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A systematic review and meta-analysis exploring the effects of tDCS on metabolic syndrome parameters in adults

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BACKGROUND: Metabolic syndrome is a group of health conditions associated with obesity, increased risk of type 2 diabetes, cardiovascular disease and mortality. Interventions, including lifestyle changes, pharmacological treatments, and surgical interventions, have limited long-term efficacy, and do not adequately address some underpinning factors in overweight/obesity, such as cognitive/inhibitory control related to eating behaviours. There is emerging evidence for the successful use of neuromodulation techniques, such as transcranial direct current stimulation (tDCS), as potential adjunctive therapies for eating and weight disorders. This systematic review and meta-analysis have investigated the potential effects of tDCS on weight and metabolic parameters, in adults with or without excess body weight.

METHODS: In accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement, a systematic search of Embase, PsychInfo and PubMed electronic databases was performed to identify randomised clinical trials (RCTs) of tDCS which reported at least one metabolic syndrome parameter. Primary outcomes were weight, body mass index (BMI), waist circumference, blood pressure, blood glucose, insulin, and lipid profile.

RESULTS: A total of 28 studies (1129 participants) were included. tDCS protocols varied in stimulation sites, current intensity, and number and duration of sessions. Meta-analyses showed small but statistically significant weight loss (MD = −1.16 kg, 95% CI: −2.29 to −0.02; $p = 0.04$) and waist circumference reduction (MD = −0.67 cm, 95% CI: −1.14 to −0.19; $p = 0.02$) following active tDCS compared to sham. A non-significant reduction in food cravings traits was observed (SMD = −0.21, $p = 0.06$). Effects on glucose and blood pressure were variable.

CONCLUSION: The modest positive effects of tDCS on weight and waist circumference, nonetheless, highlight its potential clinical relevance for treating obesity and metabolic syndrome. Well-powered RCTs using standardised assessment procedures are essential to clarify the therapeutic mechanisms of tDCS and to identify optimal dosing for this population.

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INTRODUCTION

Metabolic syndrome refers to a group of related conditions closely linked to obesity which predict adverse health outcomes [1]. Metabolic syndrome significantly elevates the risk of cardiovascular morbidity and mortality, with affected individuals exhibiting nearly twice the risk of cardiovascular disease and a fivefold increase in the likelihood of developing type 2 diabetes (T2DM) [1]. The World Health Organization (WHO) established criteria for metabolic syndrome in 1998, targeting both those predisposed to cardiovascular disease and non-diabetic individuals at elevated risk for T2DM [2, 3]. Several definitions have appeared over time, but the differences between them are relatively small [2, 3]. The International Diabetes Federation (IDF) defines it as the presence of central obesity (using ethnicity-specific waist circumference thresholds) together with at least two of the following factors: elevated triglycerides, raised blood pressure, increased fasting plasma glucose, or reduced high-density lipoprotein (HDL) cholesterol levels [4].

The prevalence of obesity and metabolic syndrome has risen in parallel [3], with lower prevalences in people with higher levels of education and income [5]. Estimates from the USA suggest that, if trends in overweight and obesity rates continue, an additional 41.4 million adults will be living with overweight or obesity by 2050 [6]. USA data also show increases in the prevalence of metabolic syndrome since 2011, with rates of 37.6% in 2011–12, and 41.8% in 2017–18 [5]. The prevalence of comorbidities (e.g., diabetes and cardiovascular diseases) associated with this condition has shown a similar upward trend, contributing to significant health consequences [5]. To mitigate this escalating public health challenge, innovative approaches to prevention and treatment are needed.

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Metabolic syndrome is multifactorial and can be driven by an imbalance between caloric intake and energy expenditure [3]. It is influenced by genetic predisposition, physical inactivity, dietary habits, and alterations in gut microbiome composition [3]. Although its prevalence parallels that of obesity and T2DM, and some definitions of metabolic syndrome require the presence of central obesity, it can also manifest in individuals without obesity [2, 3]. Therapeutic strategies for managing metabolic syndrome and obesity often share common elements, i.e. interventions targeting one condition can improve the other [7]. In particular, weight loss is a fundamental component in the management of metabolic syndrome, whether achieved through behavioural modification, pharmacotherapy or bariatric surgery [8]. Such interventions have been associated with remission of type T2DM and significant reductions in cardiovascular risk factors such as hypertension and dyslipidaemia [8].

In the past decade, non-invasive brain stimulation (NIBS) techniques have gained increasing attention, with a growing body of research investigating their potential to modify cardiovascular risk factors (e.g., reducing blood pressure) and treat obesity [9]. Transcranial direct current stimulation (tDCS) is one of the least invasive forms of NIBS. It involves application of a weak electric current (typically 0.5–2 mA for 20 min) via scalp electrodes. This induces shifts in neuronal excitability, modulates neural networks [10, 11], and leads to lasting changes in brain function, particularly with repeated administration [12]. Compared to other neuromodulation techniques, tDCS has several advantages, including feasibility for home-based use, the ability to have an effective placebo, bilateral stimulation, affordability, and a favourable safety profile with minimal adverse effects [12, 13].

Evidence suggests that tDCS influences metabolic-related parameters, including blood pressure, blood glucose, and insulin levels [14–16]. Increasing evidence has also demonstrated the potential of tDCS to alter eating behaviours, facilitate weight loss, and promote weight maintenance [17–21]. A recent systematic review has reported that active tDCS stimulation was associated with greater average body weight reduction of (−0.82 kg) among individuals with obesity relative to sham stimulation [22]. Based on these reports, tDCS appears to be a promising intervention for addressing obesity-related eating behaviours and weight reduction. However, differences remain in the literature regarding the consistency and magnitude of tDCS effects on metabolic and weight-related outcomes.

Although the mechanisms underlying these effects remain unclear, evidence suggests that targeting frontal brain regions enhances cognitive and inhibitory control, thereby improving obesity-related outcomes [19, 23, 24]. Furthermore, the prefrontal cortex has been identified as a key neural substrate in the regulation of cardiovascular function, with established associations with heart rate and heart rate variability [11]. Accordingly, neuromodulation via tDCS presents a promising approach for the management of metabolic-related syndromes. However, to our knowledge, no systematic review has comprehensively examined the therapeutic effects of tDCS on outcomes specifically associated with metabolic syndrome.

This systematic review and meta-analysis aim to evaluate whether tDCS improves metabolic syndrome-related outcomes. Specifically, it critically assesses the clinical efficacy of tDCS in adults by examining its effects on weight, BMI, waist circumference, blood pressure, blood glucose, insulin, and lipid profile. Where available, secondary outcomes such as eating behaviours, stress-related hormones, mood, leptin, and neuroplasticity markers are included.

METHODS

Study design and protocol

This review was performed in accordance with the reporting guidance provided in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [25]. The protocol for this review has been registered within the PROSPERO (registration ID: CRD42023448870).

Search strategy

Two reviewers (MA and ML) independently searched three electronic databases (Embase, PsychInfo and PubMed) from inception until the 20th of March 2026, with the following search terms: ((‘Transcranial direct current stimulatio’ OR ‘tDCS’ OR ‘Neuromodulation’ OR ‘Non-invasive brain stimulation’ OR ‘Transcranial electrical stimulation’) AND (‘Body weight’ OR ‘BMI’ OR ‘Overweight’ OR ‘Obesity’ OR ‘Obesity management’ OR ‘eating behaviour*’ OR ‘Binge eating’ OR ‘Cholesterol’ OR ‘Triglycerides’ OR ‘Lipid profile’ OR ‘Metabolic syndrome’ OR ‘Hypertension’ OR ‘Blood pressure’ OR ‘Glucose’ OR ‘Insulin’ OR ‘Hb1AC’)).

We prioritised terms related to metabolic-syndrome outcomes (our primary focus) but also included key behavioural terms (eating behaviour and binge eating) and obesity-related terms (‘body weight’, ‘BMI’, and ‘obesity management’) as supplementary search elements. These terms were chosen as they are frequently reported in intervention studies within the obesity and metabolic health literature. This ensured we captured studies that primarily reported metabolic endpoints while still identifying trials that reported eating-behaviour or other behavioural measures alongside those metabolic outcomes.

The secondary search strategy involved checking reference lists of relevant studies and reviews to identify papers for inclusion. Additionally, the search included clinical trial registries such as the International Committee of Medical Journal Editors (ICMJE) registry, the National Institutes of Health (NIH) registry, the European Union (EU) Clinical Trials Register, the World Health Organization (WHO) Clinical Registry and the International Standard Randomised Controlled Trial Number (ISRCTN) registry, dissertation databases. Unpublished data meeting eligibility criteria were included if sufficient information was available.

Eligibility criteria

Studies were selected according to the following eligibility criteria using the PICOS toll [25] detailed below:

• P	population:	Adult participants with or without excess body weight.
• I	intervention:	Single or multiple sessions of tDCS.
• C	comparator:	A sham tDCS control group or another intervention in the control group (e.g., treatment as usual).
• O	outcomes of interest:	Inclusion of at least one metabolic syndrome-specific clinical measure, changes in weight, BMI, waist circumference, blood pressure, blood glucose, insulin, lipid profile. Secondary outcomes included eating behaviours, stress-related hormones, mood, leptin and neuroplasticity markers.
• S	study design:	Experimental and clinical control studies published in English.

Selection process and data extraction

After removing duplicates, two reviewers (MA and ML) independently screened titles and abstracts against the eligibility criteria using Rayyan software. Discrepancies identified during the full-text review were resolved through consensus or assessment by a

third reviewer (US). In instances where studies included participants recruited from the same population, institution, or time period, only one independent sample was retained. Preference was given to studies reporting the most relevant outcomes for this review. Protocols identified at screening were excluded as primary reports; we searched for matching publications via databases, trial registries, and forward citation searching, and contacted protocol authors by e-mail to request full texts or study data, those protocols for which no full report or data were obtained were excluded.

All papers not meeting the inclusion criteria were excluded, with reasons for exclusion documented (Fig. 1).

The data from all included studies was extracted into a specifically designed electronic summary table by a data extractor MA, which was verified independently by another data extractor (ML). Any discrepancies were resolved through discussion and consensus. The extracted data included:

• P	population:	Age, gender, sample size, study's inclusion/exclusion criteria, diagnosis, and number of participants who were overweight/obese.
• I	intervention:	tDCS stimulation lateralisation, current intensity and duration, anode placement, and total number of sessions.
• C	comparator:	Sham control group, waitlist, and treatment as usual.
• O	outcomes of interest:	Mean and standard deviation of metabolic syndrome-related parameters at baseline and post-treatment, including weight, BMI, waist circumference, systolic and diastolic blood pressure, blood glucose, insulin, cholesterol, triglycerides, and HDL. Secondary outcomes included eating behaviours, stress-related hormones, mood, leptin, neuroplasticity markers e.g., Brain-Derived Neurotrophic Factor where available.
• S	study design:	Reference citation, study design and country.

Quality assessment

Three authors (MA, ML and Bİ) independently assessed the risk of bias using the Cochrane Risk of Bias 2.0 Tool (RoB 2.0) for the included RCTs [26] and the Cochrane Tool for Risk of Bias in Non-randomised Studies (ROBINS-I) in non-RCTs [27]. The initial level of agreement between assessors was high (89%). Any discrepancies were resolved through discussion, leading to a consensus rating. Each domain was rated as 'low risk,' 'high risk,' or 'some concerns,' in accordance with the criteria established by the Cochrane Collaboration [28].

Data synthesis and analysis

Data were synthesised both narratively and quantitatively. Statistical analyses were conducted in R. Meta-analyses of change scores were performed when data from at least four studies were available for the same outcome. Change scores for means were calculated by subtracting baseline from post-intervention means and change scores for standard deviations were calculated assuming a correlation coefficient (r) of 0.5.

Given the clinical and methodological heterogeneity across studies, random-effects models were used with restricted maximum likelihood (REML) estimation, and standard errors were adjusted using the truncated Knapp-Hartung method. For outcomes reported in the same units across studies (weight, BMI, and waist circumference), pooled effects were expressed as mean differences (MDs). For all other outcomes, pooled effects were expressed as standardised mean differences (SMDs) using Hedges' g to account for small sample bias. Heterogeneity was assessed using the I^2 statistic and Cochran's Q test. Forest plots were generated to present effect sizes, 95% confidence intervals and study weights. Egger's regression-based test and trim-and-fill analyses were used to assess small study effects and potential publication bias where sufficient studies were available. Crossover trials were no included in the quantitative synthesis due to likely carryover effects and insufficient period-specific outcome data.

RESULTS

The review flowchart is presented in accordance with the PRISMA statement guidelines [25]. Figure 1 shows that out of 712 references screened, 28 studies met the inclusion criteria for the systematic review. Two studies were excluded due to duplicate populations, and one was excluded for not reporting relevant outcomes. Table 1 summarises the 28 studies included in the systematic review, of which 13 were included in the quantitative analysis.

A narrative review of the results is provided in Supplementary Material 1.

Study characteristics

The included studies involved a total of 1129 participants across both non-clinical ($n = 17$ studies) and clinical ($n = 11$ studies) populations. 14 studies (50%) recruited participants with excess body weight (i.e., BMI ≥ 25 kg/m^2). The majority of studies (57%) applied tDCS as a stand-alone intervention, while three studies (10%) combined tDCS with a low-calorie diet, and seven studies (25%) incorporated cognitive-based therapies, including inhibitory control training, approach bias modification training, attention training, cognitive training, and mindful eating training. One study (4%) combined tDCS with a physical activity intervention. One study (4%) combined tDCS with intranasal oxytocin.

The number of stimulation sessions ranged from 1 to 20, with intensities of the current delivered between 1 and 2 mA and session durations varying from 7 to 40 min. Most studies (90%) employed the conventional bipolar montage, while only three studies (10%) used alternative approaches, including bi-anodal electrode placement, multichannel tDCS and net-tDCS. Stimulation sites also varied, with the dlPFC being the most commonly targeted area (60%), followed by the motor cortex (25%). Further details on the study characteristics are presented in Table 1.

Study quality

The results of the Cochrane risk of bias assessments for both between-subjects and crossover within-subjects study designs are presented in Fig. 1, see Supplementary Material 1. Across studies, the overall risk of bias was judged as low-to-moderate and the primary reason for concern was related to the non-availability of pre-published protocols. Among studies with a parallel design, the overall bias rate was rated as low in 25% of studies, whereas in 75% there were some concerns. None were assessed as high risk. Among studies with crossover design, the overall bias rate was rated as having 'some concerns' in 80% of studies and 20% percent were rated as 'high concerns'.

Meta-analysis results

Meta-analyses were conducted for weight, BMI, waist circumference, Food Craving Questionnaire (FCQ) State and Trait (Figs. 2–4).

Significant effects of real versus sham tDCS were observed for reduction in weight (MD = −2.01 kg, 95% CI: −2.82 to −1.35; $p < 0.001$) and waist circumference (MD = −0.67 cm, 95% CI: −1.14 to −0.19; $p = 0.02$), with no heterogeneity detected ($I^2 = 0\%$).

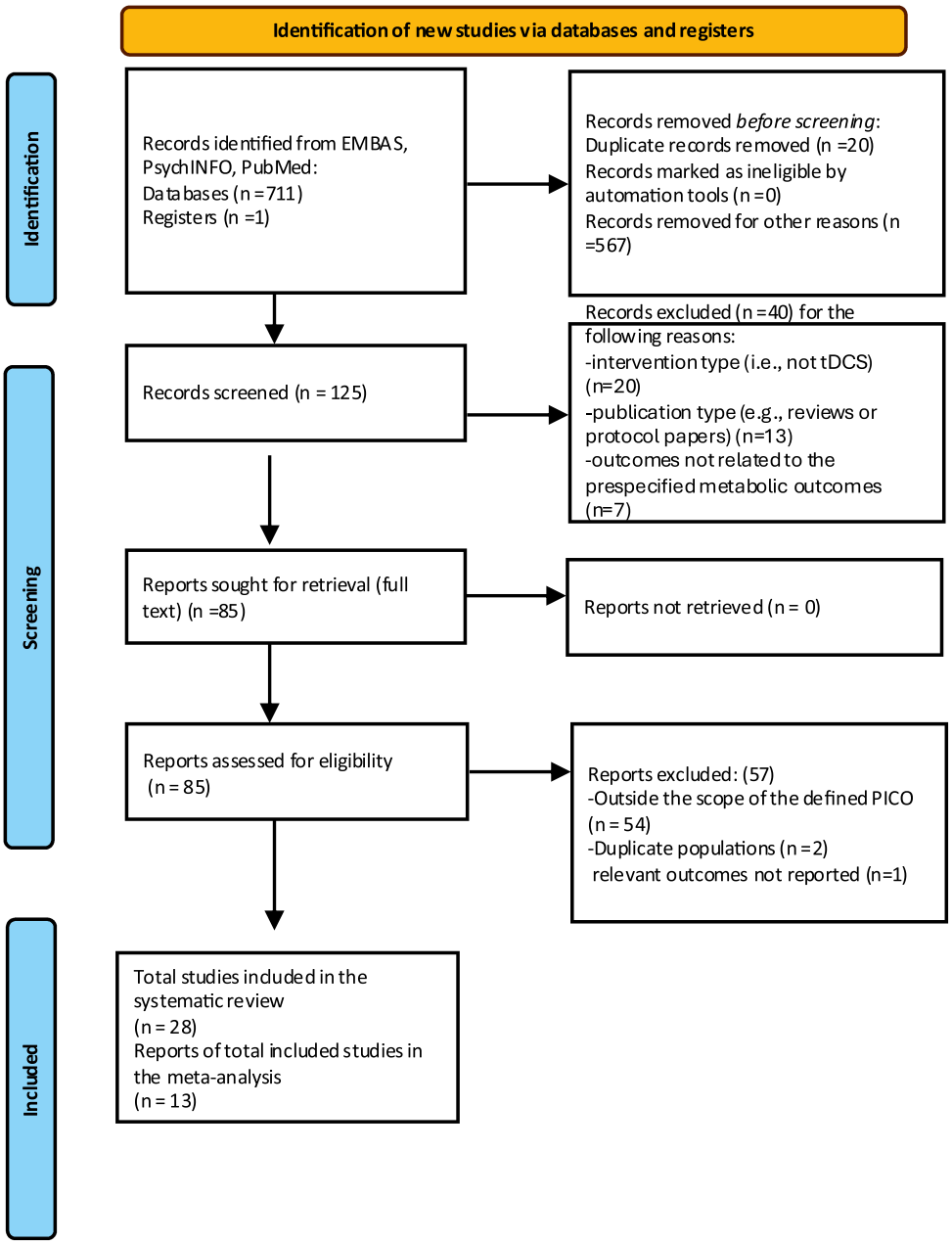


Fig. 1 PRISMA flow diagram of the systematic review.

However, no significant effect was observed for BMI (MD = −0.13 kg/m^2, 95% CI: −0.35 to 0.10; $p = 0.24$), with no heterogeneity (I^2 = 0%).

No significant effect was found for state food craving (SMD = −0.19, 95% CI: −0.77 to 0.39; $p = 0.42$), which showed moderate heterogeneity ($I^2 = 41\%$). Similarly, reductions in trait food craving favoured real tDCS but did not reach statistical significance (SMD = −0.21, 95% CI: −0.43 to 0.02; $p = 0.06$), with no heterogeneity ($I^2 = 0\%$).

Egger's regression test revealed no evidence of publication bias for weight ($p = 0.68$) and BMI ($p = 0.85$). Trim-and-fill analysis imputed three studies for weight, with the adjusted effect estimate remaining significant (MD = −2.18, 95% CI: −2.88 to −1.47, $p < 0.001$). For BMI, no studies were imputed ($k = 0$). Publication bias assessment was not conducted for other outcomes due to insufficient studies ($k < 10$).

Sensitivity analyses were conducted in relation to participants' weight status (overweight/obesity) and the results remained consistent. For details on meta-analysis results, see Supplementary Material 1.

Sensitivity analyses excluding Fassini et al. (2020), due to its large influence on the pooled estimate, resulted in a loss of statistical significance in the meta-analysis of real versus sham tDCS for weight reduction (MD = −1.68 kg; 95% CI − 3.68 to 0.33; $p < 0.10$) (Supplementary Material 2). This is likely due to Fassini et al.'s paper contributing to a large effect to the pooled estimate. Once the study was removed from the analysis, the pooled mean difference reduced and the confidence interval widened, crossing zero. Heterogeneity remained negligible (I^2 = 0%), indicating the loss of significance reflects a reduced pooled effect/precision rather than increased between-study variance. For detailed meta-analysis results, see Supplementary Material 2.

Table 1. Summary of studies included in systematic review ($N = 28$).

Reference Citation & Country	Study Design	Age (M, SD)	F%	N	Inclusion/Exclusion Criteria	Diagnosis	Participants with Overweight/ Obesity	Lateralisation	mA	min	Cathodal Placement	Anode Placement	Adjunct	Total Sessions	Comparator	Parameters measured	Findings & Adverse/ side effects of tDCS
Ageeli et al. [43] United Kingdom	Double-blind, randomised, sham-controlled parallel-design	35.4 (10)	83	52	✓Age between18 and 60; BMI ≥ 25 kg/m^2; no language barriers ⊗ Pregnancy; history of neurological disease and/or seizure(s); metallic implants in the head or body; substance dependence; any major psychiatric disorder currently requiring treatment in its own right; psychotropic medication other than a stable dosage of an antidepressant for at least 14 days; medication for weight loss. regular, current mindfulness practice; current atypical anorexia nervosa; current purging disorder with purging frequency once a week or more.	Healthy	With overweight or obesity	Right and left-handed	2	20	Left dlPFC	Right dlPFC	Mindfull eating training	*10*	Sham	1: Food cravings and BMI 2: Mood	No change in **BMI**, within **($p = 0.44$)** or between **($p = 0.054$)** arms. Within-group reduction in food craving didn't reach significance for active arm **($p = 0.06$)** but for the sham **($p = 0.00$)**. Significant reduction in negative mood only in the active arm **($p = 0.00$)**. Most frequent adverse effects: tingling, itching, buming and sleepiness. Tingling, itching and burning were significantly higher in the active arm; in contrast, a significant increase in reported sleepiness was observed in the sham arm.
Araújo de Oliveira Figueirêdo et al. [44] Brazil	Double-blind, randomised controlled trial	31.28	100	50	✓ Literate women; (BMI) ≥ 25 kg/m^2 aged between 19 and 51 y. ⊗ Pregnant or lactating; illicit drug users; on medication for weight loss; diagnosed with a psychiatric disorder; stroke; head trauma; neurosurgery; epilepsy; or diabetes mellitus; had an implanted metallic device in the head; a pacemaker; or in menopause.	Healthy	With overweight or obesity	NR	2	20	Left dlPFC	Right dlPFC	No	10	Sham	1: Waist circumference, weight, and BMI 2: Food cravings	No change in **waist circumference ($p = 0.56$), weight ($p = 0.82$), BMI ($p = 0.84$), food cravings ($p = 0.68$), and food consumption ($p = 0.24$)**, were observed (within and between groups). Most frequent adverse effects: headache, tingling and sleepiness. Their frequency did not differ significantly between active and sham arms.
Aslaksen et al. [45] Norway	Double-blind, randomised, three parallel groups design	23.5	49	75	NR	Healthy	NR	NR	2	7	Contralateral supraorbital area	Primary motor cortex	No	1	Sham	1: Blood pressure	No significant improvement in **blood pressure ($p = 0.35$)** was observed with active tDCS relative to sham (between groups). No significant improvement within conditions. Adverse effects were not reported.
Bernardes et al. [46] Brazil	Double-blind, randomised, pilot, proof-of-concept study	65.55	28	28	✓Age ≥ 18 y; a first-time middle cerebral artery ischaemic stroke diagnosed within 7 days to 3 months of symptom onset confirmed by CT; perfusion CT; or MRI.	Stroke	NR	NR	1	20	Left or right supraorbital area	Motor cortex	No	3	Sham	1: Blood pressure	No difference in **blood pressure** within **(All p-values were > 0.3)** or between groups **($p = 0.63$ for systolic and**

Table 1. continued

Reference Citation & Country	Study Design	Age (M, SD)	F%	*N*	Inclusion/Exclusion Criteria	Diagnosis	Participants with Overweight/ Obesity	Lateralisation	mA	min	Cathodal Placement	Anode Placement	Adjunct	Total Sessions	Comparator	Parameters measured	Findings & Adverse/ side effects of tDCS
					✓ Haemorrhagic stroke; metal-in-cranium injuries near the electrode placement area; intracerebral vascular clips or any other electrically sensitive support system; clinical instability; epilepsy; severe cognitive impairment; bilateral lesions; global aphasia; previous visual disturbances; pregnancy; and other neurological diseases.												***p* = 0.5 for diastolic blood pressure)**. Adverse effects were not reported.
Binkofski et al. [47] Germany	Randomised sham-controlled crossover design	24.6	0	15	✓ Healthy men. ✓ Acute or chronic internal, neurological, or psychiatric disease; nicotine or alcohol abuse; competitive sports involvement; or extraordinary mental or physical strain.	Healthy	With normal weight	NR	1	20	Left forehead	Primary motor cortex	No	1	Sham	1: Blood pressure	Active tDCS significantly reduced **blood pressure (*p* = 0.21 for systolic and *p* = 0.13 for diastolic blood pressure)** relative to sham (between arms). Within conditions NR. Adverse effects were not reported.
Chia Chang et al. [48] Taiwan	Double-blind, randomised, sham-controlled trial of bi-anodal tDCS	45	50	60	✓ Meeting the DSM-IV-TR criteria for schizophrenia or schizoaffective disorder. ✓ Pregnancy, psychiatric comorbidity; active substance use disorder; contraindications for tDCS (seizure, intracranial neoplasms/ surgery, or severe head injuries/ cerebrovascular diseases at enrolment).	Schizophrenia	With normal weight or being overweight	NR	2	20	N/A	Bi anodal over the PFC regions	No	10 sessions (two per day	Sham	1: Blood pressure	No improvement in **blood pressure (*p* = 0.91 for systolic and *p* = 0.20 for diastolic blood pressure)** was observed with active tDCS relative to sham (within and between groups). Adverse effects were not reported.
De Araujo et al. [15] Brazil	Double-blind, randomised, sham-controlled	37.5 (7)	50	28	✓ Adults 20–50 years; BMI 25–35, stable weight; no recent nutrition counselling; able to follow protocol. ✓ Medical conditions preventing weight loss; pregnancy; metal implants; brain lesions; or substance/ medication use affecting weight/ metabolism.	Healthy	With overweight or obesity	NR	2	20	Left dlPFC	Right dlPFC	Hypocaloric diet	20	Sham	1: Blood glucose, insulin and weight	Active tDCS reduced **fasting plasma glucose (*p* = 0.013)** and **insulin (*p* = 0.020)** levels relative to sham (between and within arms). No effects on **weight** within or between conditions. Most frequent adverse effects: burning sensation, itching, and tingling. Their frequency did not differ significantly between active and sham arm.
Ester-Nacke et al. [49] Germany	Double-blind, randomised, sham-controlled parallel-design	36 (13)	52	44	✓ Age between 20 and 65 y; (BMI) between 25.5 and 39 kg/m^2 with a waist circumference of ≥80 cm in women and ≥94 cm in men; stable body weight.	Healthy	With overweight or obesity	NR	2	25	Network-targeted tDCS (net-tDCS)	Network-targeted tDCS (net-tDCS)	Inhibitory Control Task	*3*	Sham	1: Food cravings and food intake	No significant change on **total intake** (kcal) **(*p* = 0.6)** was observed for sham relative anodal net-tDCS.

Table 1. continued

Reference Citation & Country	Study Design	Age (M, SD)	F%	*N*	Inclusion/Exclusion Criteria	Diagnosis	Participants with Overweight/ Obesity	Lateralisation	mA	min	Cathodal Placement	Anode Placement	Adjunct	Total Sessions	Comparator	Parameters measured	Findings & Adverse/ side effects of tDCS
					✓ T2DM; insufficient knowledge of the German language; pregnancy or lactation; history of severe mental or somatic disorders including neurological diseases drug or alcohol abuse; haemoglobin values ≤ 12 g/dl for women and ≤14 g/dl for men; MRI contra-indications; participation in a lifestyle intervention or pharmaceutical study.												Significant reduction in **Caloric intake of sweet food ($p = 0.037$)** in the active anodal relative to sham. No change in **food cravings ($p = 0.79$)** between groups. Most frequent adverse effects: tingling and itching. Their frequency did not differ significantly between active and sham arm.
Fassini et al. [50] Brazil	Double-blind, randomised, sham-controlled parallel-design	31	100	38	✓ Women, 20–39 yrs, BMI 30–35, stable weight ≥3 mo. ✓ Pregnancy; diabetes; kidney disease; pancreatitis; major medical, psych, or neuro conditions; centrally acting meds; anaemia; tDCS contraindications (skin damage, metal/ electrical implants, epilepsy).	Healthy	With obesity	NR	2	30	Right supraorbital area	Left dlPFC	Low calorie diet	16	Sham	1: Waist circumference, BMI, and weight 2: Eating behaviour	No improvement in **waist circumference ($p = 0.78$), BMI ($p = 0.96$), weight ($p = 0.55$), food cravings ($p =$ NR), eating behaviours ($p =$ NR)**, or **energy intake ($p = 0.25$)** was observed between active and sham tDCS (between and within arms). Adverse effects were not reported.
Flynn et al. [51] United Kingdom	Single-blind, randomised, sham-controlled feasibility trial	42	98	82	✓ Right-handed; adults (≥18 y); BMI ≥ 25 kg/ m^2; and met the DSM-5 criteria for BED diagnosis; normal or corrected-to-normal vision; and access to a computer with a webcam. ✓ Contraindications to tDCS (e.g. seizures or migraines).	Binge eating disorder	With overweight or obesity	Right-handed	2	20	Left dlPFC	Right dlPFC	Attention training	10	Sham	1: BMI 2: Food cravings and mood	No significant improvements in **BMI ($p = 0.53$), food craving ($p = 0.28$) and mood ($p = 0.054$)** between active relative to sham. Within group difference NR. Adverse effects were mild and transient: two occasions in real tDCS and three in sham tDCS.
Forcano et al. [52] Spain	Double-blinded, randomised, placebo-controlled parallel trial	43.45	66	18	✓: BMI ≥ 40 or ≥35 + comorbidity; age 18–60; right-handed; participants followed a 1-year pre-surgery diet programme <2 months in programme. ✓ Neuro/learning disorders; mental disorders; psychoactive drugs; lithium history; metal implants.	Healthy/ obesity related comorbidities	With obesity	Right-handed	NA	20	Multichannel tDCS	Multichannel tDCS	Cognitive training	4	Sham	1: BMI 2: Food intake	No effects on **BMI ($p = 0.73$)** between conditions Active tDCS was associated with a small positive effect size on self-reported total **kilocalorie intake ($p = 0.40$)** compared to sham; however, statistical significance was not reported. Adverse effects were not reported.
Giel et al. [53] Germany	Double-blind, randomised, sham-controlled trial	36 (16)	73	41	✓Age ≥18 y; (BMI) > 20 kg/m^2; full-syndrome BED. ✓ Insufficient language skills, pregnancy; lactation; current or lifetime psychotic disorder; current	Binge eating disorder	With normal weight or obesity	NR	2	15	Left musculus deltoideus	Right dlPFC	Inhibitory Control Training	*6*	Sham	1: BMI 2: Mood	Both groups showed reductions in **BMI ($p = 0.11$)**, with the decrease becoming statistically significant **($p = 0.002$)** only at

Table 1. continued

Reference Citation & Country	Study Design	Age (M, SD)	F%	*N*	Inclusion/Exclusion Criteria	Diagnosis	Participants with Overweight/ Obesity	Lateralisation	mA	min	Cathodal Placement	Anode Placement	Adjunct	Total Sessions	Comparator	Parameters measured	Findings & Adverse/ side effects of tDCS
					substance dependence; bipolar-I disorder, current suicidality; bariatric surgery, severe somatic illness influencing weight or eating behaviour not controlled by stable medication; severe neurologic disease; nonremovable metal parts; pacemaker; current use of neuroleptics and benzodiazepines; uncorrected impaired vision; ametropia; eye diseases preventing task execution.												the three-month follow-up. **Depressive symptoms ($p = 0.15$)** also decreased slightly in both groups, although these changes were not statistically significant. Adverse effects reported: headache, fatigue, itching, tingling on the head, tingling at the electrode, nausea. Their frequency did not differ significantly between active and sham arm.
Gordon [54] United Kingdom	Double-blind, randomised, sham-controlled trial	32	57	65	✓ A aged between 18 and 70 y; overweight or obese (BMI ≥ 25 kg/m^2); a diagnosis of full-syndrome or sub-threshold BED according to the DSM-5; fluency in English; normal or corrected to normal vision. ✓ All known contraindications to tDCS; pregnancy; a current significant unstable medical or psychiatric disorder needing acute treatment in its own right; diagnosis of bipolar disorder or borderline personality disorder, substance dependence, psychosis; taking psychotropic medication other than a stable dosage of selective serotonin reuptake inhibitors (SSRIs) for at least 14 days prior to study enrolment; allergies to any of the foods presented in the study; smoking >10 cigarettes per day; drinking >3–4 units (men) or 2–3 units (women) of alcohol per day.	Binge eating disorder	With overweight or obesity	Right and left-handed	2	20	Left dlPFC	Right dlPFC	Approach bias modification training	6	Sham	1: BMI 2: Food intake and mood	No difference in **BMI, food intake**, or **mood**, (all 95% confidence intervals included zero) between arms. Within groups NR. Adverse effects reported: minor side effects by most participants during and after stimulation.
Hamner et al. [55] United States	Single blind sham-controlled crossover design	NR	46	15	NR	Healthy	With normal weight or being overweight	NR	2	40	Right supraorbital area	Left primary motor cortex	No	1	Sham	1: Blood pressure	No improvement in **blood pressure (lowest $p = 0.55$)** was observed with active tDCS relative to sham (within and between arms). Adverse effects reported: Mild-to-moderate tingling or itching sensation and transient erythema in the area of stimulation in both

Table 1. continued

Reference Citation & Country	Study Design	Age (M, SD)	F%	*N*	Inclusion/Exclusion Criteria	Diagnosis	Participants with Overweight/ Obesity	Lateralisation	mA	min	Cathodal Placement	Anode Placement	Adjunct	Total Sessions	Comparator	Parameters measured	Findings & Adverse/ side effects of tDCS
																	active and sham stimulation.
Heinitz et al. [56] United states	Double-blinded, randomised, placebo-controlled parallel trial	35 (10)	59	31	✓ BMI: ≥30 kg/m^2; right-handed; had a stable weight (±5%) for the past 3 months. ✓ Somatic and psychiatric diseases; medication and illicit drug use possibly influencing neurocognitive processes.	Healthy	With obesity	Right-handed	2	40	Right supraorbital area	Left dlPFC	No	*3 Followed by 12*	sham	1: Weight and food intake	No change in **weight (*P* > 0.18) or food intake** (daily energy intake ***P* = 0.87**) between groups. No serious adverse effects occurred as a result of tDCS. However, other adverse effects were reported, although equally so in each group.
Jauch-Char et al. [57] Germany	Single-blind, counter-balanced, randomised, sham-controlled, crossover design	24.81	0	15	✓ Healthy male aged 21–28 y with BMI < 20 >25 kg/m^2. ✓ Disturbances in sleep continuity; shift workers, average duration <7 h/night; sleep-onset latency >30 min; regularly bed time later than 0000 during the 4 wk before the experiments.	Healthy	With normal weight	NR	1	20	Left forehead supraorbital	Right dlPFC	No	8	Sham	1: Weight 2: Eating behaviours	No change in **body weight (*P* = 0.11)** between arms. **Calorie consumption (*P* = 0.01)** was reduced following active tDCS relative to sham (between arms). Within arms, the difference was only significant in the active tDCS **(*P* = 0.02)**. No difference within the sham condition **(*P* = 0.72)**. Adverse effects reported in anode or cathode site during tDCS: skin redness (n = 9), tingling (n = 4), itching (n = 7), and feelings of skin burning (n = 2). For the sham stimulation: skin redness (n = 8), tingling (n = 1), and itching (n = 8).
Jomada et al. [58] Brazil	Double-blind, randomised, parallel-group, sham-controlled trial	47.56	100	102	✓ Fibromyalgia; minimum score of visual analogue pain scale (VAS 0–100 mm) during most days in the three months before the enrolment. ✓ Contraindications for tDCS; uncontrolled clinical or psychiatric diseases; suicidal ideation with plans; present illicit substance use; shift work; a medical history of rheumatoid arthritis; lupus; autoimmune diseases; neurological or oncological conditions; or prior bariatric surgery; eating disorders.	Fibromyalgia	With obesity	Right-handed	2	20	Left dlPFC	Left dlPFC/ Primary motor cortex	No	20	Sham	1: Waist circumference, BMI 2: Eating behaviour	Active tDCS was more effective in reducing **waist circumference (*P* = 0.041), food cravings (*P* = 0001)** than sham between groups. No change in **BMI (*P* = 0.68)** between arms. Adverse effects reported: headache, tingling, itching, burning and redness. There was no significant difference between the arms except for burning **(*p* = 0.03)**.
Kistenmacher et al. [59] Germany	Single-blind, counter-balanced, randomised crossover	24.8 (0.6)	0	15	✓ Healthy young men. ✓ Internal, neurological, or psychiatric diseases; family history of	Healthy	With normal weight	NR	1	20	Left forehead supraorbital	Primary motor cortex	No	8	Sham	1: Glucose, Insulin 2: Cortisol	Active tDCS reduced **blood glucose (*P* = 0.009)** vs. sham (between

Table 1. continued

Reference Citation & Country	Study Design	Age (M, SD)	F%	*N*	Inclusion/Exclusion Criteria	Diagnosis	Participants with Overweight/ Obesity	Lateralisation	mA	min	Cathodal Placement	Anode Placement	Adjunct	Total Sessions	Comparator	Parameters measured	Findings & Adverse/ side effects of tDCS
					diabetes; substance use; medication use; shift work; competitive sports; and acute mental or physical stress.												arms); no significant within-subject effects. **Serum insulin (*P* > 0.26)** no significant effects within or between conditions. In the sham tDCS, post-stimulation **cortisol (*P* = 0.01)** was significantly higher (within group). No significant change in the active group. Between-arms effects NR. Adverse effects were not reported.
Ljubisavljevic et al. [60] United Arab Emirates	Double-blind, randomised parallel study design	21	36	30	✓ Presence of food craving; aged ≥18 y; right-handed; and with BMI ≥ 18.5. ✓ History of eating disorders; takin part in weight loss programmes or taking medication to lose weight (currently or within last six months); recreational drug use history; and smoking (>1 cigarette per day on average).	Healthy	With normal weight or being overweight	Right-handed	2	20	Left forehead	Right dlPFC	No	5	Sham	1: Weight 2: Eating behaviours	**Weight**: NR. **Food cravings** were reduced following the active tDCS. No effect within the sham condition (within arm). The active arm showed a borderline significant difference favouring the active arm (***p* = .05)** (between arms). No adverse effects were recorded.
Lopes et al. [61] United Kingdom	Double-blind, randomised, sham-controlled parallel-design	46.8 (9.4)	57	28	✓ Age between 18 and 65 y; with a current DSM-5 diagnosis of schizophrenia, schizoaffective disorder, or psychosis unspecified; on a stable dose of antipsychotic and/or antidepressant medication for at least 6 weeks. ✓ Contraindications to tDCS; significant co-morbid medical; psychiatric conditions needing treatment in their own right.	Schizop-hrenia/schizo-affective disorder	With overweight or obesity	Right and left-handed	2	20	Left dlPFC	Right dlPFC	Approach Bias Modification Training (ABMT)	*5*	Sham	1: Food cravings and BMI 2: Mood	No significant change in **BMI (*P* = 0.51), Food craving (*p* > 0.05)** between groups. **Depressive symptoms** decreased slightly in both groups, although these changes were not statistically significant. Commonly reported adverse effects: itching, heating/warmth, stinging, tingling, headache or pain. There were no significant differences between trial arms.
Mehranpour et al. [62] Iran	Double-blind, randomised, sham-controlled parallel-design	41 (8.6)	73	75	✓BMI ≥ 30	Healthy	With obesity and food addiction	NR	2	20	Left dlPFC	Right dlPFC	Intranasal oxy-tocin	*10*	Sham	1: Weight Food cravings	Significant reduction in **weight (*p* < 0.001)** and **food cravings (*P* = NR)** in the active arm when compared to sham. Adverse effects reported: scalp tingling during tDCS (12%).

Table 1. continued

Reference Citation & Country	Study Design	Age (M, SD)	F%	*N*	Inclusion/Exclusion Criteria	Diagnosis	Participants with Overweight/ Obesity	Lateralisation	mA	min	Cathodal Placement	Anode Placement	Adjunct	Total Sessions	Comparator	Parameters measured	Findings & Adverse/ side effects of tDCS
Miler et al. [63] United Kingdom	Double-blind, randomised, sham-controlled parallel-design	21.15	70	30	✓ Right-handed, age 18–55. ✓ Metal/electronic implants; epilepsy; recent meds (past 8 wks); pregnancy; BP > 140/90; cardiovascular disease; lifetime history of psychiatric illness/ alcohol/drug dependence; smoking; BMI < 18 or ≥28; recent alcohol use.	Healthy	With normal weight	Right-handed	2	20	Right dlPFC	Left dlPFC	No	1	Sham	1: Blood pressure 2: Mood and anxiety	No improvement in **blood pressure, ($p = 0.54$ for systolic and $p = 0.40$ diastolic blood pressure), Mood ($p = 0.08$)**, and **anxiety ($p = 0.98$)** (between arms). Within conditions NR. Adverse effects were not reported.
Ministro et al. [64] Brazil	Double-blind, randomised crossover	69 (7)	57	14	✓ Resistant hypertension. ✓ <80% med adherence; secondary hypertension causes; cerebrovascular, renal and liver diseases; implanted device; and depression.	Resistant hypertension	With normal weight	NR	2	20	Right supraorbital region	Motor cortex	No	1	Sham	1: Blood pressure	Active tDCS led to a decrease only in **Max systolic blood pressure ($p = 0.0404$)** relative to sham. No change in resting blood pressure between arms **($p = 0.42$ for systolic and $p = 0.56$ diastolic blood pressure)**. Within conditions NR. No adverse effects were recorded.
Montoro et al. [65] Spain	Double-blind, randomised, trial	20.47	79	58	✓ Age between 19 and 27 y; right-handed. ✓ Neuropsychiatric, neurologic; or cardiovascular contraindications for tDCS; pregnancy; or a history of cerebrovascular or cranioencephalic trauma; a history of alcohol or drug abuse; or was receiving medication affecting the cardiovascular or central/peripheral nervous system.	Healthy	With normal weight	Right-handed	2	20	Right dlPFC	Left dlPFC	No	1	Sham	1: Blood pressure	Across the study period, **SBP** decreased significantly over time across both groups ($p = 0.001$), whereas **DBP** did not change significantly ($p > 0.19$). Between-arms differences **in blood pressure** were not significant. Adverse events reported: no significant group differences were observed for any of the measured sensations (itching, pain, burning, metallic/iron taste, heat, fatigue, and others).
Pegado et al. [66] Brazil	Double-blind, randomised, sham-controlled trial	54	73	30	✓ Aged between 18 and 75 y; undergoing 4-h session of haemodialyses for more than three months and showing chronic musculoskeletal pain; headache; or neuropathic pain (scoring >4 on the visual analogue scale for more than three months). ✓ Contraindications for tDCS; signs of severe disease or indication of hospitalisation	Undergoing haemo-dialyses	Normal and overweight	NR	2	20	Right supraorbital region	Left primary motor cortex	No	10	Sham	1: Blood pressure	No difference in **blood pressure** (all 95% confidence intervals included zero) between groups. Within groups not reported. Adverse events reported: headache or worsening of pre-existing headache (active: 0%; sham: 1.4%), nausea (active: 0%; sham: 0.7%), and tingling (active: 37.7%; sham: 0%).

Table 1. continued

Reference Citation & Country	Study Design	Age (M, SD)	F%	*N*	Inclusion/Exclusion Criteria	Diagnosis	Participants with Overweight/ Obesity	Lateralisation	mA	min	Cathodal Placement	Anode Placement	Adjunct	Total Sessions	Comparator	Parameters measured	Findings & Adverse/ side effects of tDCS
					including previous hemodynamic instability; acute myocardial infarction; infection, stroke; and psychiatric illness.												
Silva-Filho et al. [35] Brazil	Double-blinded, randomised, placebo placebo-controlled parallel trial	53.9	65	20	✓ Adults >18 with hypertension. ✓ Haematological/ neurological issues; beta-blockers; vascular disease; stroke; cognitive/epileptic disorders; seizures; physical limits; head implants; pregnancy/ lactation; ECG changes; recent med changes (<2 mo): >30 g alcohol/ day; >200 mg caffeine/ day; on hormone replacement therapy; changed antihypertensive meds.	Hypertension	With overweight or obesity	NR	2	20	Contralateral supraorbital region	Left temporal lobe	Exercise for 40 min	1	Sham	1: Blood pressure	Active tDCS led to a significant decrease in **SBP ($p = 0.04$)** 3 hours after intervention within groups. The change between arms was only significant in the **DBP ($p = 0.01$)**. No unexpected or severe adverse effect occurred during tDCS.
Usanos et al. [67] Spain	Double-blinded, randomised, placebo-controlled parallel trial	52 (1)	100	40	✓Age between 45 and 65 y; tDCS-naïve women with a stable BMI between (25 and 35 kg/m^2). ✓ Diabetes; bariatric surgery; any known condition associated with weight gain or obesity; smoking/ addiction; neurological or psychiatric illness and contraindications to receive tDCS.	Healthy	With overweight or obesity	NR	2	20	Right supraorbital area	Left dlPFC	hypocaloric diet	*5 followed by 3*	sham	1: Weight Food cravings	Active tDCS was more effective in reducing **Weight ($p = 0.02$)** than sham. **Food craving ($p = 0.3$)** showed no significant change between arms. Adverse events reported: mild-to-moderate symptoms with no group differences.
Vandermeeren et al. [68] Belgium	Single-blind, sham-controlled, parallel-group design	33.8	50	30	✓ Healthy; between 20 and 60 y. ✓ Pregnancy; chronic disease; intake of drugs modulating vital parameters or with a central action; pacemaker or any intracranial metal.	Healthy	With normal weight	NR	1	20	Tibia	Frontal midline	No	1	Sham	1: Blood pressure	**Blood pressure** increased over time with all tDCS arms **($p < 0.001$ for systolic and $p = 0.001$ for diastolic blood pressure)**. No significant differences between groups **(all $p > 0.28$)**. No adverse effect was observed

Notes: *F%* percentage of females, *mA* current intensity, *min* duration in minutes, *SBP* systolic blood pressure, *DBP* diastolic blood pressure, *dlPFC* dorsolateral prefrontal cortex, *NR* not reported, *N/A* not applicable, *CT* computed tomography, *MRI* magnetic resonance imaging; *BMI* body mass index, *T2DM* Type 2 diabetes.

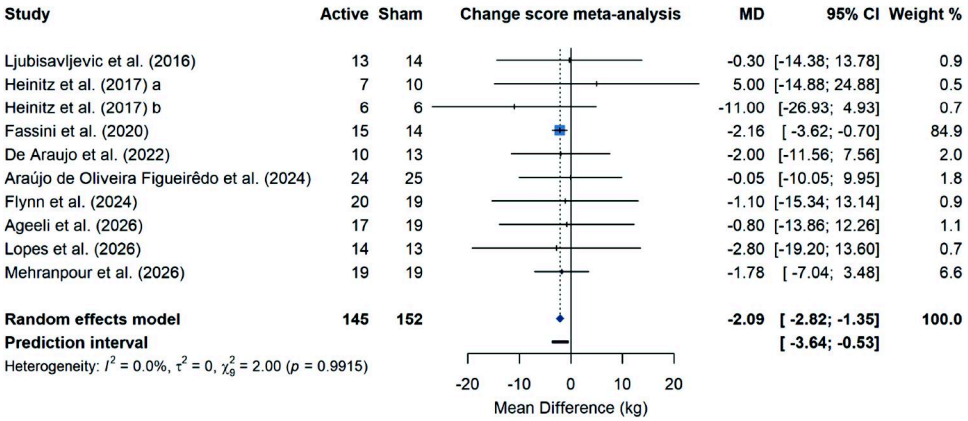


Fig. 2 Forest plot showing mean differences with 95% confidence intervals for active transcranial direct current stimulation (tDCS) versus sham stimulation on body weight (kg).

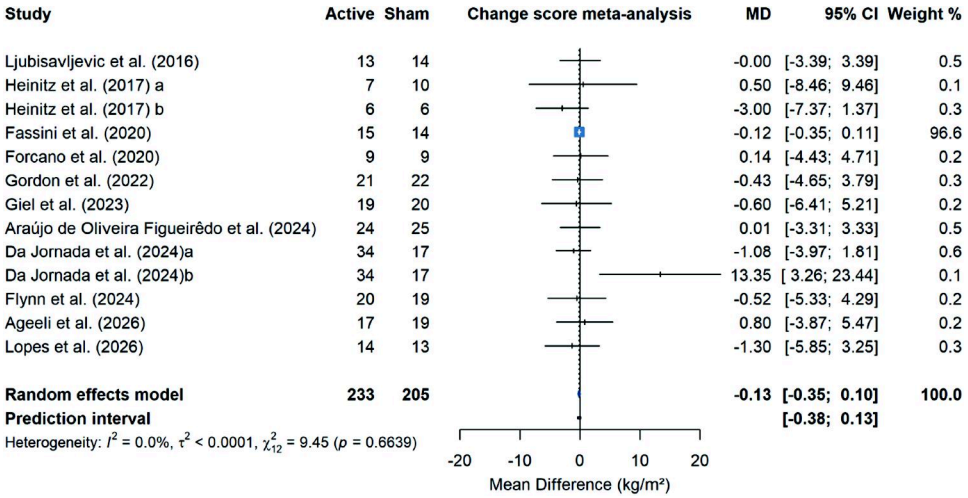


Fig. 3 Forest plot showing mean differences with 95% confidence intervals for active transcranial direct current stimulation (tDCS) versus sham stimulation on body mass index (BMI) (kg/m^2).

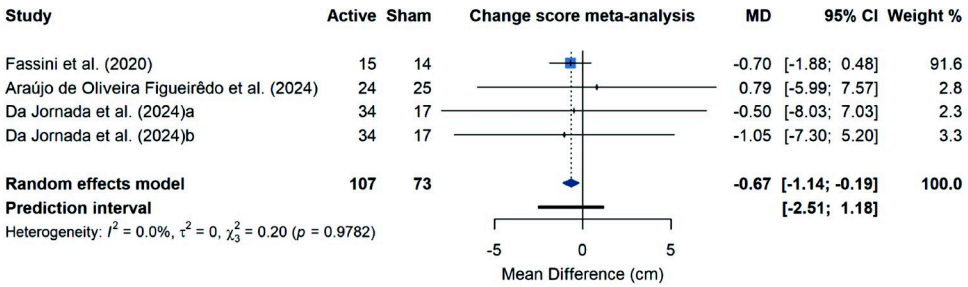


Fig. 4 Forest plot showing mean differences with 95% confidence intervals for active transcranial direct current stimulation (tDCS) versus sham stimulation on body circumference (cm).

DISCUSSION

This systematic review and meta-analysis investigated the effects of tDCS on metabolic syndrome parameters, comparing active and sham stimulation in RCTs involving adults. It synthesised data from 1129 participants across 28 studies conducted in 10 countries. To our knowledge, it is the first such comprehensive review. It replicates reported tDCS effects on weight loss and extends these findings to include a reduction in waist circumference.

Our meta-analyses found that active tDCS significantly reduced body weight (MD = −1.16 kg, $p = 0.04$) and waist circumference (MD = −0.67 cm, $p = 0.02$) compared to sham. No significant effect was observed for BMI, blood pressure, state food craving or trait food craving ($p = 0.06$).

Although the outcomes for weight loss and waist circumference are statistically significant, changes were small, and therefore their clinical significance may be limited. Future RCTs should report percentage of weight change to allow clinical significance assessment and establishment of tDCS optimal dose.

Results from individual studies support the need for research on the effects of tDCS on glucose, insulin, blood pressure, food intake and mood in adults.

The weight of the study by Fassini et al. (2020), together with its narrower confidence intervals, suggest that the estimated effect on body weight reduction was more precise than that reported by the other included studies. As a result, despite its relatively small sample size, this study had a greater influence on the overall pooled effect estimate in the meta-analysis. Although its sample size was comparable to several of the other included studies, the lower variability of its findings resulted in a substantially higher study weight under the inverse-variance weighting approach.

Several factors may explain the greater precision observed in this study. Participants had a higher baseline BMI and received a more intensive intervention, consisting of 16 sessions of tDCS combined with a hypocaloric diet, which may have produced a more consistent treatment response. In addition, the study included only young adult females, resulting in a more homogeneous sample than those of the other included studies. Together, these characteristics may have reduced variability in the outcomes and contributed to the narrower confidence intervals and greater statistical weight. However, these explanations are speculative and should be interpreted with caution.

Although adverse effects are generally considered important outcomes to monitor to ensure participant safety and intervention acceptability [29], many of the included studies did not report any adverse events. This lack of reporting highlights the need for more consistent documentation of adverse effects in future studies.

Body weight, BMI, waist circumference and eating-related behaviours

Our results are in accord with those from a meta-analysis by Alhindi et al. [22], which included only individuals who were overweight or had obesity. These authors found comparable weight loss (MD = −0.82 kg, 95% CI − 1.01 to −0.62), which was also not translated into significant reductions in BMI. However, in their meta-analysis Alhindi et al. [22], five of the eleven studies included, combined tDCS with a low-calorie diet, thus complicating interpretation of tDCS-specific effects on weight. Therefore, definitive conclusions on tDCS' effects on weight cannot be drawn, and research that isolates the effect of tDCS and lifestyle interventions is needed. As weight may be more sensitive for detecting smaller or earlier effects of tDCS than BMI, we suggest that authors report pre- and post-tDCS intervention outcomes for both parameters in future studies. Furthermore, studies should report percentage of weight loss to allow assessment of clinical efficacy and comparability of outcomes between studies.

While the significant pooled effect for waist circumference is unlikely to be clinically meaningful, due to the small number of studies ($k = 4$), it may suggest a favourable directional trend. Waist circumference is an accessible and affordable measure which can be valuable for assessing treatment effects. A reduction in waist circumference is an important step towards reducing the risk for cardiometabolic disease [30]. This finding is timely and important. Rubino, Cummings [31] have proposed the use of BMI as a population-level measure, together with the incorporation of at least one anthropometric assessment (e.g., waist circumference) to assess health risk associated with body fat excess.

We observed a non-significant reduction in trait-based food cravings following tDCS, consistent with findings reported in previous meta-analyses of Alhindi et al. [22]. Of note, their meta-analysis included only studies targeting the dorsolateral prefrontal cortex (dlPFC), a region frequently implicated in inhibitory control over food-related impulses Meng et al. [32]. Consistent with these findings, Mostafavi et al. [33] reported a significant medium-sized reduction in food cravings following active tDCS (over the dlPFC), compared to sham stimulation. Furthermore, a meta-analysis by Zheng et al. [21] reported a moderate effect size favouring active tDCS over the dlPFC relative to sham. Their analyses also indicated stronger effects of tDCS when it was delivered in multi-session protocols compared to single-session applications, and also, a greater reduction in food cravings and consumption among individuals who were overweight or had obesity. These findings reinforce the idea that specific protocol characteristics and participant profiles are critical in determining treatment efficacy and may partly explain the variability observed between reviews.

Blood pressure

The present findings are partially in accord with earlier studies. A recent meta-analysis by Silva-Filho, Gramile Silva Meira [14], which pooled four studies, found non-significant reductions in both systolic and diastolic blood pressure following tDCS in individuals with hypertension. In our meta-analysis, there were insufficient numbers of studies to confirm the positive outcomes reported in individual trials by Ministro, Castaño [34] and Silva-Filho, Albuquerque [35]. It is of note that these individual trials recruited only participants with diagnosed hypertension, highlighting the potential importance of target population characteristics in modulating tDCS efficacy for blood pressure outcomes. In light of the reported outcomes, tDCS may have promise for improving blood pressure regulation. However, the underlying mechanisms remain poorly understood, and further high-quality trials which are not limited to individuals with hypertension, but also to those at risk of metabolic syndrome, are needed to validate these preliminary findings [16].

Research and clinical implications

Metabolic syndrome and obesity are complex biopsychosocial conditions. Brain stimulation research for eating and weight disorders is relatively new and limited by small RCTs that typically focus on a single dimension, and thus do not capture the multifaceted nature of these conditions. While tDCS effects on mood are established in depression [36], we have shown that evidence for its use in weight management and eating disorder trials is still emerging. At present, data on biological and psychological markers is limited. Future trials should incorporate metabolic (e.g., glucose, insulin, lipid profiles), stress-related (e.g., cortisol), psychological (e.g., mood), and cognitive (e.g., memory, impulsivity) assessments to elucidate how tDCS modulates eating behaviour and body weight.

Research on tDCS has demonstrated that therapeutic efficacy is often enhanced when stimulation is applied concurrently with disorder-relevant cognitive or behavioural tasks that engage the targeted brain regions [37, 38]. Additionally, repeated sessions of tDCS have been associated with cumulative neuroplastic effects and longer-lasting modifications in brain function [12]. Individual differences also appear to moderate responsiveness to neuromodulation; for example, individuals without behavioural trait susceptibilities, such as tendencies towards overconsumption or high cravings, may exhibit reduced responsiveness to such interventions [39]. However, few studies in this review incorporated such information. Of the 28 included studies, only seven (25%) combined tDCS with cognitive or behavioural tasks, and 14 studies (50%) included participants with overweight or obesity, who may be more responsive to interventions targeting eating behaviours or metabolic dysfunction.

These methodological limitations may have contributed to the variability and substantial heterogeneity across the studies,

including variation in stimulation parameters (current intensity, stimulation site and montage, and the number and duration of sessions), differences in whether tDCS was delivered as a stand-alone intervention or combined with adjunct treatments (such as cognitive-based therapies, dietary interventions, or physical activity programmes), the diversity of outcome measures employed, and the inclusion of very diverse clinical and non-clinical populations. Therefore, the findings of this meta-analysis do not allow firm conclusions on the efficacy of tDCS for improving metabolic syndrome-related outcomes. Future research should prioritise the development of standardised stimulation protocols and consistent outcome measures to reduce heterogeneity and better clarify the therapeutic potential of tDCS.

Based on the evidence, we propose that tDCS positively influences problematic eating behaviour patterns in adults, especially those who are overweight or have obesity. However, sustained and healthy weight loss, particularly that which relies on changes in eating behaviours, typically requires extended periods to evaluate. In the context of the increasing availability of GLP-based pharmacotherapies, there is a critical need to integrate sustained behavioural support to maintain treatment benefits [40]. To establish long-term effects of tDCS, future RCTs following CONSORT guidelines with adequately powered-sample sizes are needed. Such studies should assess multi-session tDCS protocols in combination with concurrent disorder-relevant cognitive intervention, with and without treatment as usual (e.g., pharmacological, lifestyle, or surgical interventions). Studies should specifically recruit individuals with a tendency toward disordered eating behaviours and overweight/obesity, employing consistent, comparable outcome measurements. Evidence suggests that targeting the right dlPFC with 20 min 2 mA anodal stimulation may offer superior outcomes for obesity related outcomes [22, 41]. Clinical studies might include the use of tDCS in enhancing long-term physical and mental health outcomes of medical interventions, such as bariatric surgery Rösch, Wünsche [42] and use of GLP-1 receptor agonists.

Strengths and limitations

This review has several strengths, notably the inclusion of a broad range of metabolic syndrome-related outcomes and the integration of narrative synthesis and quantitative meta-analyses to allow a balanced interpretation of the evidence. We report significant effects of tDCS on body weight reduction and waist circumference, identify gaps in the literature and provide recommendations for future studies. Some limitations are acknowledged. Inclusion of studies which combined tDCS with low-calorie diet/weight loss/obesity treatment prevented the isolation of tDCS effects on metabolic syndrome parameters. Secondly, adding adjunct weight-management intervention as a covariate in the meta-analyses was not possible due to the small number of studies. Inclusion of participants with or without overweight/obesity may not reflect baseline clinical characteristics of individuals with metabolic syndrome and overweight/obesity, thus our findings cannot be generalised to this population. Significant heterogeneity in study designs, stimulation protocols, populations studied and participants' clinical characteristics, and outcome measures, constrain the strength of conclusions that can be drawn. Due to the relatively small number of eligible studies for meta-analyses, sensitivity analyses were conducted to attenuate these limitations, which showed consistent results. Finally, to avoid introducing carrying over effects bias of crossover trials, these studies were not included in the meta-analysis, and our meta-analysis evidence does not include those effects.

CONCLUSIONS

This systematic-review and meta-analyses found that tDCS significantly reduced body weight and waist circumference in adults. Individual studies reported promising findings on metabolic syndrome-related outcomes, but heterogeneity in study protocols, stimulation parameters, brain targets, and participant characteristics likely contributed to inconsistent results.

Large, well-powered confirmatory RCTs are needed, recruiting participants based on clinical and behavioural risk profiles. These should integrate tDCS with disorder-relevant cognitive or behavioural tasks, adopt multi-session protocols, and employ standardised stimulation parameters and outcome measures to enable replication. Until such evidence is available, conclusions regarding tDCS efficacy for metabolic syndrome-related outcomes should be made with caution.

DATA AVAILABILITY

Data sets can be supplied by the corresponding author upon reasonable request.

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AUTHOR CONTRIBUTIONS

MA drafted the initial manuscript. ML conducted the meta-analysis and performed the statistical analyses. MA and ML were involved in study selection, data extraction, and interpretation of the findings. US, IC, ML and BI critically reviewed and revised the manuscript. All authors approved the final version of the manuscript.

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COMPETING INTERESTS

The authors declare no competing interests.

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