

Systematic Review

Does Transcranial Direct Current Stimulation Improve Gait Performances in Healthy Older Adults? A Meta-Analysis

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Abstract

Background: Aging can cause degenerative changes in motor and cognition-related brain areas, presumably by interfering with gait performance in healthy aging populations. We aimed to assess the effects of transcranial direct current stimulation (tDCS) on single- and dual-task walking performances in healthy older adults using meta-analytic approaches. **Methods:** Eleven studies were qualified based on the inclusion criteria: (a) healthy older adults, (b) treatment = tDCS protocols, (c) control = sham stimulation, (d) gait performance outcomes, and (e) randomized controlled trials using parallel or crossover designs. Effect sizes were estimated using standardized mean difference (SMD) to examine gait performances between active tDCS and sham stimulation. A separate random-effect meta-analysis was performed to determine the effects of tDCS protocols on gait performance during single- and dual-task walking tasks. **Results:** During single-task walking, the random-effects meta-analysis showed improvements in stride time variability ($SMD = 0.203$; $p = 0.005$) and functional mobility ($SMD = 0.595$; $p < 0.001$). Moreover, single-task walking performances were improved when the tDCS protocols targeted the primary motor cortex ($SMD = 0.424$; $p = 0.005$) and used off-line stimulation ($SMD = 0.168$; $p = 0.008$). During dual-task walking, tDCS improved gait speed ($SMD = 0.177$; $p = 0.025$) and dual-task cost for gait speed ($SMD = 0.548$; $p < 0.001$). Dual-task walking performances were advanced when the tDCS protocols targeted the dorsolateral prefrontal cortex ($SMD = 0.231$; $p = 0.029$) and multiple areas including prefrontal cortex ($SMD = 0.382$; $p = 0.001$), and applied off-line stimulation ($SMD = 0.249$; $p < 0.001$). **Conclusions:** These findings indicate that the tDCS protocols may be a promising tool to support mobility and reduce gait-related challenges in the healthy aging population.

Keywords: aging; gait; transcranial direct current stimulation; meta-analysis; lower limb

1. Introduction

Aging can cause degenerative changes in the central and peripheral nervous systems presumably leading to impaired motor and cognitive functions [1–3]. Specifically, structural and functional changes in the motor and premotor cortical regions often occur in older adults and interfere with motor actions and executive function [4,5]. Moreover, muscle mass and strength tend to decrease with age, and this age-related muscle atrophy leads to impaired activities of daily living [6,7]. These age-related changes also affect gait performance, as indicated by the decreased gait speed and increased gait variability [8–11]. Given that single-task walking performance (i.e., locomotion without executing any other task) is normally related to a greater risk of falls [12,13], identifying an effective way to improve gait performances is necessary for advancing the independent life of a healthy aging population.

Beyond single-task walking, successful dual-task walking performances (i.e., locomotion while simultaneously executing another task such as talking, reading, or planning) on real-world surfaces are frequently required for healthy older adults [14,15]. According to the capacity-

sharing theory [16], simultaneously performing two tasks may impair performance in one or both tasks because of limited cognitive resources. Thus, executive function is crucial for successfully performing dual tasks because this cognitive process may contribute to the effective allocation of neural resources between both tasks by suppressing irrelevant responses and decreasing task-switch costs [17]. However, healthy older adults often showed lower gait speed and greater stride time variability (STV) during dual-task walking than during single-task walking [18–20]. Furthermore, older adults who exhibited lower prefrontal cortical excitability showed more impaired executive functions with lower dual-task performances [21]. Modulating cortical excitability across key cognition-related brain areas may enhance dual-task walking performances in healthy older adults.

Transcranial direct current stimulation (tDCS) may be effective way for advancing dual-task walking performance in older adults [22–24]. The potential mechanisms underlying tDCS-induced neuromodulation posited that anodal stimulation may facilitate cortical excitability by depolarizing the membrane, while cathodal stimulation may suppress



cortical excitability by hyperpolarizing the membrane [25–27]. Further, the excitatory and inhibitory effects caused by tDCS protocols may be sustained for a few hours [28]. A recent meta-analysis study confirmed a possibility of positive effects on dual-task performances after tDCS in older adults [29]. However, these meta-analytic findings did not focus on healthy older adults (e.g., one out of three studies including mild cognitive impairments) and failed to report effects on single-task performance. Potentially, these findings could be affected by confounding bias because of clinical characteristic of participants and task difficulty [30]. Thus, this systematic review and meta-analysis aimed to examine the effects of tDCS protocols on walking performance in healthy older adults. We focused on healthy older population who had no motor and cognitive deficits, and further estimated tDCS effects on both single- and dual-task walking performances.

2. Methods

2.1 Study Identification

Based on Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines, a systematic review and meta-analysis was performed [31]. The PRISMA checklist is shown in **Supplementary Material**. We established five inclusion criteria using the Population, Intervention, Comparison, Outcomes and Study (PICOS) framework for establishing reliable selection criteria: (a) Population: healthy older adults aged 60 years or over; (b) Intervention: tDCS protocols; (c) Comparison: controls with sham stimulation; (d) Outcome: gait performance; (e) Study design: randomized control trials (RCT) using a parallel or crossover design [32]. Consistent with previous meta-analyses [33–35], we excluded studies involving participants diagnosed with neurological diseases or significant medical, psychiatric, or cognitive deficits. Further, studies that did not explicitly state the exclusion of participants with such conditions were also excluded. We removed review articles, case studies, animal studies, and studies that failed to provide sufficient data for computing effect sizes. Using three databases including the PubMed (<https://pubmed.ncbi.nlm.nih.gov/>), Web of Science (<http://www.webofscience.com/wos/woscc/basic-search>), and Cochrane Library (<https://www.cochranelibrary.com/>), two researchers (BJC and HL) independently performed a literature search. All articles published by August 1, 2024 were carefully screened. The following keywords were used: (older adults OR elderly OR aged) AND (non-invasive brain stimulation OR NIBS OR transcranial electrical stimulation OR TES OR transcranial direct current stimulation OR tDCS) AND (gait OR walking OR timed up and go OR Timed up and Go test (TUG) OR locomotion OR mobility).

2.2 Meta-Analytic Procedures

For conducting meta-analysis procedures, we applied the Comprehensive Meta-Analysis software version 4.0

(Biostat, Englewood, NJ, USA). All effect sizes were estimated by calculating the standardized mean difference (SMD). For RCT using a parallel design, individual effect sizes were quantified by comparing mean and standard deviation values of gait performance between tDCS and sham stimulation groups. For RCT using a crossover design, individual effect sizes were calculated by conducting paired analysis that used sample size and mean difference values with standard error [36,37]. The analysis may decrease possibility of disguising clinically important heterogeneity induced by incorporating crossover design as if parallel design [38].

The greater values of SMD indicated more improvements in gait performance after receiving active tDCS protocols than those for sham tDCS protocols. We used the random-effects model for minimizing inherent heterogeneity caused by different experimental conditions such as participants and study protocols [39]. A separate random-effect meta-analysis was performed to determine effects of tDCS protocols on gait performance during single- and dual-task walking tasks.

For single- and dual-task performances, we performed three moderator variable analyses to examine effects of tDCS protocols based on the following conditions: (a) gait variable, (b) targeted brain areas, and (c) stimulation timing. Additional meta-regression analyses were conducted to identify relationship between tDCS effects and demographic characteristics (i.e., mean age and female ratio) and tDCS parameter (i.e., stimulation intensity, duration, and session), respectively.

Using Higgins and Green's I-squared, we estimated levels of heterogeneity across individual effect sizes [40]. Specific ranges of heterogeneity include: (a) low I-squared (<25%), (b) moderate I-squared (50%–75%), and (c) high I-squared (>75%). To evaluate potential publication bias, we used the Egger's regression test [41,42]. An asymmetrical funnel plot and a p -value (<0.05) for the intercept (β_0) denote significant publication bias. Moreover, a funnel plot was provided for visual inspection after applying the trim and fill technique [41].

2.3 Quality Estimation for Potential Methodological Issues

Two researchers (BJC and HL) conducted independent methodological quality assessment for each qualified study based on the Cochrane risk of bias assessment tool version 2 [43]. The tool comprised six domains: (a) randomization process, (b) timing of identification or recruitment of participants, (c) deviations from intended intervention, (d) missing outcome data, (e) measurement of the outcome, and (f) selection of the reported results [44]. Consistent with the protocols in the Cochrane risk bias assessment tool [45], the risk of bias for each domain was determined: (a) low risk of bias, (b) some concern, and (c) high risk of bias.

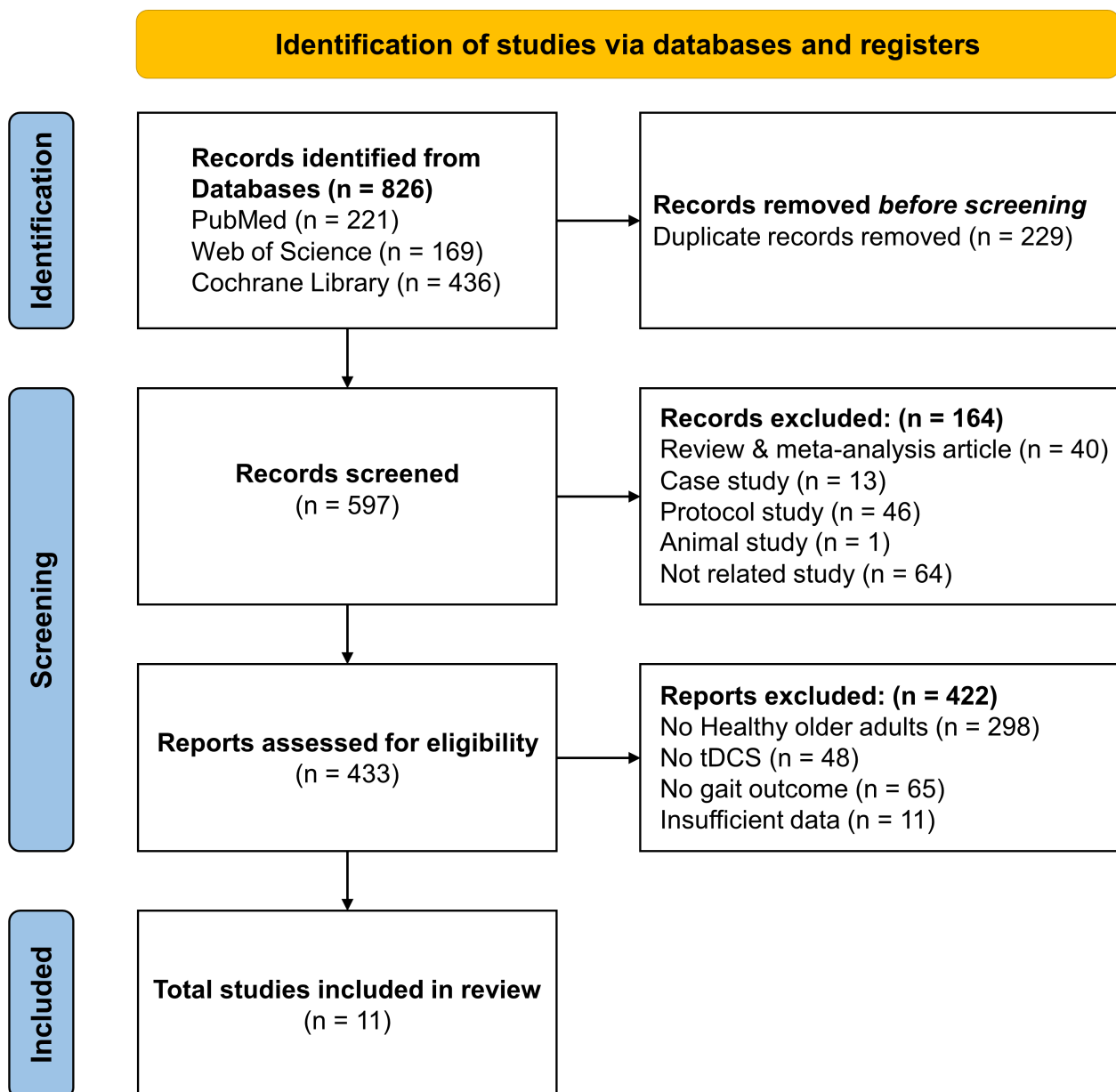


Fig. 1. PRISMA flowchart for the study identification procedure. tDCS, transcranial direct current stimulation; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-analyses.

3. Results

3.1 Study Identification

Initially, we found 826 studies involving 221 from the PubMed, 169 from the Web of Science, and 436 from the Cochrane Library. After removing 229 duplicated studies, we additionally excluded 164 studies (i.e., 40 review articles, 13 case studies, 46 protocol studies, one animal study, and 64 studies that irrelevant to our topic). After screening, 422 studies that did not fulfill the inclusion criteria were removed: (a) 298 studies that did not recruit healthy older adults (i.e., 63 studies that did not focus on older adults, 94 studies involving patients with neurodegenerative disorders, 89 studies involving patients with cerebrovascular dis-

orders, 12 studies involving patients with musculoskeletal disorders, 40 studies involving patients with motor and cognitive disorders), (b) 48 studies that did not apply tDCS protocol, (c) 65 studies that did not assess gait performances, and (d) 11 studies that reported insufficient data. Finally, 11 studies were included in this study [22–24,46–53]. The PRISMA flow diagram describes specific study identification procedure (Fig. 1).

3.2 Demographic Characteristics

The 11 included studies focused on 338 healthy older adults who have no motor and cognitive deficits (range of mean age = 61.0–78.8 years, body mass index (BMI) =

Table 1. Participants characteristics.

Study	Study design	Total (N)	Age (yrs)	Gender (F/M)	Height (m)	Weight (kg)	BMI (kg/m ²)	Motor and cognitive function			
Chatterjee <i>et al.</i> [46] 2023	Parallel	Real: 18	76.1 ± 6.8	11 F, 7 M	NA	NA	NA	ABC	81.5 ± 10.4	BBS	48.6 ± 5.4
		Sham: 15	73.7 ± 6.1	11 F, 4 M					83.9 ± 13.0		50.1 ± 5.0
Clark <i>et al.</i> [47] 2021	Parallel	Real: 7	75.4 ± 5.8	5 F, 2 M	NA	NA	31.5 ± 3.0	ABC	81.5 ± 9.8	BBS	46.6 ± 5.4
		Sham: 5	70.6 ± 5.2	4 F, 1 M			31.6 ± 5.7		77.1 ± 16.8		48.8 ± 6.4
Manor <i>et al.</i> [22] 2016	Crossover	Total: 37	61.0 ± 5.0	25 F, 12 M	1.7 ± 0.1	71 ± 9	NA			NA	
Orcioli-Silva <i>et al.</i> [48] 2021	Parallel	Real: 10	66.0 ± 6.3	5 F, 5 M	1.71 ± 0.1	71.0 ± 9.4	NA	MoCA	28.2 ± 1.1	FES-I	17.6 ± 1.2
		Sham: 8	69.9 ± 4.8	7 F, 1 M	1.67 ± 0.1	73.6 ± 8.3			28.3 ± 1.6		18.1 ± 0.9
Rodrigues <i>et al.</i> [49] 2023	Parallel	Real: 14	71.3 ± 7.6	8 F, 6 M	NA	NA	NA	MMSE		27.6 ± 1.7	
		Sham: 13	70.9 ± 7.6	10 F, 3 M						26.1 ± 2.2	
Rostami <i>et al.</i> [50] 2020	Parallel	Real: 16	68.8 ± 8.1	8 F, 8 M	NA	NA	NA			NA	
		Sham: 16	67.3 ± 5.3	8 F, 8 M							
Sayig-Keren <i>et al.</i> [23] 2023	Crossover	Total: 20	72.6 ± 5.0	9 F, 11 M	NA	NA	26.3 ± 2.8	MoCA	25.8 ± 2.8	CCI	3.4 ± 1.4
Schneider <i>et al.</i> [51] 2021	Crossover	Total: 25	73.9 ± 5.2	20 F, 5 M	NA	NA	26.6 ± 3.0	MoCA		26.6 ± 2.8	
Yi <i>et al.</i> [52] 2021	Parallel	Real: 31	78.1 ± 4.8	21 F, 10 M	1.56 ± 8.7	62.2 ± 8.3	25.5 ± 3.2			NA	
		Sham: 26	78.8 ± 4.8	17 F, 9 M	1.57 ± 8.6	61.5 ± 8.6	24.8 ± 2.4				
Zhou <i>et al.</i> [53] 2018	Crossover	Total: 20	61.0 ± 4.0	NA	1.58 ± 0.04	61.0 ± 8.0	NA			NA	
Zhou <i>et al.</i> [24] 2021	Crossover	Total: 57	75.0 ± 5.0	43 F, 14 M	1.6 ± 0.1	74.3 ± 16.8	NA	MoCA		26.5 ± 3.0	

Data are mean ± standard deviations. ABC, Activities specific balance confidence scale [54]; BBS, Berg balance scale [55]; BMI, Body mass index; CCI, Charlson comorbidity index; F, Female; FES-I, Falls efficacy scale international; M, Male; NA, not applicable; MMSE, Mini-mental state examination [57]; MoCA, Montreal cognitive assessment [56].

Table 2. Specific parameters of tDCS protocols and gait variables.

Study	Group	Targeted Brain Area		Intensity	Duration	Timing	Surface	Session (Period)	Gait Variables	
		Anodal	Cathodal						Single Task	Dual Task
Chatterjee <i>et al.</i> [46] 2023	Trt	R-DLPFC	L-DLPFC	2 mA	20 min	On	35 cm ²	1	Gait speed	NA
Clark <i>et al.</i> [47] 2021	Trt	R-DLPFC	L-DLPFC	2 mA	20 min	On	35 cm ²	18 (6 weeks)	Gait speed, Figure-8 walk time	NA
Manor <i>et al.</i> [22] 2016	Trt	L-DLPFC	R-supraorbital ridge	2 mA	20 min	Off	35 cm ²	1	Gait speed	Gait speed, Gait speed cost
Orcioli-Silva <i>et al.</i> [48] 2021	Trt	L-PFC, M1	R-mastoid	0.6 mA	20 min	On	9 cm ²	1	NA	STV cost
Rodrigues <i>et al.</i> [49] 2023	Trt	L-DLPFC	R-supraorbital ridge	2 mA	20 min	Off	25 cm ²	16 (8 weeks)	TUG	NA
Rostami <i>et al.</i> [50] 2020	Trt	L-M1	R-supraorbital ridge	1 mA	20 min	Off	55.25 cm ²	5 (1 week)	TUG, Figure-8 walk time	NA
Sayig-Keren <i>et al.</i> [23] 2023	Trt	L-DLPFC	R-APC, L-LPC, L-MPC	2 mA	20 min	Off	16 cm ²	1	Gait speed, STV	Gait speed, Gait speed cost, STV
Schneider <i>et al.</i> [51] 2021	Trt	L-DLPFC, M1	R-APC, L-LPC, L-MPC, L-S1,	1.5 mA	20 min	On	3.14 cm ²	1	NA	Gait speed cost
Yi <i>et al.</i> [52] 2021	Trt	M1	L-M1, R-M1	1.98 mA	20 min	Off	24 cm ²	1	Gait speed, TUG	NA
Zhou <i>et al.</i> [53] 2018	Trt	M1	R-supraorbital ridge	2 mA	20 min	Off	35 cm ²	1	TUG	NA
Zhou <i>et al.</i> [24] 2021	Trt 1	L-DLPFC	R-APC, L-LPC, L-MPC							
	Trt 2	M1	R-APC, L-MPC, L-S1	1.5 mA	20 min	Off	3.14 cm ²	1	Gait speed, STV	Gait speed, Gait speed cost, STV, STV cost
	Trt 3	L-DLPFC, M1	R-APC, L-LPC, L-MPC, L-S1							

APC, anterior prefrontal cortex; DLPFC, dorsolateral prefrontal cortex; L, left; LPC, lateral premotor cortex; M1, primary motor cortex; MPC, medial premotor cortex; R, right; S1, primary somatosensory cortex; STV, stride time variability; Trt, treatment; PFC, prefrontal cortex; TUG, Timed up and Go test [58].

24.8–31.6 kg/m², and female ratio = 45–80%). Seven studies reported levels of motor or cognitive functions at baseline: (a) activities-specific balance confidence scale from two studies (a range of mean = 77.1–83.9) [54], (b) Berg balance scale from two studies (a range of mean = 46.6–50.1) [55], and (c) Montreal cognitive assessment from four studies (a range of mean = 25.8–28.3) [56]. Table 1 (Ref. [22–24,46–57]) show more specific details for demographic information about participants.

3.3 tDCS Protocols

Four studies administered tDCS protocols during gait assessments (i.e., on-line timing) and seven studies applied tDCS before gait assessment (i.e., off-line timing). Eight out of 11 studies administered a single tDCS session (i.e., only one session during the experiment) and three studies provided multiple sessions of tDCS protocol (i.e., 5–18 sessions). For targeted brain areas of stimulation, anodal stimulation was applied to: (a) dorsolateral prefrontal cortex (DLPFC) from five studies, (b) primary motor cortex (M1) from three studies, and (c) multiple regions including DLPFC–M1 and prefrontal cortex (PFC)–M1 from two studies. Moreover, one study applied three different protocols stimulating DLPFC, M1, and DLPFC–M1, respectively [24]. Specific information for tDCS protocols is shown in Table 2 (Ref. [22–24,46–53,58]).

3.4 Gait Variables During Single- and Dual-tasks

Nine studies assessed single-task walking performances: (a) gait speed from two studies, (b) gait-related functional mobility (i.e., timed up and go (TUG) [58] and Figure-eight walk time) from three studies, (c) both gait and gait-related functional mobility from two studies, and (d) both gait speed and STV from two studies. Furthermore, five studies evaluated gait performances during dual-task walking: (a) gait speed cost (i.e., differences in gait speed from single-task walking to dual-task walking; lower values of cost indicating better dual-task walking performance) from one study, (b) both gait speed and gait speed cost from one study, (c) STV cost (i.e., differences in STV from single-task walking to dual-task walking; lower values of cost indicating better dual-task walking performance) from one study, (d) one study evaluated gait speed, gait speed cost, STV, and (e) one study assessed all gait speed, gait speed, STV, and STV cost.

3.5 Methodological Quality Across Included Studies

The Cochrane risk-of-bias revealed a low risk of methodological biases for each domain (Fig. 2): (a) randomization process (all studies with low risk), (b) timing of identification or recruitment of participants (all studies with low risk), (c) deviations from intended intervention (all studies with low risk), (d) measurement of the outcome (10 studies with low risk and one study with some concern), and (e) selection of the reported result (all studies with low

risk). For the missing outcome data, we found a relatively moderate methodological biases (three studies with some concerns) because missingness in the outcome because of the dropout of participants.

3.6 tDCS Effects on Single-Task Walking Performance from Meta-Analysis

A random-effects meta-analysis revealed that tDCS significantly enhanced single-task walking performances in healthy older adults (18 comparisons reported by nine studies; $SMD = 0.142$; standard error = 0.064; 95% confidence interval (CI) = 0.016 to 0.269; $Z = 2.209$; $p = 0.027$; I-squared = 38.9%; Egger's $\beta_0 = 0.395$ with $p = 0.578$; funnel plot in **Supplementary Fig. 1**). First moderator variable analysis indicated that tDCS significantly improved two gait variables (Fig. 3): (a) STV (four comparisons reported by two studies; $SMD = 0.203$; standard error = 0.073; 95% CI = 0.060 to 0.347; $Z = 2.780$; $p = 0.005$; I-squared = 0.0%; Egger's $\beta_0 = -1.568$ with $p = 0.289$; funnel plot in **Supplementary Fig. 2A**) and (b) functional mobility (six comparisons reported by six studies; $SMD = 0.595$; standard error = 0.137; 95% CI = 0.327 to 0.863; $Z = 4.346$; $p < 0.001$; I-squared = 0.0%; Egger's $\beta_0 = -0.917$ with $p = 0.958$; funnel plot in **Supplementary Fig. 2B**). However, the analysis found no significant effects on gait speed (eight comparisons reported by five studies; $SMD = -0.033$; standard error = 0.064; 95% CI = -0.159 to 0.093; $Z = -0.511$; $p = 0.609$; I-squared = 0.0%; Egger's $\beta_0 = -1.327$ with $p = 0.011$; funnel plot in **Supplementary Fig. 2C**).

For targeted brain regions, moderator variable analysis indicated that tDCS targeting the M1 significantly enhanced gait variables (Fig. 4) (six comparisons reported by four studies; $SMD = 0.424$; standard error = 0.150; 95% CI = 0.129 to 0.719; $Z = 2.818$; $p = 0.005$; I-squared = 63.3%; Egger's $\beta_0 = 3.188$ with $p = 0.033$; funnel plot in **Supplementary Fig. 3A**). However, the analysis indicated no significant effects of tDCS on the DLPFC (10 comparisons reported by six studies; $SMD = 0.039$; standard error = 0.069; 95% CI = -0.095 to 0.174; $Z = 0.573$; $p = 0.567$; I-squared = 0.0%; Egger's $\beta_0 = -0.757$ with $p = 0.236$; funnel plot in **Supplementary Fig. 3B**). For stimulation timing, the moderator variable analysis indicated that off-line timing significantly improved gait variables (Fig. 5) (14 comparisons reported by seven studies; $SMD = 0.168$; standard error = 0.063; 95% CI = 0.045 to 0.292; $Z = 2.664$; $p = 0.008$; I-squared = 39.0%; Egger's $\beta_0 = 1.962$ with $p = 0.040$; funnel plot in **Supplementary Fig. 4A**). However, on-line timing showed no significant effects on gait variables (four comparisons reported by two studies; $SMD = -0.345$; standard error = 0.247; 95% CI = -0.830 to 0.139; $Z = -1.396$; $p = 0.163$; I-squared = 0.0%; Egger's $\beta_0 = 2.366$ with $p = 0.321$; funnel plot in **Supplementary Fig. 4B**).

The meta-regression analyses failed to report significant relationships between enhancements in single-task walking performances after tDCS and following demo-

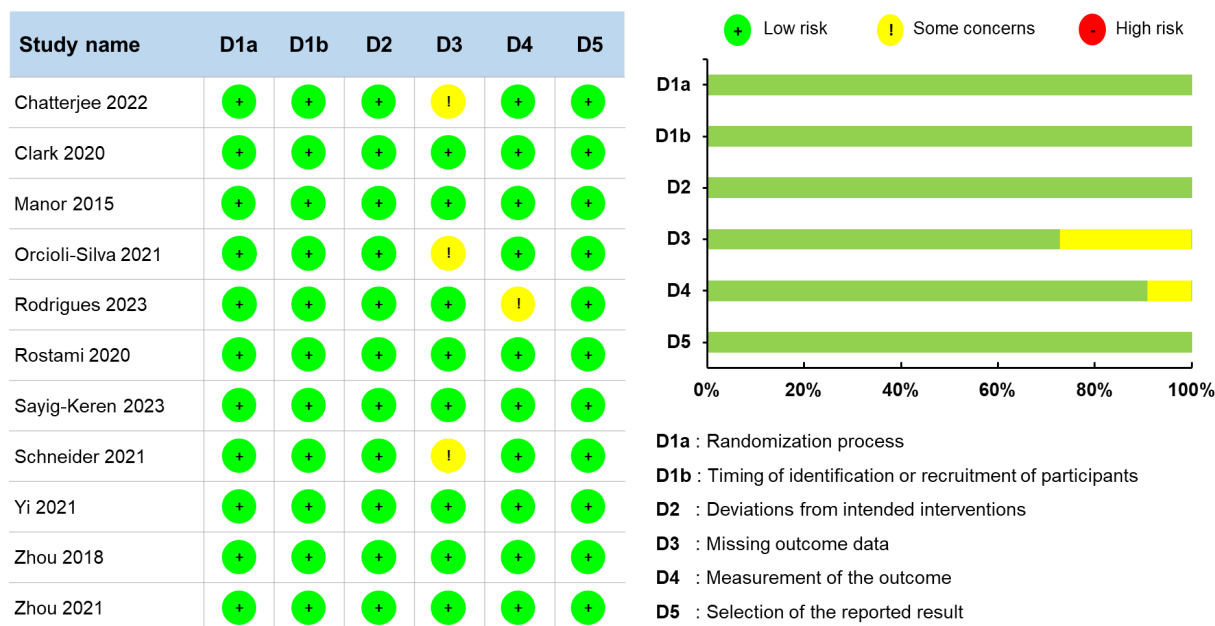


Fig. 2. Methodological quality estimation.

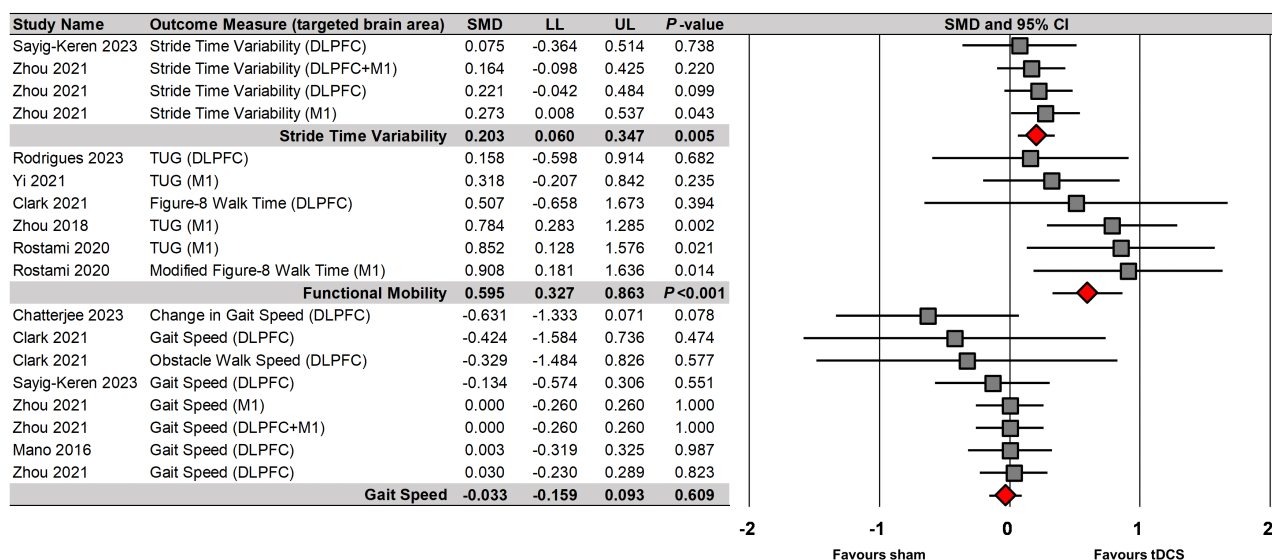


Fig. 3. tDCS effects on different gait variable during single-task walking. CI, confidence interval; LL, lower limit; SMD, standardized mean difference; UL, upper limit.

graphic characteristics and tDCS parameters: (a) age (18 comparisons reported by nine studies; $Y = 1.472 - 0.018X$; $p = 0.150$), (b) female ratio (17 comparisons reported by eight studies; $Y = 0.162 - 0.079X$; $p = 0.873$), (c) intensity of stimulation (18 comparisons reported by nine studies; $Y = 0.712 - 0.349X$; $p = 0.104$), and (d) session of stimulation (19 comparisons reported by five studies; $Y = 0.128 - 0.003X$; $p = 0.841$). Meta-regression analyses were not conducted on the duration of stimulation in single-task walking performances because all studies applied same tDCS protocols.

3.7 tDCS Effects on Dual-Task Walking Performance from Meta-Analysis

A random-effects meta-analysis denoted that tDCS significantly enhanced dual-task walking performances in healthy older adults (19 comparisons reported by five studies; $SMD = 0.281$; standard error = 0.061; 95% CI = 0.162 to 0.400; $Z = 4.612$; $p < 0.001$; I-squared = 63.9%; Egger's $\beta_0 = 3.497$ with $p = 0.013$; funnel plot in **Supplementary Fig. 5**). First moderator variable analysis indicated that tDCS significantly improved two gait variables (Fig. 6): (a) gait speed (five comparisons reported by three studies; $SMD =$

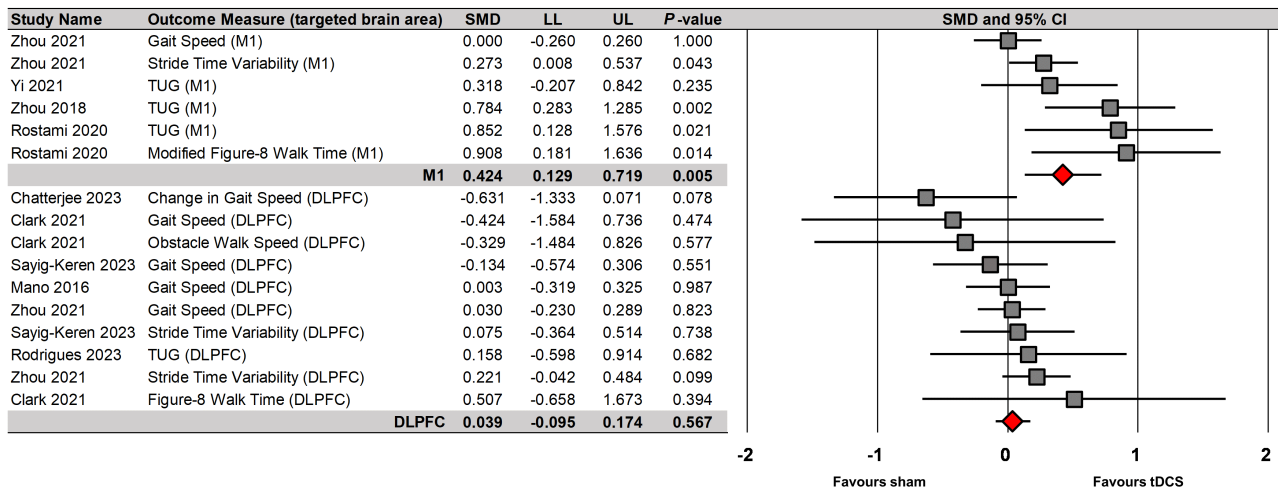


Fig. 4. tDCS effects on single-task walking performances based on targeted brain regions.

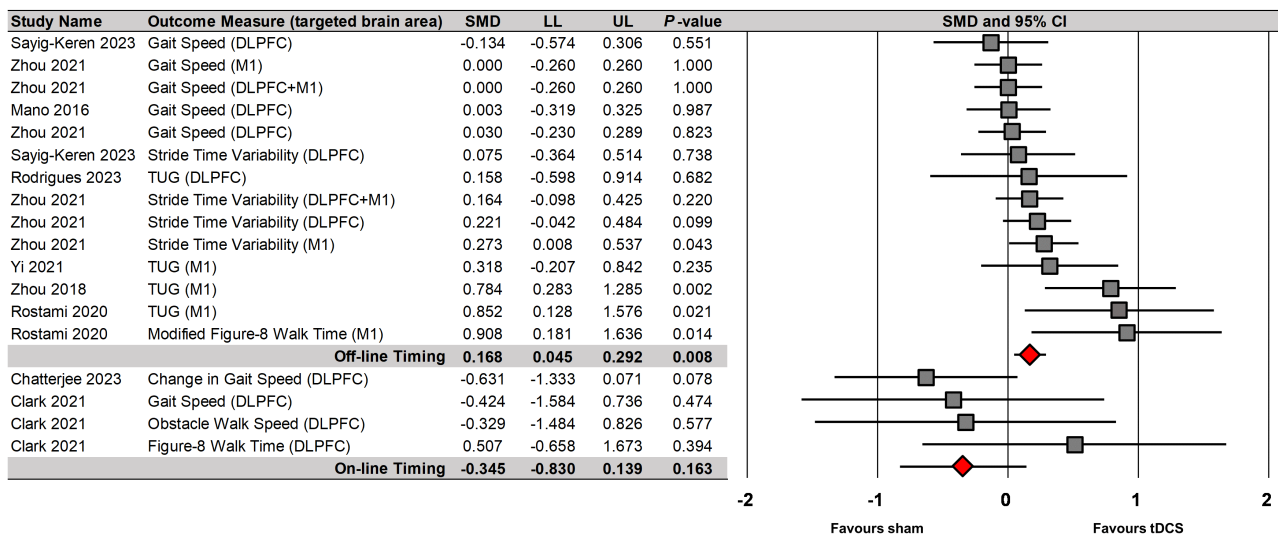


Fig. 5. tDCS effects on single-task walking performances based on timing of tDCS.

0.177; standard error = 0.079; 95% CI = 0.022 to 0.332; $Z = 2.241$; $p = 0.025$; I-squared = 25.5%; Egger's $\beta_0 = 0.786$ with $p = 0.821$; funnel plot in **Supplementary Fig. 6A**) and (b) gait speed cost (six comparisons reported by four studies; $SMD = 0.548$; standard error = 0.121; 95% CI = 0.311 to 0.785; $Z = 4.531$; $p < 0.001$; I-squared = 66.3%; Egger's $\beta_0 = 4.592$ with $p = 1.143$; funnel plot in **Supplementary Fig. 6B**). However, the analysis indicated no significant effects on STV (four comparisons reported by two studies; $SMD = 0.109$; standard error = 0.073; 95% CI = -0.033 to 0.252; $Z = 1.501$; $p = 0.133$; I-squared = 0.0%; Egger's $\beta_0 = -1.847$ with $p = 0.308$; funnel plot in **Supplementary Fig. 6C**) and STV cost (four comparisons reported by two studies; $SMD = 0.246$; standard error = 0.153; 95% CI = -0.053 to 0.546; $Z = 1.611$; $p = 0.107$; I-squared = 68.9%; Egger's $\beta_0 = 3.748$ with $p = 0.093$; funnel plot in **Supplementary Fig. 6D**).

For targeted brain regions, moderator variable analysis denoted significant effects of tDCS on two brain area (Fig. 7): (a) DLPFC (nine comparisons reported by three studies; $SMD = 0.231$; standard error = 0.106; 95% CI = 0.023 to 0.438; $Z = 2.181$; $p = 0.029$; I-squared = 72.0%; Egger's $\beta_0 = 4.071$ with $p = 0.130$; funnel plot in **Supplementary Fig. 7A**) and (b) multiple regions (six comparisons reported by three studies; $SMD = 0.382$; standard error = 0.111; 95% CI = 0.165 to 0.600; $Z = 3.443$; $p = 0.001$; I-squared = 61.1%; Egger's $\beta_0 = 3.642$ with $p = 0.039$; funnel plot in **Supplementary Fig. 7B**). For stimulation timing, the moderator variable analysis indicated that off-line timing significantly improved gait variables (Fig. 8) (17 comparisons reported by three studies; $SMD = 0.249$; standard error = 0.058; 95% CI = 0.135 to 0.363; $Z = 4.297$; $p < 0.001$; I-squared = 60.1%; Egger's $\beta_0 = 3.112$ with $p = 0.128$; funnel plot in **Supplementary Fig. 8**). How-

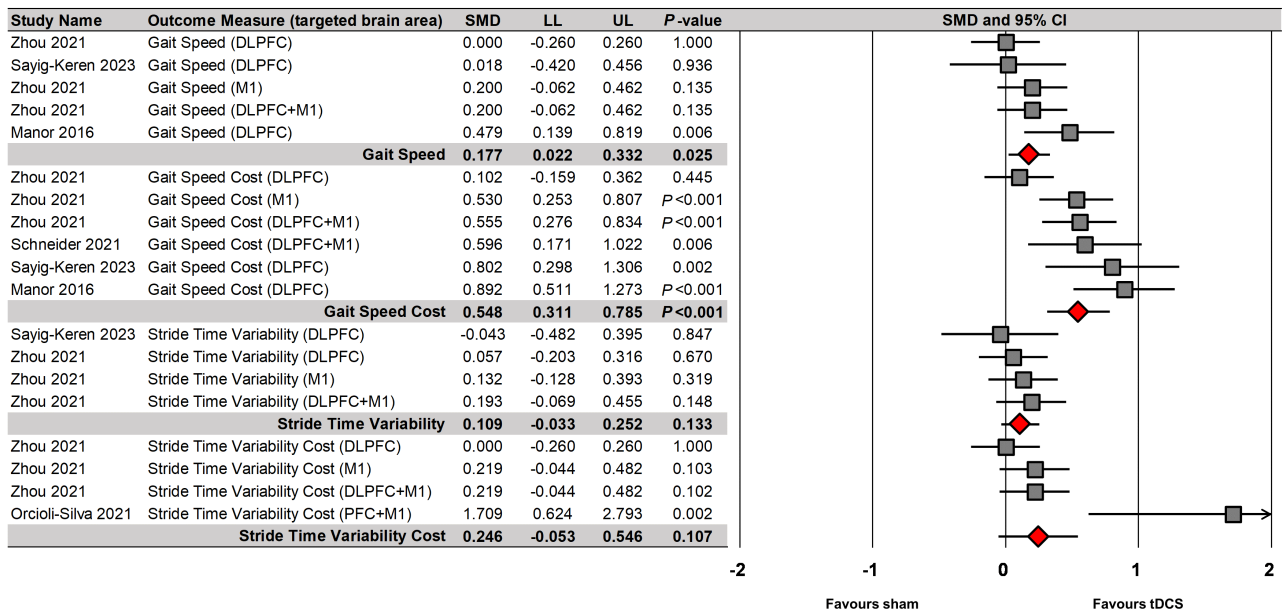


Fig. 6. tDCS effects on different gait variables during dual-task walking.

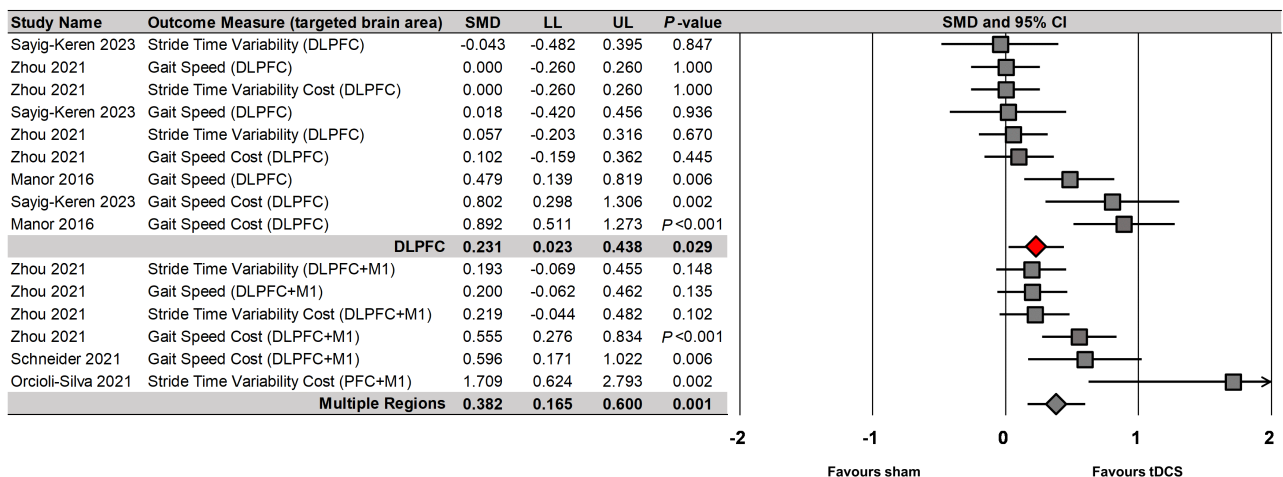


Fig. 7. tDCS effects on dual-task walking performances based on targeted brain regions.

ever, on-line timing showed no significant effects on gait variables (two comparisons reported by two studies; $SMD = 1.036$; standard error = 0.544; 95% CI = -0.030 to 2.102 ; $Z = 1.905$; $p = 0.057$; I-squared = 71.4%).

The random-effect meta-regression analysis confirmed enhancements in dual-task walking performances after tDCS were significantly correlated with decreased age (19 comparisons reported by five studies; $Y = 3.007 - 0.037X$; $p = 0.003$; **Supplementary Fig. 9**). However, the analysis found no significant relationships between enhancements in dual-tasks after tDCS and following two variables; (a) female ratio (19 comparisons reported by five studies; $Y = 0.583 - 0.425X$; $p = 0.498$) and (b) intensity of stimulation (19 comparisons reported by five studies; $Y = 0.454 - 0.110X$; $p = 0.598$). Meta-regression analyses were

not conducted on the session and duration of stimulation in dual-task walking performances because all studies applied same tDCS protocols.

4. Discussion

This meta-analysis investigated the effects of tDCS on gait performance during single- and dual-task walking in healthy older adults. The findings revealed that tDCS significantly improved overall gait performance during single- and dual-task walking. Specifically, improvements in STV, TUG, and figure-eight walk time were observed for single-task performances, while increases in gait speed and reductions in speed cost were observed for dual-task performances. For targeted brain regions, tDCS stimulating M1 significantly advanced the gait performance during single-

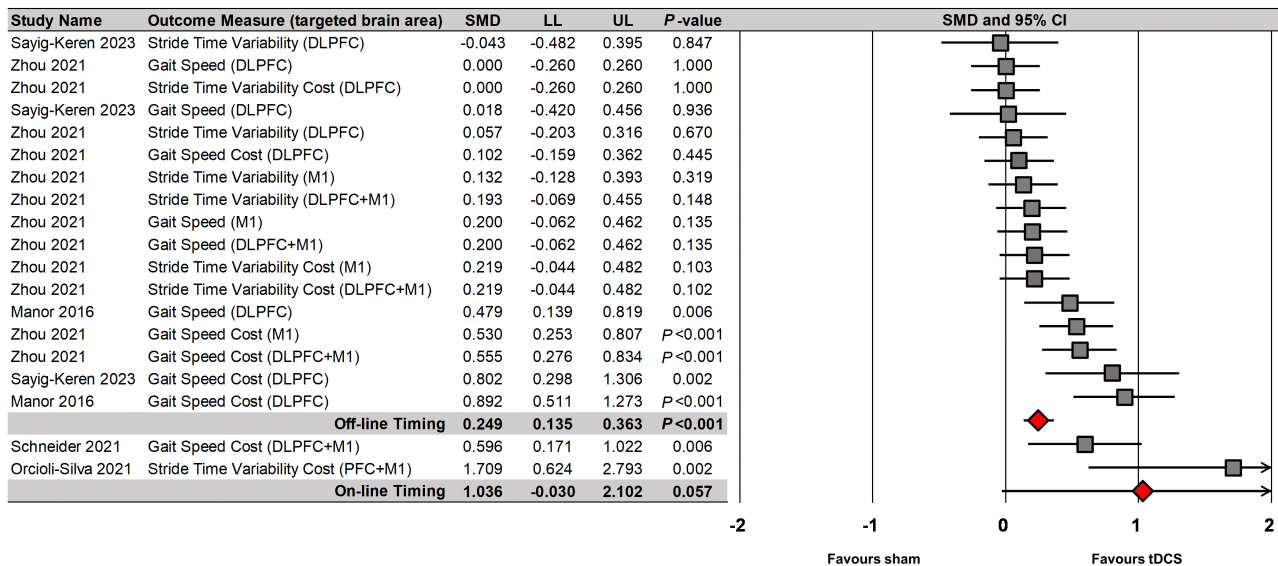


Fig. 8. tDCS effects on dual-task walking performances based on timing of tDCS.

task walking, and tDCS protocols stimulating multiple areas including prefrontal cortex were beneficial for dual-task walking performance. For both single- and dual-task walking performances, off-line tDCS protocols were effective. Improvements in dual-task walking performances after tDCS decreased with increasing age for older adults.

Positive effects of tDCS on gait-related performances during single- and dual-task walking in healthy older adults reinforce the previous meta-analytic findings that tDCS improved dynamic balance and postural control in elderly people [59,60]. To the best of our knowledge, this meta-analysis was the first to show tDCS effects on gait performance improvements by focusing on healthy older adults who had no physical and cognitive impairments. Some studies reported inconsistent results in motor improvements after tDCS protocols because of ceiling effects potentially caused by characteristics of participants (e.g., healthy older adults) and task difficulty (e.g., single-task walking) [61–63]. Importantly, our findings suggest that applying tDCS protocols transiently may improve gait performances in healthy older adults regardless of how challenging a task is to complete.

For dual-task walking, the meta-analytic results revealed significant improvements in gait speed-related outcome variables (i.e., speed and speed cost) although these improvements were not observed in single-task walking. Dual-task costs during gait performance (i.e., altered gait functions from single task to dual task) may increase because of insufficient neural resources necessary for simultaneously completing both cognitive and motor task requirements (e.g., walking while checking watch or phone) [12,24]. Moreover, age-related cognitive impairments may interfere with effective allocation of neural resources in the brain, leading to greater reduction of gait speed while performing cognitive tasks [12,23]. Previous meta-analysis

studies reported that tDCS protocols facilitated neural excitability across prefrontal cortical regions, resulting in improved cognitive functions (e.g., faster reaction time and better executive function) in older adults [29,64,65]. Perhaps, these findings indicate that the contribution of tDCS protocols to cognition-related neural plasticity may enhance dual-task walking performances in healthy older adults.

In fact, our moderator variable analysis identified that tDCS stimulating M1 significantly advanced single-task walking performances, while tDCS protocols stimulating multiple areas including prefrontal cortex improved dual-task walking performances. These findings support a proposition that altered motor cortical excitability by tDCS may affect gait performances requiring lower level of cognitive resources, whereas tDCS protocols targeting prefrontal cortical regions may be effective for improving daily walking on the ground that normally requires greater cognitive resources [51,52,66]. Motor improvements in healthy older adults (i.e., single- and dual-task gait performances) with tDCS protocols that stimulated cognition-related regions may be associated with cognitive-motor integration [67]. Cognitive-motor integration refers to concurrent interaction between cognitive processes and motor control systems through neural networks for goal-directed actions [68]. Previous studies reported that distinct brain areas predominately involved in cognitive and motor tasks were integrated into a single network when both tasks were performed simultaneously [69,70]. For example, a study using functional magnetic resonance imaging revealed increased excitability in both M1 and DLPFC during dual tasks (i.e., a stepping task combined with a serial subtraction task or verbal fluency) as compared with excitability level of the cortical regions during single task (i.e., executing motor and cognitive task, separately) [71]. These findings sup-

port a proposition that dual-task walking performance may require the involvement of motor cortical regions as well as cognition-related brain areas such as prefrontal cortical regions. Presumably, applying tDCS protocols may modulate cortical excitability in a specific region that can further influence anatomically or functionally connected areas contributing to neural communications across cognitive and motor networks. For example, anodal stimulation on the left DLPFC improved both cognitive function (i.e., Montreal Cognitive Assessment score) and motor performance (i.e., gait and standing postural sway) compared with sham tDCS condition [72]. Moreover, Lee and colleagues [67] reported positive effects of anodal stimulation with DLPFC on isometric pinch force control capabilities. Taken together, healthy aging population may receive beneficial effects on gait performances by reinforcing their cognitive functions with tDCS protocols.

Interestingly, we found that off-line tDCS protocols were effective for improving both single- and dual-task walking performances, which is consistent with previous findings that off-line tDCS protocols significantly advanced motor and cognitive functions [73,74]. These findings support a proposition that tDCS protocols may be suitable for clinical application in healthy older adults because participants can concentrate and naturally execute walking practice with minimized distraction and discomfort in off-line tDCS condition. However, no significant effects of on-line tDCS protocols may be attributed to the insufficient number of studies (e.g., two studies for single- and dual-task walking). Thus, further studies will be necessary to confirm on-line tDCS effects. Interestingly, the meta-regression analysis identified that greater enhancements in dual-task walking performances after tDCS occurred in younger elderly individuals. Previous studies raised a possibility that tDCS-induced neural plasticity may be affected by age [75,76]. Potentially, tDCS effects on dual-task walking decreased with altered excitatory effects of anodal stimulation for older adults.

Despite the positive effects of tDCS on single- and dual-task performances in healthy older adults, caution is necessary when interpreting these findings. First, the positive overall effects of tDCS protocols on gait functions were acquired from a insufficient number of included studies (e.g., 2–6 studies). For dual-gait performances, five out of 11 qualified studies assessed dual-task performances before and after tDCS protocols. Second, tDCS protocols used for each study were inconsistent. Further, our meta-regression findings confirmed different tDCS parameters were not correlated with overall effects so that optimal parameters (e.g., targeted brain area, intensity, frequency, and sessions) for improving gait performance in healthy older adults are still inclusive. Thus, further studies that focused on healthy older adults with standardized tDCS protocols are necessary to support current findings. In addition to the transient effects observed in this meta-analysis, administering multi-

ple sessions of tDCS protocols may lead to retention effects on gait performances [46,72]. Perhaps, home-based tDCS training program may be effective for long-term of gait rehabilitation in aging population because of the safety and feasibility of tDCS protocols [77,78]. Finally, tDCS effects may be influenced by different tDCS parameters [79,80] so that future studies should explore individualized tDCS parameters for optimizing gait performances in older adults.

5. Conclusion

This systematic review and meta-analysis confirmed that tDCS significantly enhanced single- and dual-gait performances in healthy older adults. Specifically, applying tDCS protocols enhanced gait STV and gait-related mobility (i.e., TUG and Figure-eight walk time) in single tasks and improved gait speed in dual tasks. Further, tDCS stimulating motor cortical regions advanced single-gait performances, whereas tDCS targeting prefrontal cortical regions was beneficial for improving dual-gait performances. Off-line tDCS protocols showed positive effects on both single- and dual-gait performances. These findings indicate that tDCS protocols may be a promising tool to support mobility and reduce gait-related challenges in healthy aging populations.

Availability of Data and Materials

All data points generated or analyzed during this study are included in this article and there are no further underlying data necessary to reproduce the results.

Author Contributions

BJC and HL contributed to acquisition of data and statistical analyses. BJC, HL, and NK performed data interpretation, manuscript drafts and editorial changes. NK conceived and designed the study. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

Not applicable.

Acknowledgment

Not applicable.

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Conflict of Interest

The authors declare no conflict of interest. Nyeonju Kang is serving as one of the Guest editors of this journal. We declare that Nyeonju Kang had no involvement in the peer review of this article and has no access to information

regarding its peer review. Full responsibility for the editorial process for this article was delegated to Yoshihiro Noda.

Supplementary Material

Supplementary material associated with this article can be found, in the online version, at <https://doi.org/10.31083/JIN36636>.

References

- [1] Chen L, Nelson DR, Zhao Y, Cui Z, Johnston JA. Relationship between muscle mass and muscle strength, and the impact of comorbidities: a population-based, cross-sectional study of older adults in the United States. *BMC Geriatrics*. 2013; 13: 74. <https://doi.org/10.1186/1471-2318-13-74>.
- [2] Raz N, Lindenberger U, Rodrigue KM, Kennedy KM, Head D, Williamson A, *et al.* Regional brain changes in aging healthy adults: general trends, individual differences and modifiers. *Cerebral Cortex* (New York, N.Y.: 1991). 2005; 15: 1676–1689. <https://doi.org/10.1093/cercor/bhi044>.
- [3] Harada CN, Natelson Love MC, Triebel KL. Normal cognitive aging. *Clinics in Geriatric Medicine*. 2013; 29: 737–752. <https://doi.org/10.1016/j.cger.2013.07.002>.
- [4] Seidler RD, Bernard JA, Burutolu TB, Fling BW, Gordon MT, Gwin JT, *et al.* Motor control and aging: links to age-related brain structural, functional, and biochemical effects. *Neuroscience and Biobehavioral Reviews*. 2010; 34: 721–733. <https://doi.org/10.1016/j.neubiorev.2009.10.005>.
- [5] Buckner RL. Memory and executive function in aging and AD: multiple factors that cause decline and reserve factors that compensate. *Neuron*. 2004; 44: 195–208. <https://doi.org/10.1016/j.neuron.2004.09.006>.
- [6] Cruz-Jentoft AJ, Baeyens JP, Bauer JM, Boirie Y, Cederholm T, Landi F, *et al.* Sarcopenia: European consensus on definition and diagnosis: Report of the European Working Group on Sarcopenia in Older People. *Age and Ageing*. 2010; 39: 412–423. <https://doi.org/10.1093/ageing/afq034>.
- [7] Larsson L, Degens H, Li M, Salvati L, Lee YI, Thompson W, *et al.* Sarcopenia: Aging-Related Loss of Muscle Mass and Function. *Physiological Reviews*. 2019; 99: 427–511. <https://doi.org/10.1152/physrev.00061.2017>.
- [8] Callisaya ML, Blizzard L, Schmidt MD, McGinley JL, Srikanth VK. Ageing and gait variability—a population-based study of older people. *Age and Ageing*. 2010; 39: 191–197. <https://doi.org/10.1093/ageing/afp250>.
- [9] Aboutorabi A, Arazpour M, Bahramizadeh M, Hutchins SW, Fadayevatan R. The effect of aging on gait parameters in able-bodied older subjects: a literature review. *Aging Clinical and Experimental Research*. 2016; 28: 393–405. <https://doi.org/10.1007/s40520-015-0420-6>.
- [10] Michalska J, Kamieniarz A, Sobota G, Stania M, Juras G, Słomka KJ. Age-related changes in postural control in older women: transitional tasks in step initiation. *BMC Geriatrics*. 2021; 21: 17. <https://doi.org/10.1186/s12877-020-01985-y>.
- [11] Osoba MY, Rao AK, Agrawal SK, Lalwani AK. Balance and gait in the elderly: A contemporary review. *Laryngoscope Investigative Otolaryngology*. 2019; 4: 143–153. <https://doi.org/10.1002/liv.2.252>.
- [12] Montero-Odasso M, Verghese J, Beauchet O, Hausdorff JM. Gait and cognition: a complementary approach to understanding brain function and the risk of falling. *Journal of the American Geriatrics Society*. 2012; 60: 2127–2136. <https://doi.org/10.1111/j.1532-5415.2012.04209.x>.
- [13] Verghese J, Holtzer R, Lipton RB, Wang C. Quantitative gait markers and incident fall risk in older adults. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*. 2009; 64: 896–901. <https://doi.org/10.1093/gerona/glp033>.
- [14] Bayot M, Dujardin K, Dissaux L, Tard C, Defebvre L, Bonnet CT, *et al.* Can dual-task paradigms predict Falls better than single task? - A systematic literature review. *Neurophysiologie Clinique = Clinical Neurophysiology*. 2020; 50: 401–440. <https://doi.org/10.1016/j.neucli.2020.10.008>.
- [15] Nohelova D, Bizovska L, Vuillerme N, Svoboda Z. Gait Variability and Complexity during Single and Dual-Task Walking on Different Surfaces in Outdoor Environment. *Sensors* (Basel, Switzerland). 2021; 21: 4792. <https://doi.org/10.3390/s21144792>.
- [16] Tombu M, Jolicoeur P. A central capacity sharing model of dual-task performance. *Journal of Experimental Psychology. Human Perception and Performance*. 2003; 29: 3–18. <https://doi.org/10.1037/0096-1523.29.1.3>.
- [17] Strobach T, Salminen T, Karbach J, Schubert T. Practice-related optimization and transfer of executive functions: a general review and a specific realization of their mechanisms in dual tasks. *Psychological Research*. 2014; 78: 836–851. <https://doi.org/10.1007/s00426-014-0563-7>.
- [18] Hausdorff JM, Schweiger A, Herman T, Yogev-Seligmann G, Giladi N. Dual-task decrements in gait: contributing factors among healthy older adults. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*. 2008; 63: 1335–1343. <https://doi.org/10.1093/gerona/63.12.1335>.
- [19] Hennah C, Ellis G, Doumas M. Dual task walking in healthy aging: Effects of narrow and wide walking paths. *PLoS One*. 2021; 16: e0261647. <https://doi.org/10.1371/journal.pone.0261647>.
- [20] Smith E, Cusack T, Cunningham C, Blake C. The Influence of a Cognitive Dual Task on the Gait Parameters of Healthy Older Adults: A Systematic Review and Meta-Analysis. *Journal of Aging and Physical Activity*. 2017; 25: 671–686. <https://doi.org/10.1123/japa.2016-0265>.
- [21] Ohsugi H, Ohgi S, Shigemori K, Schneider EB. Differences in dual-task performance and prefrontal cortex activation between younger and older adults. *BMC Neuroscience*. 2013; 14: 10. <https://doi.org/10.1186/1471-2202-14-10>.
- [22] Manor B, Zhou J, Jor'dan A, Zhang J, Fang J, Pascual-Leone A. Reduction of Dual-task Costs by Noninvasive Modulation of Prefrontal Activity in Healthy Elders. *Journal of Cognitive Neuroscience*. 2016; 28: 275–281. https://doi.org/10.1162/jocn_a_00897.
- [23] Sayig-Keren RM, Dagan M, Cornejo Thumm P, Brozgol M, Gazit E, Manor B, *et al.* The Potential of Transcranial Alternating Current Stimulation to Alleviate Dual-Task Gait Costs in Older Adults: Insights from a Double-Blinded Pilot Study. *Gerontology*. 2023; 69: 513–518. <https://doi.org/10.1159/000527171>.
- [24] Zhou J, Manor B, Yu W, Lo OY, Gouskova N, Salvador R, *et al.* Targeted tDCS Mitigates Dual-Task Costs to Gait and Balance in Older Adults. *Annals of Neurology*. 2021; 90: 428–439. <https://doi.org/10.1002/ana.26156>.
- [25] Stagg CJ, Antal A, Nitsche MA. Physiology of Transcranial Direct Current Stimulation. *The Journal of ECT*. 2018; 34: 144–152. <https://doi.org/10.1097/YCT.0000000000000510>.
- [26] Yamada Y, Sumiyoshi T. Neurobiological Mechanisms of Transcranial Direct Current Stimulation for Psychiatric Disorders; Neurophysiological, Chemical, and Anatomical Considerations. *Frontiers in Human Neuroscience*. 2021; 15: 631838. <https://doi.org/10.3389/fnhum.2021.631838>.
- [27] Nitsche MA, Paulus W. Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *The Journal of Physiology*. 2000; 527 Pt 3: 633–639. <https://doi.org/10.1111/j.1469-7793.2000.t01-1-00633.x>.

- [28] Nitsche MA, Paulus W. Sustained excitability elevations induced by transcranial DC motor cortex stimulation in humans. *Neurology*. 2001; 57: 1899–1901. <https://doi.org/10.1212/wnl.57.10.1899>.
- [29] Usman JS, Wong TWL, Ng SSM. Effects of transcranial direct current stimulation on dual-task performance in older and young adults: A systematic review and meta-analysis. *Archives of Gerontology and Geriatrics Plus*. 2024; 1: 100047. <https://doi.org/10.1016/j.aggp.2024.100047>.
- [30] Yan H, Karmur BS, Kulkarni AV. Comparing Effects of Treatment: Controlling for Confounding. *Neurosurgery*. 2020; 86: 325–331. <https://doi.org/10.1093/neuros/nyz509>.
- [31] Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, *et al.* The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ (Clinical Research Ed.)*. 2021; 372: n71. <https://doi.org/10.1136/bmj.n71>.
- [32] Amir-Behghadami M, Janati A. Population, Intervention, Comparison, Outcomes and Study (PICOS) design as a framework to formulate eligibility criteria in systematic reviews. *Emergency Medicine Journal: EMJ*. 2020; 37: 387. <https://doi.org/10.1136/emmermed-2020-209567>.
- [33] Vaportzis E, Niechcial MA, Gow AJ. A systematic literature review and meta-analysis of real-world interventions for cognitive ageing in healthy older adults. *Ageing Research Reviews*. 2019; 50: 110–130. <https://doi.org/10.1016/j.arr.2019.01.006>.
- [34] Kelly ME, Loughrey D, Lawlor BA, Robertson IH, Walsh C, Brennan S. The impact of exercise on the cognitive functioning of healthy older adults: a systematic review and meta-analysis. *Ageing Research Reviews*. 2014; 16: 12–31. <https://doi.org/10.1016/j.arr.2014.05.002>.
- [35] Zhu X, Yin S, Lang M, He R, Li J. The more the better? A meta-analysis on effects of combined cognitive and physical intervention on cognition in healthy older adults. *Ageing Research Reviews*. 2016; 31: 67–79. <https://doi.org/10.1016/j.arr.2016.07.003>.
- [36] Borenstein M, Hedges LV, Higgins JP, Rothstein HR. Introduction to meta-analysis. John Wiley & Sons: Oxford. 2021.
- [37] Stedman MR, Curtin F, Elbourne DR, Kesselheim AS, Brookhart MA. Meta-analyses involving cross-over trials: methodological issues. *International Journal of Epidemiology*. 2011; 40: 1732–1734. <https://doi.org/10.1093/ije/dyp345>.
- [38] Chandler J, Cumpston M, Li T, Page MJ, Welch V. *Cochrane handbook for systematic reviews of interventions*. Wiley: Hoboken. 2019.
- [39] Borenstein M, Hedges LV, Higgins JPT, Rothstein HR. A basic introduction to fixed-effect and random-effects models for meta-analysis. *Research Synthesis Methods*. 2010; 1: 97–111. <https://doi.org/10.1002/jrsm.12>.
- [40] Borenstein M. How to understand and report heterogeneity in a meta-analysis: The difference between I-squared and prediction intervals. *Integrative Medicine Research*. 2023; 12: 101014. <https://doi.org/10.1016/j.imr.2023.101014>.
- [41] Duval S, Tweedie R. Trim and fill: A simple funnel-plot-based method of testing and adjusting for publication bias in meta-analysis. *Biometrics*. 2000; 56: 455–463. <https://doi.org/10.1111/j.0006-341x.2000.00455.x>.
- [42] Egger M, Davey Smith G, Schneider M, Minder C. Bias in meta-analysis detected by a simple, graphical test. *BMJ (Clinical Research Ed.)*. 1997; 315: 629–634. <https://doi.org/10.1136/bmj.315.7109.629>.
- [43] Cumpston M, Li T, Page MJ, Chandler J, Welch VA, Higgins JP, *et al.* Updated guidance for trusted systematic reviews: a new edition of the Cochrane Handbook for Systematic Reviews of Interventions. *The Cochrane Database of Systematic Reviews*. 2019; 10: ED000142. <https://doi.org/10.1002/14651858.ED000142>.
- [44] Higgins J, Savović J, Page M, Elbers R, Sterne J. Assessing risk of bias in a randomized trial. *Cochrane handbook for systematic reviews of interventions* (pp. 205–228). John Wiley & Sons: Chichester. 2019. <https://doi.org/10.1002/9781119536604.ch8>.
- [45] Higgins J, Thomas J, Chandler J, Cumpston M, Li T, Page M, *et al.* *Cochrane handbook for systematic reviews of interventions version 6.4* (updated August 2023). Cochrane, 2023. Available at: <https://training.cochrane.org/handbook> (Accessed: 22 July 2024).
- [46] Chatterjee SA, Seidler RD, Skinner JW, Lysne PE, Sumonthee C, Wu SS, *et al.* Effects of Prefrontal Transcranial Direct Current Stimulation on Retention of Performance Gains on an Obstacle Negotiation Task in Older Adults. *Neuromodulation: Journal of the International Neuromodulation Society*. 2023; 26: 829–839. <https://doi.org/10.1016/j.neurom.2022.02.231>.
- [47] Clark DJ, Chatterjee SA, Skinner JW, Lysne PE, Sumonthee C, Wu SS, *et al.* Combining Frontal Transcranial Direct Current Stimulation With Walking Rehabilitation to Enhance Mobility and Executive Function: A Pilot Clinical Trial. *Neuromodulation: Journal of the International Neuromodulation Society*. 2021; 24: 950–959. <https://doi.org/10.1111/ner.13250>.
- [48] Orcioli-Silva D, Islam A, Baker MR, Gobbi LTB, Rochester L, Pantall A. Bi-Anodal Transcranial Direct Current Stimulation Combined With Treadmill Walking Decreases Motor Cortical Activity in Young and Older Adults. *Frontiers in Aging Neuroscience*. 2021; 13: 739998. <https://doi.org/10.3389/fnagi.2021.739998>.
- [49] Rodrigues NO, Vidal Bravallhier AA, Moraes TPD, Barros JA, Ansai JH, Christofoletti G. Efficacy of Transcranial Direct Current Stimulation (tDCS) on Cognition, Anxiety, and Mobility in Community-Dwelling Older Individuals: A Controlled Clinical Trial. *Brain Sciences*. 2023; 13: 1614. <https://doi.org/10.3390/brainsci13121614>.
- [50] Rostami M, Mosallanezhad Z, Ansari S, Ehsani F, Kidgell D, Nourbakhsh MR, *et al.* Multi-session anodal transcranial direct current stimulation enhances lower extremity functional performance in healthy older adults. *Experimental Brain Research*. 2020; 238: 1925–1936. <https://doi.org/10.1007/s00221-020-05827-6>.
- [51] Schneider N, Dagan M, Katz R, Thumm PC, Brozgol M, Giladi N, *et al.* Combining transcranial direct current stimulation with a motor-cognitive task: the impact on dual-task walking costs in older adults. *Journal of Neuroengineering and Rehabilitation*. 2021; 18: 23. <https://doi.org/10.1186/s12984-021-00826-2>.
- [52] Yi D, Sung Y, Yim J. Effect of Transcranial Direct Current Stimulation on Walking Speed, Functional Strength, and Balance in Older Adults: A Randomized, Double-Blind Controlled Trial. *Medical Science Monitor: International Medical Journal of Experimental and Clinical Research*. 2021; 27: e932623. <https://doi.org/10.12659/MSM.932623>.
- [53] Zhou J, Lo OY, Lipsitz LA, Zhang J, Fang J, Manor B. Transcranial direct current stimulation enhances foot sole somatosensation when standing in older adults. *Experimental Brain Research*. 2018; 236: 795–802. <https://doi.org/10.1007/s00221-018-5178-6>.
- [54] Powell LE, Myers AM. The Activities-specific Balance Confidence (ABC) Scale. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*. 1995; 50A: M28–34. <https://doi.org/10.1093/gerona/50a.1.m28>.
- [55] Blum L, Korner-Bitensky N. Usefulness of the Berg Balance Scale in stroke rehabilitation: a systematic review. *Physical Therapy*. 2008; 88: 559–566. <https://doi.org/10.2522/ptj.20070205>.
- [56] Nasreddine ZS, Phillips NA, Bédirian V, Charbonneau S, Whitehead V, Collin I, *et al.* The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment.

- Journal of the American Geriatrics Society. 2005; 53: 695–699. <https://doi.org/10.1111/j.1532-5415.2005.53221.x>.
- [57] Tombaugh TN, McIntyre NJ. The mini-mental state examination: a comprehensive review. *Journal of the American Geriatrics Society*. 1992; 40: 922–935. <https://doi.org/10.1111/j.1532-5415.1992.tb01992.x>.
- [58] Shumway-Cook A, Brauer S, Woollacott M. Predicting the probability for falls in community-dwelling older adults using the Timed Up & Go Test. *Physical Therapy*. 2000; 80: 896–903.
- [59] Baharlouei H, Saba MA, Shaterzadeh Yazdi MJ, Jaberzadeh S. The effect of transcranial direct current stimulation on balance in healthy young and older adults: A systematic review of the literature. *Neurophysiologie Clinique = Clinical Neurophysiology*. 2020; 50: 119–131. <https://doi.org/10.1016/j.neucli.2020.01.006>.
- [60] Guo Z, Bao D, Manor B, Zhou J. The Effects of Transcranial Direct Current Stimulation (tDCS) on Balance Control in Older Adults: A Systematic Review and Meta-Analysis. *Frontiers in Aging Neuroscience*. 2020; 12: 275. <https://doi.org/10.3389/fnagi.2020.00275>.
- [61] Balasubramanian CK. The community balance and mobility scale alleviates the ceiling effects observed in the currently used gait and balance assessments for the community-dwelling older adults. *Journal of Geriatric Physical Therapy* (2001). 2015; 38: 78–89. <https://doi.org/10.1519/JPT.0000000000000024>.
- [62] Deroost N, Baetens K, Vandenbossche J, Kerckhofs E. Anodal tDCS of the primary motor cortex and motor sequence learning in a large sample of patients with Parkinsons disease. *Neuropsychiatry*. 2018; 8: 35–46. <https://doi.org/10.4172/neuropsychiatry.1000323>.
- [63] Furuya S, Klaus M, Nitsche MA, Paulus W, Altenmüller E. Ceiling effects prevent further improvement of transcranial stimulation in skilled musicians. *The Journal of Neuroscience: the Official Journal of the Society for Neuroscience*. 2014; 34: 13834–13839. <https://doi.org/10.1523/JNEUROSCI.1170-14.2014>.
- [64] Lee JH, Lee TL, Kang N. Transcranial direct current stimulation decreased cognition-related reaction time in older adults: A systematic review and meta-analysis. *Ageing Research Reviews*. 2021; 70: 101377. <https://doi.org/10.1016/j.arr.2021.101377>.
- [65] Cespón J, Rodella C, Miniussi C, Pellicciari MC. Behavioural and electrophysiological modulations induced by transcranial direct current stimulation in healthy elderly and Alzheimer's disease patients: A pilot study. *Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology*. 2019; 130: 2038–2052. <https://doi.org/10.1016/j.clinph.2019.08.016>.
- [66] Zhou J, Hao Y, Wang Y, Jor'dan A, Pascual-Leone A, Zhang J, *et al.* Transcranial direct current stimulation reduces the cost of performing a cognitive task on gait and postural control. *The European Journal of Neuroscience*. 2014; 39: 1343–1348. <https://doi.org/10.1111/ejn.12492>.
- [67] 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. *Perceptual and Motor Skills*. 2020; 127: 803–822. <https://doi.org/10.1177/0031512520935695>.
- [68] Rogojin A, Gorbet DJ, Hawkins KM, Sergio LE. Cognitive-Motor Integration Performance Is Affected by Sex, APOE Status, and Family History of Dementia. *Journal of Alzheimer's Disease: JAD*. 2019; 71: 685–701. <https://doi.org/10.3233/JAD-190403>.
- [69] Wu T, Liu J, Hallett M, Zheng Z, Chan P. Cerebellum and integration of neural networks in dual-task processing. *NeuroImage*. 2013; 65: 466–475. <https://doi.org/10.1016/j.neuroimage.2012.10.004>.
- [70] Leone C, Feys P, Moumdjian L, D'Amico E, Zappia M, Patti F. Cognitive-motor dual-task interference: A systematic review of neural correlates. *Neuroscience and Biobehavioral Reviews*. 2017; 75: 348–360. <https://doi.org/10.1016/j.neubiorev.2017.01.010>.
- [71] Reinhardt J, Rus-Oswald OG, Bürki CN, Bridenbaugh SA, Krumm S, Michels L, *et al.* Neural Correlates of Stepping in Healthy Elderly: Parietal and Prefrontal Cortex Activation Reflects Cognitive-Motor Interference Effects. *Frontiers in Human Neuroscience*. 2020; 14: 566735. <https://doi.org/10.3389/fnhum.2020.566735>.
- [72] Manor B, Zhou J, Harrison R, Lo OY, Trivison TG, Hausdorff JM, *et al.* Transcranial Direct Current Stimulation May Improve Cognitive-Motor Function in Functionally Limited Older Adults. *Neurorehabilitation and Neural Repair*. 2018; 32: 788–798. <https://doi.org/10.1177/1545968318792616>.
- [73] Živanović M, Paunović D, Konstantinović U, Vulić K, Bjekić J, Filipović SR. The effects of offline and online prefrontal vs parietal transcranial direct current stimulation (tDCS) on verbal and spatial working memory. *Neurobiology of Learning and Memory*. 2021; 179: 107398. <https://doi.org/10.1016/j.nlm.2021.107398>.
- [74] Pol F, Salehinejad MA, Baharlouei H, Nitsche MA. The effects of transcranial direct current stimulation on gait in patients with Parkinson's disease: a systematic review. *Translational Neurodegeneration*. 2021; 10: 22. <https://doi.org/10.1186/s40035-021-00245-2>.
- [75] Ghasemian-Shirvan E, Farnad L, Mosayebi-Samani M, Verstraeten S, Meesen RLJ, Kuo MF, *et al.* Age-related differences of motor cortex plasticity in adults: A transcranial direct current stimulation study. *Brain Stimulation*. 2020; 13: 1588–1599. <https://doi.org/10.1016/j.brs.2020.09.004>.
- [76] Fujiyama H, Hyde J, Hinder MR, Kim SJ, McCormack GH, Vickers JC, *et al.* Delayed plastic responses to anodal tDCS in older adults. *Frontiers in Aging Neuroscience*. 2014; 6: 115. <https://doi.org/10.3389/fnagi.2014.00115>.
- [77] Pilloni G, Vogel-Eyny A, Lustberg M, Best P, Malik M, Walton-Masters L, *et al.* Tolerability and feasibility of at-home remotely supervised transcranial direct current stimulation (RS-tDCS): Single-center evidence from 6,779 sessions. *Brain Stimulation*. 2022; 15: 707–716. <https://doi.org/10.1016/j.brs.2022.04.014>.
- [78] Cappon D, den Boer T, Jordan C, Yu W, Lo A, LaGanke N, *et al.* Safety and Feasibility of Tele-Supervised Home-Based Transcranial Direct Current Stimulation for Major Depressive Disorder. *Frontiers in Aging Neuroscience*. 2022; 13: 765370. <https://doi.org/10.3389/fnagi.2021.765370>.
- [79] Dedoncker J, Brunoni AR, Baeken C, Vanderhasselt MA. A Systematic Review and Meta-Analysis of the Effects of Transcranial Direct Current Stimulation (tDCS) Over the Dorsolateral Prefrontal Cortex in Healthy and Neuropsychiatric Samples: Influence of Stimulation Parameters. *Brain Stimulation*. 2016; 9: 501–517. <https://doi.org/10.1016/j.brs.2016.04.006>.
- [80] Lefebvre S, Liew SL. Anatomical Parameters of tDCS to Modulate the Motor System after Stroke: A Review. *Frontiers in Neurology*. 2017; 8: 29. <https://doi.org/10.3389/fneur.2017.00029>.