enhance cortical activation and neuroplasticity in post-stroke patients, but the relationship between increased brain activity and functional recovery remains complex and requires further investigation. Tailored DT programs that consider individual neurophysiological and functional capacities are recommended to optimize rehabilitation outcomes.

**Key Words:** Stroke, DT, Cortical activation, Rehabilitation, Neuroplasticity

## Introduction

Stroke is a serious health issue that, according to the World Health Organization (WHO), is the second most common cause of death and disability worldwide [1]. In South Korea, the number of stroke patients increased by 7.1% from 634,177 in 2018 to 2022 according to the Health Insurance Review and Assessment Service's report on cerebrovascular disease treatment status. Despite early and appropriate treatment, many survivors still experience various degrees of disability that impair their quality of life [2]. Stroke patients exhibit impairments in cognitive functions and motor skills such as walking, and these impairments are more pronounced during Dual-task (DT) activities [3-5]. The goal of rehabilitation for stroke patients is to maximize recovery of residual functions to facilitate a return to complex daily activities requiring cognitive, sensory, and physical performance [6].

DT, which involves performing two tasks simultaneously rather than sequentially, typically results in

**Received:** Jun 2, 2024 **Revised:** Jun 26, 2024 **Accepted:** Jun 27, 2024
**Corresponding author:** Chang-Sik An (**ORCID** https://orcid.org/0009-0005-0665-8342)
Department of Physical Therapy, College of Health Science, Eulji University
553, Sanseong-daero, Sujeong-gu, Seongnam-si, Gyeonggi-do [13135], Republic of Korea
**Tel:** ***-****-**** **Fax:** +82-31-740-7376 **E-mail:** acsik@eulji.ac.kr

a degradation in the performance of at least one of the tasks due to cognitive-motor interference [7]. This can lead to an increased risk of falls and decreased efficiency in task execution [3]. Despite an increase in prefrontal cortex activation, stroke patients demonstrate a decrease in motor and cognitive abilities during DT performance [8]. This indicates inefficiencies in brain resource utilization and can result in a decline in performance [9, 10]. Therefore, for effective performance in DTs, it is crucial to understand functional connectivity and networks within the brain cortex [11].

Among the existing brain imaging techniques, functional Magnetic Resonance Imaging (fMRI) detects high-resolution cerebral blood flow signals but requires a controlled environment and is unsuitable for patients with metal implants [12]. Electroencephalography (EEG) offers high temporal resolution but low spatial resolution and is susceptible to motion artifacts, making it challenging to apply in dynamic DT training. On the other hand, functional near-infrared spectroscopy (fNIRS), based on the principle of neurovascular coupling that regulates blood flow to meet the energy demands of active neurons [13], allows for the real-time monitoring of hemodynamic changes in the brain during activities and walking without spatial or temporal restrictions [14].

fNIRS provides better resistance to motion artifacts and greater experimental flexibility compared to other neuroimaging methods, making it more suitable for use in neurologic patients [15-17]. However, most prior studies using fNIRS have focused only on activation in the prefrontal cortex[11, 18-22], often overlooking other brain areas such as the premotor cortex (PMC), which is involved in motor planning and preparation, the sensorimotor cortex (SMC), which handles motor output or sensory input, and the posterior parietal cortex (PPC), which is important for sensorimotor integration[19, 23-25]. Therefore, systematic investigations of changes in cortical activity and functional connectivity from single to multiple tasks are necessary beyond the prefrontal cortex [26]. Additionally, the relationship between brain activation and clinical measurements remains unclear [25]. One study reported that poor motor function in stroke patients was associated with increased compensatory prefrontal cortex activation, while lower cognitive function corresponded to reduced activation in the same region [27]. Another study showed a negative correlation between motor status and DT brain activation [28]. Therefore, further research is needed to establish the relationship between clinical measurements and levels of brain activation in stroke patients [26].

In this review, we aim to synthesize studies that have examined changes in cortical excitability during DTs in post-stroke patients using fNIRS, and to analyze and evaluate the comparative effectiveness of different DT protocols and the relationships between the evaluated cortical regions.

## Methods

### Study Design

This study is a systematic literature review conducted to analyze the cortical activation and functional connectivity efficiency of various DT training programs applied to stroke patients with different durations of illness and cognitive and motor functions. It follows the guidelines of the Cochrane Collaboration's handbook for systematic reviews of interventions and PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) for reporting available literature. Additionally, the methodological protocol of this systematic review has been registered with the PROSPERO International Prospective Register of Systematic Reviews (CRD42024523192).

### Eligibility Criteria

Eligibility criteria were established based on the PICOSD framework, which includes Participants [P], Intervention [I], Comparison [C], Outcomes [O], and Study Design [SD].

Studies were selected following the PRISMA FLOW DIAGRAM guidelines and organized according to the PICOS framework. This study's participants (P) encompass both acute and chronic stroke patients. The intervention (I) involved DT. Comparisons (C) were made with control groups receiving standard interventions excluding DT, selected from studies with homogeneous control groups. The outcomes (O)

focused on the measurement of cortical areas' HbO and HbR using fNIRS. Study designs (SD) included all studies that examined changes in fNIRS during DT training in stroke patients. Studies excluded were those only published as abstracts, non-English language studies, studies only presented at academic conferences, and studies that were more than ten years old.

### Search Strategy

The systematic review were conducted in April 2023 by researchers with experience in systematic review. The search strategy utilized key terms related to Participants, Intervention, and Outcomes, based on MeSH (Medical Subject Heading). Keywords used included combinations of "stroke OR cerebrovascular accident OR cva OR post-stroke OR stroke patients" AND "functional near-infrared spectroscopy OR near-infrared spectroscopy OR hemodynamics" AND "Dual-task OR Dual-task training OR Dual-tasking OR Dual-task performance". Searches were performed across international databases such as the Cumulative Index of Nursing and Allied Health Literature (CINAHL), Excerpta Medica Database (Embase), Medical Literature Analysis and Retrieval System Online (MEDLINE), and Web of Science.

### Data Extraction

Data from selected studies were extracted into Microsoft Excel (Microsoft Excel 16.71, Microsoft, USA) to eliminate duplicates. Following PRISMA guidelines, titles and abstracts were initially screened, followed by a detailed review of the full texts for studies that did not meet initial criteria. Selections were based on the defined eligibility criteria, and any disagreements among researchers were resolved through joint review.

### Risk of Bias Assessment

Risk of bias for randomized controlled trials was assessed using a tool developed by the Cochrane Bias Method Group, consisting of seven items [29]. Two researchers independently rated the risk of bias as low ( + ), high ( - ), or uncertain (?). Disagreements were settled by jointly revisiting the original texts. Cross-sectional studies were evaluated using the ROBINS-E tool (Risk Of Bias In Non-randomized Studies - of Exposures) [30], where the risk of bias was determined to be critical (I), serious (x), moderate ( - ), low ( + ), and not applicable (Na).

## Results

### Literature Search and Characteristics of Included Studies

As depicted in Figure 1, a total of 158 studies were initially identified from four international electronic databases and search engines. First, 42 duplicate studies were identified and removed using Excel. Following this, the titles and abstracts were screened by researchers, resulting in the exclusion of 107 studies. Lastly, one study that did not provide data according to the eligibility criteria was also excluded after a full-text review. Ultimately, 8 studies were included for qualitative analysis [31-38].

### Risk of Bias of Synthesized Studies

The risk of bias assessment of the eight studies had 100% agreement among researchers. The results of the three RCTs and five other studies are shown in Figure 2.

### Cortical Activation Changes between DTs in Stroke Patients.

Recent research on stroke patients highlights that DT compared to single-task significantly increases brain activation, particularly in the prefrontal cortex and other related areas such as the premotor and posterior parietal cortex. This increased activation correlates with greater energy expenditure and improved cognitive and motor function integration. However, excessive activation does not always translate to functional improvements, suggesting a complex interaction between brain activation and motor recovery.

## Discussion

This systematic review elucidates the dynamic

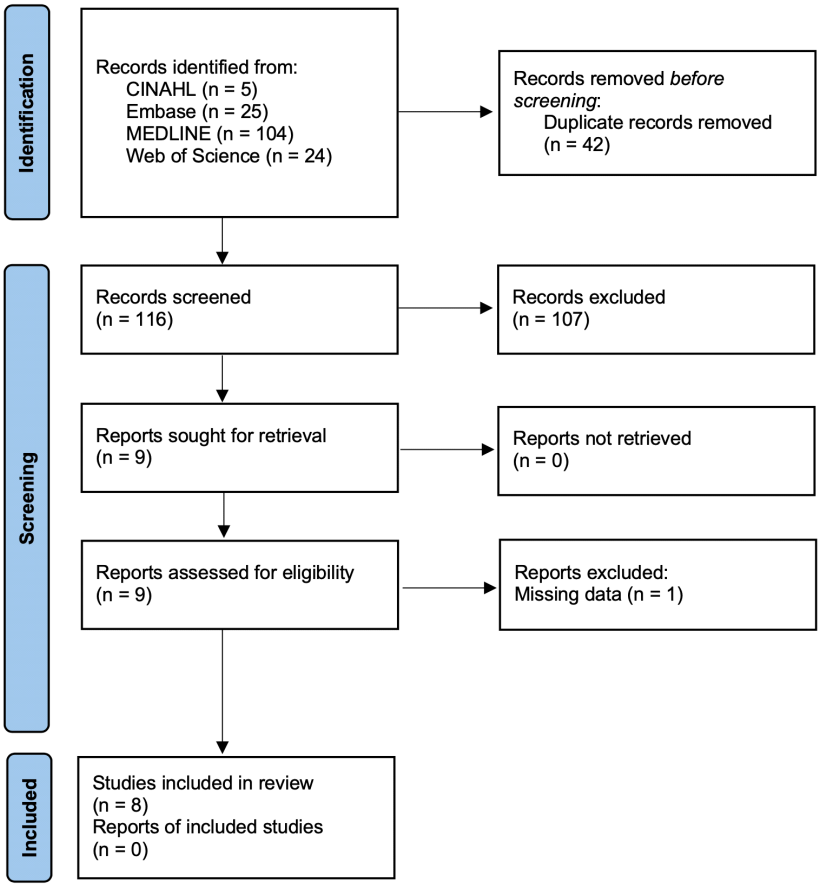


**Figure 1.** PRISMA flow diagram

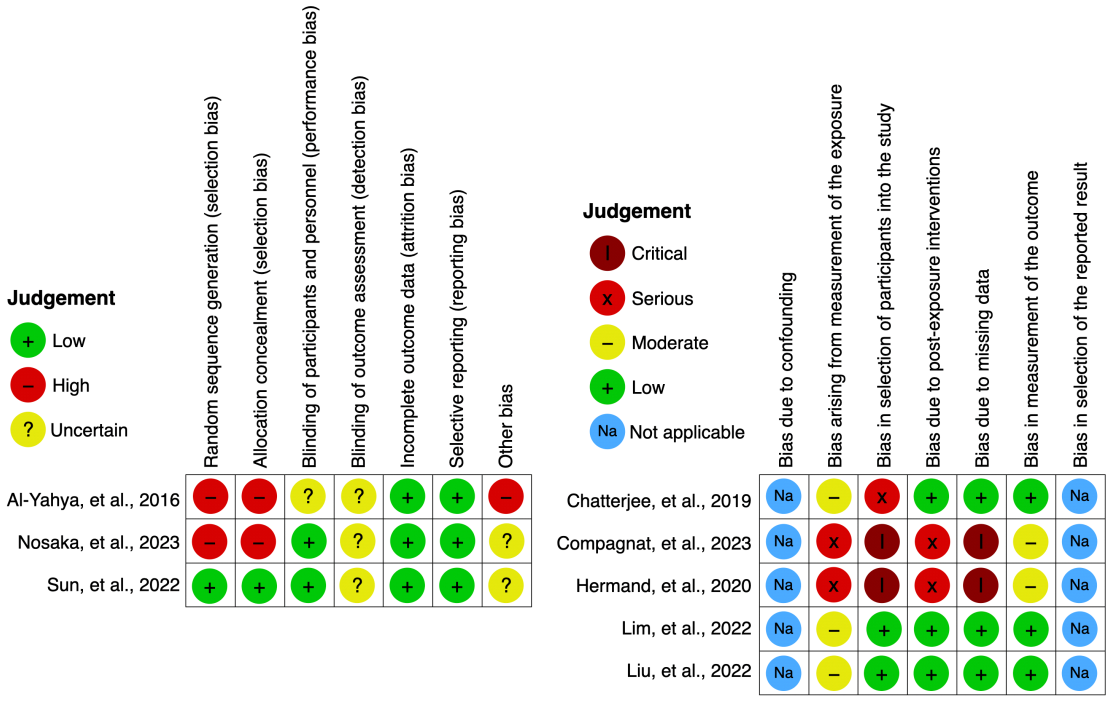


**Figure 2.** Risk of bias summary

**Table 1.** Characteristics of the included trials

| Study | Condition Participants (n) | Study design | Intervention | fNIRS ROI | Author's conclusion |
|---|---|---|---|---|---|
| Al-Yahya, et al., 2016 [31] | Experiment 1<br>EG (17): Chronic stroke<br>CG (20): Healthy<br>Experiment 2<br>EG (9): Chronic stroke<br>CG (10): Healthy | Randomized controlled trial | Experiment 1 (fNIRS)<br>EG & CG:<br>(A) STmot: Treadmill walking task<br>(B) STcog: Count backward in sevens from a random number between 291 and 299 in standing<br>(C) CMDT: Treadmill walking task with counting backward<br><br>Experiment 2<br>(fNIRS & fMRI)<br>(A) STcog: Counting backward covertly in threes from a given number only<br>(B) STmot: Simulated walking (feet movement only)<br>(C) CMDT: Counting and feet movement concurrently | fNIRS: PFC<br>fMRI: Inferior temporal gyri, Superior frontal gyri and Cingulate gyri bilaterally, and the Right precentral gyrus | • Enhanced brain activity is associated with motor decrements during DT walking.<br>• In both groups of Experiment 1, PFC activation increased during DT walking compared to ST walking.<br>• In Experiment 2, stroke patients showed more bilateral PFC activation under CMDT conditions than controls.<br>• Patients with the greatest behavioral cost during DT walking showed compensatory PFC recruitment for top-down control to manage responses based on task goals and environmental constraints. |
| Chatterjee, et al., 2019 [32] | EG (31)<br>1) Chronic post-stroke (at least 6 months post-stroke)<br>2) Affected Hemisphere (Left/Right) 16/17<br>3) Lesion Location (ACA/MCA/BG&IC /Pons) 4/10/14/5 | Cross-sectional study | (A) STmot: Walk<br>(B) STcog: Serial-7 subtraction randomly assigned number between 91 and 99 in a seated position (Serial7)<br>(C) CMDT: Walking while Serial7 | Prefrontal recruitment from the anterior prefrontal cortex (Brodmann Area 10) | • For Walk, poor balance confidence (ABC Scale score) significantly predicted greater prefrontal with compensatory over-recruitment.<br>• For DT, poor cognitive function (MMSE score) significantly predicted lower prefrontal recruitmentduring DT walking, consistent with a lower ''ceiling'' of brain resource recruitment |
| Compagnat, et al., 2023 [33] | EG (19 )<br>1) Sub-acute phase of stroke (between 1 week and 6 months post-stroke)<br>2) High functioning patients with a BI of 95<br>3) FAC of 5<br>4) Walking velocity > 0.65 m/s<br>5) The left or right temporal-parietal regions (outside the prefrontal regions type of stroke)<br>6) Stroke subtype (ischaemic/hemorrhagic) 18/4<br>7) Stroke localization in the MCA region<br>Subcortical right 7<br>Subcortical left 10<br>Cortical right 2<br>Cortical left 3 | Retrospective cross-sectional study | (A) STcog: 1-back task<br>(B) STmot: Walk at their spontaneous comfort speed in their usual walking in a straight line more than 30 meters long<br>(C) CMDT: Walking while performing a 1-back | Symmetrical PFC Fp1 and Fp2 | • CMDT leads to increased cerebral $HbO_2$ and energy cost of walking, particularly affecting those with higher baseline motor task costs.<br>• Significant PFC activity variations in the contralesional hemisphere suggest adaptive recruitment in response to task demands. ·Additionally, in the acute phase of stroke, there is a negative laterality index due to reduced activity in the ipsilesional hemisphere and compensatory activity increase in the contralesional hemisphere. |
| Hermand, et al., 2020 [34] | EG1 (8): LoB (lower BI between 61 and 90); moderate dependency<br>EG2 (13): HiB (higher BI between 91 and 100); slight dependency<br>1) Acute or subacute stroke (left or right middle cerebral artery)<br>2) Affected hemisphere (Left/Right)<br>EG1 4/4, EG2 8/5<br>3) Stroke subtype (Ischemic/Hemorrhagic)<br>EG1 6/2, EG2 11/2 | Retrospective cross-sectional study | Randomly<br>(A) STcog: A 2-back task<br>(B) STmot: A walking<br>(C) CMDT: Walking while a 2-back task | Symmetrical prefrontal sites Fp1 and Fp2 | • HiB showed a lower PFC activation and better gait parameters in single and DTs compared to LoBwho exhibited decreased gait performances despite a higher PFC activation, especially in the unaffected side.<br>• PFC overactivation in less functional subacute stroke patients may be due to the loss of stepping automaticity. |

**Table 1.** (continued)

| Study | Condition Participants (n) | Study design | Intervention | fNIRS ROI | Author's conclusion |
|---|---|---|---|---|---|
| Lim, et al., 2022 [35] | EG (20)<br>1) Chronic stroke (> 6 months previous)<br>2) Lesion depth (cortical/subcortical /mixed) 0/17/3<br>3) Lesion side (Left/Right) 7/13 | Cross-sectional study | (A) STmot: Walking 50-m hallway<br>(B) DT-Easy: Walking while saying a word repeatedly; ma, pa, da, ba, ta.<br>(C) CMDT Hard: Walking while completing a verbal fluency task; started with one of the following letters: B, R, D, C, H | PFC, PMC, SMC, PPC | • Importance of Brain Regions: The study highlights that areas involved in executive function, motor planning, and sensorimotor integration are crucial for managing dual-task walking post-stroke.<br>• Activation Thresholds: Findings indicate a limit to how much brain activation increases with dual-task difficulty, suggesting a plateau where additional complexity does not enhance activation. |
| Liu, et al., 2022 [36] | EG (23)<br>1) Chronic post-stroke hemiparesis ; at least 6 months post-stroke<br>2) Stroke type (I/H) 12/11<br>3) Hemiparetic side (left/right) 11/12 | Cross-sectional study | (A) STmot: Walking comfortable speed<br>(B) CMDT: Walking while subtracting 3 from an initial three-digit number serially<br>(C) WMT: Walking while carrying a tray with a bottle of water on the tray with their unaffected hand. | PFC, PMC, SMA | • Gait Performance Impact: Stroke patients showed decreased gait speed, cadence, and stride length with increased stride time during dual-task walking versus single walking.<br>Brain Activity<br>• Differences: Significant brain activity increases were noted in the non-lesioned SMA and bilateral premotor cortices during dual-task walking.<br>• Comparison of Dual Tasks: No significant differences in gait performance were found between cognitive and motor dual tasks despite changes in gait and brain activity. |
| Nosaka, et al., 2023 [37] | EG1 (11): FAC scores ≤2<br>EG2 (11): FAC scores > 2<br>1) Stroke onset within 2weeks to 3months<br>2) Subtype (ischemic/hemorrhagic) EG1 7/4 EG2 4/7<br>3) Lesion hemisphere (left/right) EG 13/8, EG2 4/7<br>4) Lesion depth (cortical/subcortical/mixed) EG1 1/6/4, EG2 0/9/2 | Randomized controlled trial | EG1<br>(A) STcog: Letter fluency task; word recall using the first letter of the word (e.g., those beginning with "a") while seated in a chair (CT)<br>(B) STmot: Normal seated stepping (NSS)<br>(C) DT: Seated stepping while letter fluency task (DTSS)<br>EG2<br>(A) STcog: CT<br>(B) STmot: Normal walking (NW)<br>(C) DT: Walking while letter fluency task (DTW) | Symmetrical PFC Fp1 and Fp2 (Brodmann area 10 at the bilateral frontal poles) | • PFC Activation and Task Type: The study indicated that DTSS activated the PFC more than single tasks, highlighting increased cognitive demands.<br>• Hemodynamic Responses: Increases in oxygenated hemoglobin were more pronounced in the contralesional hemisphere during dual-task walking, showcasing brain asymmetry in stroke patients.<br>• Functional Correlations: Positive correlations were found between PFC activation, Frontal Assessment Battery scores, and cognitive performance, suggesting the efficacy of dual-task activities in enhancing cognitive functions in subacute stroke patients. |
| Sun, et al., 2022 [38] | EG(17): DT<br>CG(16): STcog<br>1) Type (I/H)*<br>EG 11/6<br>CG 12/4<br>2) post-stroke cognitive impairment (PSCI)<br>− IQCODE 9 < and ≤3.3<br>− MMSE 9 < and < 27<br>− MoCA < 26 | Randomized controlled trial | 1) Progressive training program for 4 weeks 40 min of training per day, 5 days a week<br>2) High accuracy (> 90%) was required to upgrade to the next difficulty level<br>EG<br>CMDT: 20 min of rehabilitation treadmill and 20 min of walking on a flat surface<br>while VFT consisted of three different characters with the same pronunciation (20s / a Chinese character)<br>CG<br>STcog: VFT | Frontal lobe | • The average peak level of oxy-Hb in the frontal lobe increased in the CMDT group and STcog group<br>• CMDT trainingsignificantly increased the rate of oxygen supply to the frontal lobe.<br>• CMDT training shortened the reaction time of central neurons and accelerated the nerve conduction velocity to accelerate the speed of cognitive processing and improve cognitive function more effectively. |

BI: Barthel index, CG: control group, CMDT: cognitive motor daul task, CMDT: cognitive-motor dual-task, EG: experimental group, FAC: functional ambulation categories, IQCODE: Informant questionnaire on cognitive decline in the elderly, LI: laterality index, MMSE: mini-mental state examination, MoCA: Montreal cognitive assessment, PFC: prefrontal cortex, PMC: premotor cortex, PPC: posterior parietal cortex, SMA: supplementary motor areas, SMC: sensorimotor cortex, STcog: cognitive Single-task, STmot: motor Single-task, VFT: the verbal fluency task, WMT: walking while performing motor task.

interplay between cognitive and motor functionalities in post-stroke patients during DT activities, highlighting the critical role of cortical activations across various regions such as the PFC, PMC, PPC, and SMA. These findings suggest that DT interventions might significantly influence brain activation patterns, promoting better integration of cognitive and motor functions.

### Cortical Activation and Functional Outcomes

Increased activation of the PFC during DTs, as noted in multiple studies, underscores its integral role in managing combined cognitive and motor demands [27]. However, enhanced PFC activation does not uniformly translate into improved functional outcomes. This discrepancy suggests that in some instances, increased activation may represent compensatory mechanisms rather than recovery, highlighting a complex relationship between brain activation and actual functional enhancement.

### Metabolic Costs and Contralateral Activation

The review corroborates findings that DT markedly increases metabolic demands, evidenced by heightened energy expenditure and corresponding increases in contralateral PFC activation [33]. This response indicates significant neurophysiological adaptation and suggests that the brain's effort to handle multiple tasks can substantially elevate metabolic costs, which could be a consideration in designing rehabilitation programs.

### Integration of Cortical Responses

The extensive activation of cortical networks involving the PMC and PPC, in addition to the PFC, suggests an integrated response to increased demands during DT [19, 25]. This broad activation pattern may reflect the brain's strategy to engage multiple networks to preserve task performance under more demanding conditions.

### Neuroplasticity and Functional Improvement

The potential for DT to enhance neuroefficiency offers promising avenues for rehabilitation. Mechanisms that potentially accelerate oxygen supply to the PFC might optimize neuronal response times, enhancing cognitive processing speed and overall task performance [31, 38].

### Hemispheric Activation Patterns

Findings from Nosaka, et al., 2023 [37] highlight that DT conditions lead to the highest levels of PFC activation, suggesting robust adaptive neuroplastic changes that extend beyond the affected hemisphere. This bilateral engagement might be pivotal in harnessing the full potential of the brain's adaptive capacity post-stroke.

### Consideration through Synthesized Results

The prefrontal cortex (PFC) is crucial for the demand of cognitive and executive control resources, supporting functions such as attention, working memory, motor planning, and task switching. In the context of dual-task performance, when cognitive function is insufficient, it may reach what is termed the "ceiling effect." This is where the maximum recruitment of brain resources is achieved, indicating that the recruitment of the prefrontal cortex may be inadequate. Higher recruitment is considered beneficial when there is a greater availability of cognitive resource reserves [32, 39, 40]. Furthermore, "compensatory recruitment" occurs when the recruitment of basic brain areas or networks is inadequate to support task performance. In stroke patients with severe mobility or motor deficits, there is compensatory recruitment of executive control resources to compensate for the loss of automatic or healthy control mechanisms [33, 41, 42]. Additionally, the "neural mechanisms contributing to brain over-recruitment" involve inefficient processing that requires increased brain recruitment to achieve a specific level of task performance, poor specificity in recruiting specialized networks leading to widespread recruitment, and reactive recruitment in response to subpar task performance, as a means to enhance performance [31, 43].

### Limitations and Future Research

This review reveals several limitations affecting the

interpretation of findings and future research design. The heterogeneity in study designs, participant demographics, and intervention types challenges the generalizability of results. Many studies use retrospective designs, which may introduce selection and reporting biases and limit causal inferences. Additionally, the small number of studies included may not fully represent the variability in stroke rehabilitation research, reducing the statistical power and robustness of conclusions. There is also a quantitative imbalance, with a predominance of qualitative over quantitative research, which could skew results towards observational insights rather than measurable outcomes. Moreover, the use of fNIRS for measuring cortical activity, despite its non-invasiveness and suitability for dynamic settings, lacks the spatial resolution of techniques like fMRI, which could compromise the precision of brain activation localization and the accuracy of correlating neural changes with functional outcomes.

To address the limitations noted in this review, future research should incorporate prospective studies to better understand the long-term effects and causal relationships of DT interventions in stroke recovery. Expanding the scope and diversity of studies will improve the reliability and applicability of findings. A balanced mix of qualitative and quantitative research will offer a comprehensive view of intervention effectiveness. Additionally, correlating specific brain activation patterns with functional outcomes using standardized measures will enable the development of targeted rehabilitation strategies. Integrating advanced imaging techniques like fMRI with fNIRS will provide more detailed insights into spatial brain activity, enhancing the understanding of recovery processes and their clinical implications. These steps will help develop more effective, tailored rehabilitation protocols for stroke survivors, potentially transforming stroke rehabilitation practices.

### Clinical Implications

Clinically, these insights underscore the need for personalized DT rehabilitation programs that consider individual differences in neurophysiological responses and functional capacities. Rehabilitation specialists should consider the metabolic costs and potential for compensatory mechanisms when designing interventions. Optimizing DT interventions may involve varying the complexity and nature of tasks to maximize patient engagement and neuroplastic potential.

## Conclusion

Overall, this review suggests that tailored dual-task interventions could optimize recovery and enhance functional independence in stroke patients by leveraging the intrinsic capabilities of the brain's motor and cognitive networks. This necessitates a nuanced approach that considers individual variability in response to dual-task conditions, paving the way for more effective post-stroke rehabilitation strategies. Further exploration into the relationship between cortical activation patterns observed during dual-task and clinical outcomes is essential to refine these therapeutic interventions.

## Conflicts of interest

The authors declare no conflict of interest.

## References

1. Saini V, Guada L, Yavagal DR. Global Epidemiology of Stroke and Access to Acute Ischemic Stroke Interventions. Neurology. 2021;97:S6-S16.
2. Barker-Collo S, Feigin V, Parag V, Lawes C, Senior H. Auckland stroke outcomes study: part 2: cognition and functional outcomes 5 years poststroke. Neurology. 2010;75:1608-16.
3. Grotta JC, Albers GW, Broderick JP, Kasner SE, Lo EH, Sacco RL, et al. Stroke: pathophysiology, diagnosis, and management. 7th ed. Philadelphia, USA: Elsevier Inc.; 2021.
4. Al-Yahya E, Dawes H, Smith L, Dennis A, Howells K, Cockburn J. Cognitive motor interference while walking: a systematic review and meta-analysis. Neurosci Biobehav Rev. 2011;35:715-28.
5. Plummer P, Eskes G, Wallace S, Giuffrida C, Fraas M, Campbell G, et al. Cognitive-motor interference

during functional mobility after stroke: state of the science and implications for future research. Arch Phys Med Rehabil. 2013;94:2565-74. e6.
6. Filiatrault J, Arsenault AB, Dutil E, Bourbonnais D. Motor function and activities of daily living assessments: a study of three tests for persons with hemiplegia. Am J Occup Ther. 1991;45:806-10.
7. Abernethy B. Dual-task methodology and motor skills research: some applications and methodological constraints. J Hum Mov Stud. 1988;14 :101-32.
8. Tsang CSL, Pang MYC. Association of subsequent falls with evidence of dual-task interference while walking in community-dwelling individuals after stroke. Clin Rehabil. 2020;34:971-80.
9. Bishnoi A, Holtzer R, Hernandez ME. Brain activation changes while walking in adults with and without neurological disease: systematic review and meta-analysis of functional near-infrared spectroscopy studies. Brain Sci. 2021;11:291.
10. Wagshul ME, Lucas M, Ye K, Izzetoglu M, Holtzer R. Multi-modal neuroimaging of dual-task walking: Structural MRI and fNIRS analysis reveals prefrontal grey matter volume moderation of brain activation in older adults. Neuroimage. 2019;189: 745-54.
11. Mirelman A, Maidan I, Bernad-Elazari H, Nieuwhof F, Reelick M, Giladi N, et al. Increased frontal brain activation during walking while dual tasking: an fNIRS study in healthy young adults. J Neuroeng Rehabil. 2014;11:1-7.
12. Mehagnoul-Schipper DJ, van der Kallen BFW, Colier WNJM, van der Sluijs MC, van Erning LJTO, Thijssen HOM, et al. Simultaneous measurements of cerebral oxygenation changes during brain activation by near-infrared spectroscopy and functional magnetic resonance imaging in healthy young and elderly subjects. Hum Brain Mapp. 2002;16 :14-23.
13. Csipo T, Mukli P, Lipecz A, Tarantini S, Bahadli D, Abdulhussein O, et al. Assessment of age-related decline of neurovascular coupling responses by functional near-infrared spectroscopy (fNIRS) in humans. Geroscience. 2019;41:495-509.
14. Pinti P, Tachtsidis I, Hamilton A, Hirsch J, Aichelburg C, Gilbert S, et al. The present and future use of functional near-infrared spectroscopy (fNIRS) for cognitive neuroscience. Ann N Y Acad Sci. 2020;1464:5-29.
15. Huo C, Xu G, Li W, Xie H, Zhang T, Liu Y, et al. A review on functional near-infrared spectroscopy and application in stroke rehabilitation. Med Nov Technol Devices. 2021;11:100064.
16. Obrig H. NIRS in clinical neurology－a 'promising' tool? Neuroimage. 2014;85:535-46.
17. Yücel MA, Selb JJ, Huppert TJ, Franceschini MA, Boas DA. Functional near infrared spectroscopy: enabling routine functional brain imaging. Curr Opin Biomed Eng. 2017;4:78-86.
18. Chen Y, Cao Z, Mao M, Sun W, Song Q, Mao D. Increased cortical activation and enhanced functional connectivity in the prefrontal cortex ensure dynamic postural balance during dual-task obstacle negotiation in the older adults: A fNIRS study. Brain Cogn. 2022;163:105904.
19. Lu C-F, Liu Y-C, Yang Y-R, Wu Y-T, Wang R-Y. Maintaining gait performance by cortical activation during dual-task interference: a functional near-infrared spectroscopy study. PLoS One. 2015;10 :e0129390.
20. Maidan I, Nieuwhof F, Bernad-Elazari H, Reelick MF, Bloem BR, Giladi N, et al. The Role of the Frontal Lobe in Complex Walking Among Patients With Parkinson's Disease and Healthy Older Adults:An fNIRS Study. Neurorehabil Neural Repair. 2016;30:963-71.
21. Meester D, Al-Yahya E, Dawes H, Martin-Fagg P, Piñon C. Associations between prefrontal cortex activation and H-reflex modulation during dual task gait. fnhum. 2014;8:78.
22. Mirelman A, Maidan I, Bernad-Elazari H, Shustack S, Giladi N, Hausdorff JM. Effects of aging on prefrontal brain activation during challenging walking conditions. Brain Cogn. 2017;115:41-6.
23. Pelicioni PH, Tijsma M, Lord SR, Menant J. Prefrontal cortical activation measured by fNIRS during walking: effects of age, disease and secondary task. PeerJ. 2019;7:e6833.
24. Suzuki M, Miyai I, Ono T, Oda I, Konishi I, Kochiyama T, et al. Prefrontal and premotor cortices are involved in adapting walking and running speed on the treadmill: an optical imaging study.

Neuroimage. 2004;23:1020-6.
25. Lim SB, Peters S, Yang C-l, Boyd LA, Liu-Ambrose T, Eng JJ. Frontal, sensorimotor, and posterior parietal regions are involved in dual-task walking after stroke. Front Neurol. 2022;13:904145.
26. Ding Q, Ou Z, Yao S, Wu C, Chen J, Shen J, et al. Cortical activation and brain network efficiency during dual tasks: an fNIRS study. Neuroimage. 2024:120545.
27. Chatterjee SA, Fox EJ, Daly JJ, Rose DK, Wu SS, Christou EA, et al. Interpreting prefrontal recruitment during walking after stroke: influence of individual differences in mobility and cognitive function. Front Hum Neurosci. 2019;13:194.
28. Hawkins KA, Fox EJ, Daly JJ, Rose DK, Christou EA, McGuirk TE, et al. Prefrontal over-activation during walking in people with mobility deficits: Interpretation and functional implications. Hum Mov Sci. 2018;59:46-55.
29. Gibson N, Williams M, Maitland C, McCunn R. A framework for progressing and regressing core training within athletic and general populations. Strength Cond J. 2017;39:45-50.
30. Higgins JPT, Morgan RL, Rooney AA, Taylor KW, Thayer KA, Silva RA, et al. A tool to assess risk of bias in non-randomized follow-up studies of exposure effects (ROBINS-E). Environ Int. 2024;186 :108602.
31. Al-Yahya E, Johansen-Berg H, Kischka U, Zarei M, Cockburn J, Dawes H. Prefrontal Cortex Activation While Walking Under Dual-Task Conditions in Stroke: A Multimodal Imaging Study. Neurorehabil Neural Repair. 2016;30:591-9.
32. Chatterjee SA, Fox EJ, Daly JJ, Rose DK, Wu SS, Christou EA, et al. Interpreting Prefrontal Recruitment During Walking After Stroke: Influence of Individual Differences in Mobility and Cognitive Function. Front Hum Neurosci. 2019;13:194.
33. Compagnat M, Daviet JC, Hermand E, Billot M, Salle JY, Perrochon A. Impact of a dual task on the energy cost of walking in individuals with subacute phase stroke. Brain Inj. 2023;37:114-21.
34. Hermand E, Compagnat M, Dupuy O, Salle JY, Daviet JC, Perrochon A. Functional Status Is Associated With Prefrontal Cortex Activation in Gait in Subacute Stroke Patients: A Functional Near-Infrared Spectroscopy Study. Front Neurol. 2020;11:559227.
35. Lim SB, Peters S, Yang CL, Boyd LA, Liu-Ambrose T, Eng JJ. Frontal, Sensorimotor, and Posterior Parietal Regions Are Involved in Dual-Task Walking After Stroke. Front Neurol. 2022;13:904145.
36. Liu YC, Yang YR, Tsai YA, Wang RY, Lu CF. Brain Activation and Gait Alteration During Cognitive and Motor Dual Task Walking in Stroke-A Functional Near-Infrared Spectroscopy Study. IEEE Trans Neural Syst Rehabil Eng. 2018;26:2416-23.
37. Nosaka S, Imada K, Saita K, Okamura H. Prefrontal activation during dual-task seated stepping and walking performed by subacute stroke patients with hemiplegia. Front Neurosci. 2023;17 :1169744.
38. Sun R, Li X, Zhu Z, Li T, Zhao M, Mo L, et al. Effects of dual-task training in patients with post-stroke cognitive impairment: A randomized controlled trial. Front Neurol. 2022;13:1027104.
39. Lee J, Dong S, Jeong J, Yoon B. Effects of transcranial direct current stimulation over the dorsolateral prefrontal cortex (PFC) on cognitive-motor dual control skills. Percept Mot Skills. 2020;127 :803-22.
40. Corrêa FI, Kunitake AI, Segheto W, Duarte de Oliveira M, Fregni F, Ferrari Corrêa JC. The effect of transcranial direct current stimulation associated with video game training on the postural balance of older women in the community: A blind, randomized, clinical trial. Physiother Res Int. 2024;29 :e2046.
41. Fettrow T, Hupfeld K, Tays G, Clark DJ, Reuter-Lorenz PA, Seidler RD. Brain activity during walking in older adults: Implications for compensatory versus dysfunctional accounts. Neurobiol Aging. 2021;105:349-64.
42. Park DC, Smith ET. Facilitation of Cognition in Older Adults: Traditional and Non-Traditional Approaches to Inducing Change. Med Res Arch. 2022;10.
43. Dexter M, Ossmy O. The effects of typical ageing on cognitive control: recent advances and future directions. Front Aging Neurosci. 2023;15.