DYSTONIA

TYPE Review
PUBLISHED 17 April 2026
DOI 10.3389/dyst.2026.15695

OPEN ACCESS

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RECEIVED 03 October 2025
REVISED 05 January 2026
ACCEPTED 09 March 2026
PUBLISHED 17 April 2026

CITATION
Konczak J, Özkul C, Rooney S and Amini S (2026) Vibro-tactile stimulation as a non-invasive neuromodulation method to treat motor symptoms in focal dystonia: a systematic review. *Dystonia* 5:15695.
doi: 10.3389/dyst.2026.15695

Vibro-tactile stimulation as a non-invasive neuromodulation method to treat motor symptoms in focal dystonia: a systematic review

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Background: Superficial vibrotactile stimulation (VTS) is a non-invasive form of neuromodulation targeting tactile and proprioceptive mechanoreceptors known to influence reflexive and voluntary motor behavior and conscious proprioception.

Objectives: Systematically review empirical evidence on the behavioral, biomechanical and neurophysiological effects of VTS in focal dystonia and evaluate its suitability and potential as a clinical intervention in patients with focal dystonia.

Methods: PUBMED, MEDLINE, CINAHL, and Cochrane Library databases were searched up to September 6, 2025. Included were studies that investigated underlying neurophysiological mechanisms of VTS and the behavioral effects in patients with dystonia. A total of 24 eligible studies were reviewed.

Results: The review of empirical data indicated that VTS of dystonic regions is typically fast acting and can lead to symptoms reduction within minutes. Results show than VTS can 1) induce head righting and reduce pain in cervical dystonia, 2) improve voice quality and reduce speech effort in laryngeal dystonia, 3) normalize muscle activation in upper limb and cervical dystonia. Based on objective behavioral and biomechanical measures as well as subjective effect ratings by patients, between 57% and 85% of participants responded to VTS by reducing the frequency and magnitude of symptoms. Temporal post-treatment VTS effects varied widely, with short applications (4 s –15 min) decaying within minutes and longer applications (20–45 min) showing effects for hours or days. Major observable electrophysiological responses to VTS included 1) a reduction in EMG activity of vibrated muscle and its synergists, and increased activity of antagonistic muscles, 2) reduction of excessive neuronal synchronization over somatosensory-motor cortex, 3) and altered motor-evoked potentials of vibrated muscles, their synergists and antagonists.

Conclusion: The reviewed empirical evidence indicates that VTS can reduce unwanted muscle spasms in various forms of focal dystonia. At present, there is

no knowledge of optimal daily or weekly dosage. Initial evidence indicates that at-home application of VTS over months is feasible, but there is only inconclusive evidence about the long-term effects of VTS on FD symptoms and what differentiates responders from non-responders to VTS.

KEYWORDS

dystonia, intervention, sensorimotor, somatosensory, stimulation training

Introduction

Focal dystonia (FD) is a movement disorder characterized by sustained or intermittent muscle contractions that cause abnormal and often repetitive movements and sustained postures in distinct muscle systems [1]. It is the third most common movement disorder after Parkinson's disease and essential tremor with a prevalence of 30.9 per 100,000 [2]. The most prevalent clinical presentations are cervical dystonia, blepharospasm, upper limb dystonia, oromandibular dystonia, and laryngeal dystonia. It may present as segmental dystonia affecting two or more continuous regions or as multifocal dystonia affecting two or more non-contiguous regions.

The pathophysiology of FD is incompletely understood but there is consensus that it is a disorder affecting a broad motor control network comprising the basal ganglia, brainstem, cerebellum, thalamus, somatosensory, and motor cortex [3]. FD is characterized by excessive levels of neural activity over sensorimotor cortex that ultimately lead to involuntary muscle contractions [4]. Different presentations of FD reveal abnormalities in primary sensorimotor, supplementary motor, and frontoparietal areas [5–8] and demonstrated altered regional connectivity in frontoparietal and somatosensory networks [9–16].

Numerous research reports documented somatosensory deficits in FD (for review see [17]). For example, proprioceptive position sense thresholds of the forearm and finger as well as the perception of arm motion are abnormal in patients with cervical dystonia, laryngeal dystonia or blepharospasm [18–20]. The abnormalities in tactile and proprioceptive processing are not restricted to the affected dystonic musculature but were also documented in non-affected body regions [20–22]. The susceptibility of FD to somatosensory stimulation has long been known, because patients with focal dystonia may use so-called sensory tricks (*geste antagoniste*) to temporarily alleviate dystonic symptoms by touching areas of or near the dystonic musculature [23, 24]. Research on cervical dystonia documented that effective sensory tricks are associated with pallidal and motor cortical desynchronization at low frequencies (6–8 Hz) [25].

As a somatosensory input, vibrotactile stimulation (VTS) stimulates muscle spindles and cutaneous mechanoreceptors [26–30]. It is widely recognized that the resulting afferent signals from these mechanoreceptors are essential for the control of muscle tone, balance and volitional movement. Muscle vibration between 40 and 100 Hz is known to produce a kinaesthetic illusion, i.e., the perception of bodily movement while the body is motionless [31–33]. A short-term VTS applied over seconds to a relaxed muscle increases voluntary phasic innervation [34], while prolonged VTS over minutes suppresses excitatory input to spinal α-motor neurons [35].

The usefulness of VTS has been recognized for treating abnormal muscle tone, balance and gait in neurological diseases such as stroke [36–38], cerebral palsy [39], Parkinson's disease [40], and multiple sclerosis [41]. Given the overwhelming evidence that somatosensory processing is affected in focal dystonia [17], VTS may also be a useful non-invasive form of neuromodulation for treating symptoms associated with focal dystonia. This study systematically reviewed the current empirical evidence of this claim based on biomechanical, electrophysiological, and clinical outcomes measures to document possible therapeutic effects of VTS in patients with focal dystonia.

Methods

Search strategy

A systematic review of the literature was performed following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines [42]. PUBMED, MEDLINE, CINAHL, and Cochrane Library databases were searched up to September 6, 2025. The searches included the following Medical Subject Headings (MeSH) terms: ("Dystonia" OR "blepharospasm" OR "cervical dystonia" OR "cranial dystonia" OR "laryngeal dystonia" OR "meige syndrome" OR "musician's dystonia" OR "oromandibular dystonia" OR "spasmodic dysphonia" OR "spasmodic torticollis" OR "task-specific dystonia" OR "torticollis" OR "writer's cramp") AND ("Vibration" OR "vibration therapy" OR "vibratory training" OR "vibrotactile stimulation" OR "focal vibration" OR "local vibration" OR "muscle vibration"). The search was limited to English language and human subjects. A complete list of combinations of search terms used in each database can be found in Supplementary Table S1.

TABLE 1 Summary of all reviewed studies listed by first author in alphabetical order.

Authors	Study design	Participant characteristics	VTS protocol	Outcomes measures	Effect of vibration
Amini et al. [45]	Quasi-experimental (pretest/posttest)	Clinical population: Adult-onset, isolated focal task-specific laryngeal dystonia n = 32 Age: 62.3 ± 15.2 years Sex (M/F): 11/21 Disease duration: 12.84 ± 10.09 years BoNT: 19/32 treated ≥2 weeks	Frequency: 100–150 Hz Amplitude: 1.7–2 G Muscles or sites: Bilaterally on the lateral area of the thyroid cartilage Duration: 20 min/day over 8 weeks	Perceived speech effort (PSE) (scale of 0–10, 10 = maximum vocal effort) Voice Quality Change (VQC) (scale 1 = very unnoticeable, 5 = very noticeable	Laryngeal VTS significantly decreased mean PSE by 13.5% during first 4 weeks and by 14.1% during second 4 weeks $p < 0.0001$) Laryngeal VTS increased group mean VQC from 2.9 (neutral) to 3.8 (noticeable) over 8 weeks
Avanzino et al. [46]	Quasi-experimental (pretest/posttest)	Clinical population: Adult-onset, isolated focal cervical dystonia n = 67 Age (year): 61.1 ± 12.5 years Sex (M/F): 23/44 Disease duration: 13.9 ± 12.7 years BoNT: 60/67 treated	Frequency: 100 Hz Amplitude: 1.7 G Muscles or sites: Sternocleidomastoid and trapezius muscles Duration: 45 min	Head angle index (HAI) EMG root mean square over 1 min segment	Neck muscle VTS reduced the median head angle by at least 4.5°, with reductions of up to 47.6° in severe cases 85% (57/67) of participants responded to VTS with a 10% or higher reduction in HAI. 39% (26/67) of participants reduced HAI by 50% or higher Mean relative reduction in HAI due to VTS ranged between 13% and 37% per CD phenotype
Bove, Brichetto et al. [47]	Case-control	Clinical population: Adult-onset, isolated focal cervical dystonia n = 12 Age: 59 ± 15.1 (33–82) yrs Sex (M/F): 4/8 Disease duration: 9.4 ± 5.5 years BoNT: 7/12; last injection at least 3 months prior Control group: Healthy adults n = 12 Age: 51 ± 15.5 (31–76) yrs. Sex (M/F): 7/5	Frequency: 90 Hz Amplitude: NA Muscles or sites: Left or right sternocleidomastoid Duration: 51.2 s	Center of foot pressure (COP) during the stance trials Stepping frequency Head rotation (yaw angle)	Neck muscle vibration significantly increased mediolateral COP in healthy controls ($p < 0.001$), but not in CD participants ($p > 0.05$) Neck muscle vibration did not change stepping frequency in either the CD or healthy control group ($p > 0.05$) Neck muscle vibration did not change head rotation in CD ($p > 0.05$) but significantly increased it in controls ($p < 0.005$)
Bove, Brichetto et al. [48]	Case-control	Clinical population: Adult-onset, isolated focal cervical dystonia n = 16 Age: 60.2 ± 14 (33–82) yrs Sex (M/F): 4/12 Disease duration: 8.8 yrs. (range: 2–21 yrs.) BoNT: 11/16; last injection at least 3 months prior Control group: Healthy adults n = 12 Age: 51 ± 15.5 (31–76) yrs Sex (M/F): 7/5	Frequency: 90 Hz amplitude: NA Sites: Left or right sternocleidomastoid Duration: 51.2 s	Center of foot pressure (COP) displacement in sagittal and frontal plane COP sway path COP sway area	Neck muscle vibration significantly increased mediolateral COP in healthy controls ($p < 0.005$), but not in CD participants ($p > 0.05$) Neck muscle vibration did not change COP sway path in CD participants ($p > 0.05$), but significantly increased COP sway path in controls ($p < 0.0005$) Neck muscle vibration significantly increased COP sway area in controls ($p < 0.03$) but not in CD group ($p > 0.05$)

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TABLE 1 Continued

Authors	Study design	Participant characteristics	VTS protocol	Outcomes measures	Effect of vibration
Brugger et al. [49]	Case-control	Clinical population: Adult-onset, isolated focal cervical dystonia (CD with sensory trick) n = 20 Age: 54.4 ± 8.5 years Sex (M/F): 6/14 Disease duration: 15.3 ± 12.4 BoNT: 18/20 treated ≥3 months prior (CD without sensory trick) n = 15 Age: 60.7 ± 8.3 years Sex (M/F): 6/9 Disease duration: 16.5 ± 12.7 BoNT: 14/15 treated ≥3 months prior Control group: Healthy adults n = 16 Age: 58.7 ± 10.0 years Sex (M/F): 5/11	Frequency: 100 Hz Amplitude: NA Muscles or sites: Left and right trapezius Duration: 10 s	Center of pressure (COP) displacement in the sagittal plane Forward body sway produced by ankle flexion Head movements (head-on-trunk extension, head-in-space backwards tilt)	Neck muscle vibration increased anteroposterior COP in CD participants with a sensory trick ($p < 0.02$) and in healthy controls ($p < 0.02$), but produced no significant change in CD participants without a sensory trick ($p > 0.05$) Neck muscle vibration reduced forward body sway during ankle flexion in CD participants without a sensory trick compared to CD participants with a sensory trick and healthy controls ($p < 0.010$, between groups) Neck muscle vibration reduced head-on-trunk extension ($p = 0.021$) and head-in-space backward tilt ($p = 0.003$) in the CD-ST group. There was no significant difference between CD+ST and the control group
Carment et al. [50]	Case-control	Clinical population: Adult-onset, isolated focal cervical dystonia (CD with retrocollis) n = 7 Age: 48.7 ± 14.9 years Sex (M/F): 3/4 Disease duration: 4.3 ± 3.2 months BoNT: 6/7 treated ≥3 months prior (CD without retrocollis) n = 11 Age: 54.5 ± 12.2 years Sex (M/F): 3/8 Disease duration: 7 ± 5.7 months BoNT: 7/11 treated ≥3 months prior Control group: Healthy adults n = 19 Age: 52.7 ± 13.8 years Sex (M/F): 7/12	Frequency: 70 Hz Amplitude: NA Muscles or sites: Left and right trapezius Duration: During the entire task (neck extension)	Isometric neck extension force accuracy (5% MVC, 20% MVC) Isometric neck extension force accuracy at 5% and 20% MVC	Neck muscle decreased force accuracy in CD R+ participants significantly more than CD R-participants ($p < 0.001$) and healthy controls ($p = 0.006$) No significant effect was observed at 20% MVC in any group ($p > 0.05$) Neck muscle vibration at 5% MVC caused CD participants without retrocollis to produce significantly higher forces than those with retrocollis ($p = 0.001$) No significant effect was observed at 20% MVC in any group ($p > 0.05$)

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TABLE 1 Continued

Authors	Study design	Participant characteristics	VTS protocol	Outcomes measures	Effect of vibration
Dwenger et al. [51]	Quasi-experimental (pretest/posttest)	Clinical population: Adult-onset, isolated focal task-specific laryngeal dystonia n = 5 Age: 67 (27) yrs. (Median + IQR) Sex (M/F): 3/2 Disease duration: NA BoNTs: treated ≥3 months prior Essential voice tremor n = 5 Age: 71 (6) yrs. (Med + IQR) Sex (M/F): 3/2 Disease duration: NA Control group: Healthy adults n = 5 Age: 59 (32) yrs. (Med + IQR) Sex (M/F): 5/11	Frequency: 70 Hz Amplitude: Muscles or sites: Skin above larynx Duration: 7 min	Perceived voice quality rated by listeners Self-rated vocal effort relative to baseline Smoothed cepstral peak prominence (CPPS)	Laryngeal VTS decreased perceived voice quality ratings in the essential voice tremor group ($p = 0.007$), but not in the laryngeal dystonia group ($p = 0.05$) Neck muscle vibration showed no significant effect on self-rated vocal effort Laryngeal VTS significantly decreased CPPS ($B = -1.09$, $SE = 0.27$, $p < 0.001$), indicating worsened acoustic voice quality in LD
Feiwell et al. [52]	Case-control	Clinical population: Adult-onset, isolated focal cranial dystonia affecting eyelids (blepharospasm) n = 7 Age: 65 ± 8.2 (57–78) yrs Sex (M/F): 2/5 Disease duration: 9 ± 2.2 years BoNT: All treated 1–3 months prior Control group: Healthy adults n = 7 Age: 53 ± 17.4 (25–72) yrs. Sex (M/F): 2/5	Frequency: NA Amplitude: NA Muscles or sites: Left or right hand or side of the mouth Duration: 40 s	Regional cerebral flow (rCBF) activation	Mouth-side VTS significantly decreased rCBF in bilateral ipsilateral ($p = 0.0004$) and contralateral primary sensorimotor cortical area ($p = 0.0009$) in blepharospasm patients when compared to controls SMA rCBF showed no group differences to mouth-side VTS ($p > 0.05$) Hand vibration showed no group differences ($p > 0.05$)
Karnath et al. [53]	Single-case study (pretest/posttest)	Clinical population: Adult-onset, isolated focal cervical dystonia n = 1 Age: 54 years Sex (M/F): 0/1 Disease duration: 6 years BoNT: Treated with 6 injections/yrs., no response	Frequency: 80 Hz Amplitude: 0.4 mm Muscles or sites: Splenius muscle Duration: 5 s and 15 min	Head tilt angle Retention time	5s vibration of the affected muscle decreased head tilt angle, but the correction disappeared within seconds ($p < 0.05$) Continuous vibration of the affected muscle for 15 min decreased head tilt angle. Corrected posture persisted for several minutes after stimulation
Khosravani et al. [54]	Quasi-experimental (pretest/posttest)	Clinical population: Adult-onset, isolated focal task-specific laryngeal dystonia n = 13 Age: 58.6 ± 12.5 years Sex (M/F): 5/8 Disease duration:163.77 ± 146.49 months BoNT: 12/13 treated ≥2 months prior (range 2–36 months)	Frequency: 100 Hz Amplitude: ~1.7 G Muscles or sites: Bilaterally on the lateral area of the thyroid cartilage Duration: 29.4 min	Number of voice breaks Smoothed sepstral peak prominence (CPPS) Event-related spectral power over sensorimotor cortex	Voice breaks were reduced in 9 of 13 LD patients CPPS increased significantly by more than +1 dB across patients ($p = 0.02$) Cortical oscillatory activity showed reduced theta-band power over the left motor cortex ($p = 0.012$) and increased gamma power over the right somatosensory–motor cortex electrodes ($p = 0.015$–0.027)

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TABLE 1 Continued

Authors	Study design	Participant characteristics	VTS protocol	Outcomes measures	Effect of vibration
Konczak et al. [55]	Randomized crossover trial	Clinical population: Adult-onset, isolated focal task-specific laryngeal dystonia n = 39 Age: 60 ± 11.3 years Sex (M/F): 21/18 Disease duration: 13.7 ± 11.6 years BoNT: 22/17 treated ≥2 weeks prior	Frequency: 40 or 100 Hz Amplitude: 1.7G Muscles or sites: Lateral area of thyroid cartilage Duration: 20 min/day for 1 or 3 times/week over 11 weeks	Smoothed cepstral peak prominence (CPPS) Perceived speech effort (PSE) (scale of 0–10, 10 = maximum vocal effort)	VTS increased CPPS significantly immediately post-treatment. No significant changes were observed at 20 or 60 min post-VTS VTS reduced PSE significantly by −1.0 immediately post-treatment and at 20 min, while the effect was no longer present at 60 min
Leis et al. [56]	Quasi-experimental	Clinical population: Adult-onset, isolated focal cervical dystonia n = 11 Age: 49.7 ± 9.4 years Sex (M/F): 4/7 Disease duration: 6.4 ± 5.5 years BoNT: 6/11 treated (time not specified)	Frequency: 150 Hz Amplitude: 2–3 mm Muscles or sites: Forehead, occiput, cervical spine, paraspinal and shoulder girdle muscles, masseter, suprahyoid muscles, neck flexors and extensors Duration:10 s	EMG root mean square	Vibration of cranio-cervical and shoulder girdle muscles led to reduced muscle activity in some participants (3/11 participants)
Lekhel et al. [57]	Case-control	Clinical population: Adult-onset, isolated focal cervical dystonia n = 19 Age: 42.4 ± 7 years Sex (M/F): 7/12 Disease duration: 9 ± 2.17 years All treated with BoNT Control group: Healthy adults n = 19 Age: 33.8 ± 10 years Sex (M/F): 12/7	Condition 1: Frequency: 90 Hz Amplitude: 0.5 mm Muscles: Right or left trapezius Duration: 35 s or 4 s Condition 2: Frequency: 70 Hz Amplitude: 0.5 mm Site: Achilles tendon Duration: 4 s	Sway deviation of the foot center of pressure (CoP) in the sagittal and frontal plane relative to baseline Head movement in the sagittal plane	Neck muscle vibration induced smaller postural sway amplitudes in CD when compared to controls Sway deviation in the sagittal plane of the CD group was smaller when compared to the control group during 4 s ($p = 0.0002$) and the 35 s epoch of vibration ($p < 0.05$) Neck vibration induced head extension in a subset of CD participants (n = 7)
Macerollo et al. [58]	Case-control	Clinical population: Adult-onset, isolated focal non–task-specific upper-limb dystonia n = 6 Adult-onset, isolated segmental dystonia involving cervical and upper limb regions n = 6 Adult-onset, isolated segmental limb dystonia involving upper and lower limbs n = 2 Age: 51.2 ± 12.4 years Sex (M/F): 7/7 Disease duration: NA BoNT: Not treated >3 months prior Control group: Healthy controls n = 17 Age: 48 ± 7.4 years Sex (M/F): 7/10	Frequency: 80 Hz Amplitude: 0.2–0.5 mm Muscles or sites: Right hand palm	SEP suppression index (ratio of SEP amplitude at movement onset to SEP amplitude at rest.)	Palm vibration reduced SEP suppression during movement in both patients and controls, making SEPs less attenuated (ratios closer to 1)

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TABLE 1 Continued

Authors	Study design	Participant characteristics	VTS protocol	Outcomes measures	Effect of vibration
Mahnan et al. [59]	Quasi-experimental (pretest/posttest)	Clinical population: Adult-onset, isolated focal task-specific laryngeal dystonia n = 11 Age: 56.1 ± 10.6 years Sex (M/F): 1/10 Disease duration:11.5 ± 5.8 years BoNTs: 7/11 patients treated	Frequency: 100 Hz Amplitude: ~1.7 G Muscles or sites: Bilaterally on the lateral area of the thyroid cartilage Duration: 24 min	Smoothed cepstral peak prominence (CPPS) Cumulative sentence duration (CSD) Cumulative word duration (CWD)	VTS increased CPPS (>1 dB) in 4/11 participants (36%) Post-VTS, 45% retained improvements at 20 min, and 27% retaining improvements at 60 min Laryngeal VTS decreased CSD in responders Laryngeal VTS decreased CWD in responders with a mean reduction of −8.0 s (range: −2.1 to −18.1 s)
Rosenkranz et al. [60]	Case-control	Clinical population: Adult-onset, isolated focal task-specific upper-limb dystonia (Musician's dystonia - MD) n = 5 Age: 38.6 ± 11.4 years Sex (M/F): - Disease duration: 5.8 ± 2.9 years BoNT: Not reported Control group 1: Healthy musicians n = 5 Age: Age-matched Control group 2: Healthy non-musicians n = 5 Age: Age-matched	Frequency: 80 Hz Amplitude: 0.5 mm Muscles or sites: Flexor carpi radialis (symptomatic side of patients; right or left side of controls) Duration: 10 s (with random intertrial intervals of 4–7 s)	MEP latency (ms) MEP area (mV*ms) as a measure of cortical facilitation or inhibition	Vibration of FCR produced no significant change in latency of either agonist (FCR) or antagonist (ECR) for the MD, healthy musician and healthy non-musician groups Vibration of FCR increased agonist MEP area in all groups ($p < 0.05$), but less in MD ($p < 0.04$ vs. controls) Vibration of FCR decreased antagonist MEP area in controls ($p < 0.001$) but not in MD ($p < 0.01$ vs. controls)
Rosenkranz et al. [61]	Case-control	Clinical population: Adult-onset, isolated focal task-specific upper-limb dystonia (Musician's dystonia - MD) n = 7 Age: 41 ± 3 years Sex (M/F): 6/1	Frequency: 80 Hz Amplitude: 0.2–0.5 mm Muscles or sites: abductor pollicis brevis, abductor digiti minimi, first dorsal interosseus muscle Duration: 1.5 s for every 5 s	MEP amplitude (mV) Short-latency intracortical inhibition (SICI, %) Intracortical facilitation (ICF, %)	Vibration of hand muscles in MD increased MEP amplitude in the vibrated muscle but produced no change in non-vibrated muscles. In WC, vibration did not significantly alter MEP amplitude in either vibrated or non-vibrated muscles Vibration of hand muscles in MD reduced SICI across all hand muscles, whereas in WC, vibration did not alter SICI in either vibrated or non-vibrated muscles Vibration of hand muscles did not significantly change ICF in either musician's dystonia or writer's cram

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TABLE 1 Continued

Authors	Study design	Participant characteristics	VTS protocol	Outcomes measures	Effect of vibration
		Disease duration: 6.9 ± 4.1 yrs BoNT: 3/7 treated ≥6 months prior Adult-onset, task specific dystonia of the face, jaw or mouth (embouchure dystonia) n = 2 Age: 44 ± 1 year Sex (M/F): 2/0 Disease duration: 4 ± 2.83 years BoNT: 0/2 treated ≥6 months prior Adult-onset, isolated focal task-specific upper-limb dystonia (Writer's cramp - WC) n = 6 Age: 44 ± 4 years Sex (M/F): 4/2 Disease duration: 8.8 ± 3.8 years BoNT: 2/6 treated ≥6 months prior Control groups: Healthy musicians n = 8 Age: 23 ± 1 year Sex (M/F): 3/5 Healthy non-musicians n = 8 Age:31 ± 2 years Sex (M/F): 5/3			
Rosenkranz et al. [62]	Randomized crossover trial	Clinical population: Adult-onset, isolated focal task-specific upper-limb dystonia (Musician's dystonia) n = 6 Age: 38.5 ± 3.4 years Sex (M/F): 4/2 Disease duration: 6.2 ± 3.4 years BoNT: No patients treated Adult-onset, isolated focal task-specific upper-limb dystonia (Writer's cramp) n = 6 Age: 38.3 ± 1.9 years Sex (M/F): 4/2 Disease duration: 8 ± 4 years BoNT: 2/6 treated ≥6 months prior	Frequency: 80 Hz Amplitude: 0.2–0.5 mm Muscles or sites: Abductor pollicis brevis muscle Duration: 2 s on, 2 s off for 15 min	Short interval-intracortical-inhibition (SICI)	Vibration of the thumb muscles reduced SICI in both vibrated and non-vibrated muscles in musician's dystonia ($p < 0.0001$) In writer's cramp, vibration did not change SICI in either vibrated or non-vibrated muscles ($p > 0.05$)

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TABLE 1 Continued

Authors	Study design	Participant characteristics	VTS protocol	Outcomes measures	Effect of vibration
Serrien et al. [63]	Case-control	Clinical population: Adult-onset, isolated focal task-specific upper-limb dystonia (Simple writer's cramp) n = 5 Adult-onset, isolated focal non-task-specific upper-limb dystonia (Complex writer's cramp) n = 3 Age: 51 ± 17 (35–73) yrs Sex (M/F): 5/3 Disease duration: NA BoNT: 2/8 treated Control group: Healthy adults n = 5 Age: 46 ± 13 (37–68) yrs Sex (M/F): 4/1	Frequency: 100 Hz Amplitude: 0.2–0.5 mm Muscles or sites: Extrinsic hand/finger muscles Duration: During the entire drawer opening task	Grip-load force ratio	Vibration of the hand muscles increased the grip–load force ratio in patients with writer's cramp for both hands ($p < 0.02$) In healthy controls, vibration of the same muscles did not significantly change the grip–load force ratio ($p > 0.05$)
Siggelkow et al. [64]	Case-control	Clinical population: Adult-onset, isolated focal cervical dystonia n = 11 Age: 35–49 years Sex (M/F): 5/6 Disease duration: 10.7 years BoNT: Not reported Control group: Healthy adults n = 11 Age: Age-matched with CD participants Sex (M/F): 5/6	Frequency: 80 Hz Amplitude: 0.5 mm Muscles or sites: Right extensor carpi radialis (ECR) Duration: 4 s (with random intervals between 12 and 22 s)	MEP area (mV·ms) indicating intracortical inhibition or facilitation	Vibration of the forearm muscles did not significantly change intracortical inhibition in CD compared to controls ($p > 0.05$) Vibration of the forearm muscles increased intracortical facilitation in CD compared with controls ($p < 0.05$)
Tempel & Perlmutter [65]	Case-control	Clinical population: Adult-onset, isolated focal task-specific upper-limb dystonia (Simple writer's cramp) n = 3 (Dystonic writer's cramp) n = 2 (Dystonic typist's cramp) n = 2 Adult-onset, isolated focal non–task-specific upper-limb dystonia n = 1 Adult-onset, isolated segmental dystonia (idiopathic torsion dystonia) n = 1	Frequency: 130 Hz Amplitude: 2 mm Muscles or sites: All finger pads of either right or left hand simultaneously Duration: 40 s	Regional cerebral blood flow (rCBF) in sensorimotor cortex Regional CBF (rCBF) response magnitude	Vibration of the finger pads increased rCBF in the contralateral sensorimotor cortex in both healthy and UD group The magnitude of the vibration-induced rCBF response was significantly smaller in dystonia compared to healthy group for both contralateral and ipsilateral hemispheres ($p = 0.0022$)

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TABLE 1 Continued

Authors	Study design	Participant characteristics	VTS protocol	Outcomes measures	Effect of vibration
		Adult-onset, isolated focal lower-limb dystonia n = 1 Adult-onset, isolated hemidystonia (DOPA-sensitive hemidystonia) n = 1 Age: 49 ± 16 (24–70) yrs Sex (M/F): 4/7 Disease duration: 11.4 ± 13.9 years BoNT: Not reported Control group: Healthy adults n = 18 Age: 24.6 ± 4.7 (20–39) yrs Sex (M/F): 11/7			
Tempel & Perlmutter [66]	Case-control	Clinical population: Adult-onset, Isolated task-specific focal hand dystonia (Writer's cramp) n = 6 Age: 45 ± 20 (24–72) yrs Sex (M/F): 2/4 Disease duration: 6.5–50 years BoNT: Not reported Control group: Healthy adults n = 8 Age: 44 ± 21 (21–72) yrs Sex (M/F): 3/5	Frequency: 130 Hz Amplitude: 2 mm Muscles or sites: All finger pads of right or left hand simultaneously Duration: 40 s	Global cerebral blood flow (CBF) Regional CBF (rCBF) response magnitude	Vibration of the hand did not change CBF in either patients with writer's cramp or controls Vibration of the hand produced reduced PSA (primary responses in writer's cramp patients with a 20% reduction in the affected hemisphere ($p = 0.007$) and a 30% reduction in the unaffected hemisphere ($p = 0.01$)
Xu et al. [67]	Single-case study (pretest/posttest)	Clinical population: Childhood-onset, isolated focal cervical dystonia with right torticollis n = 1 Age: 10 years Sex (M/F): 0/1 Disease duration: NA BoNT: at the end of treatment cycle	Frequency: 90–110 Hz Amplitude: N/A Muscles or sites: Right and left sternocleidomastoid and trapezius muscles Duration: 6 min per muscle (total 24 min)	Change in sEMG power Frequency of dystonic movements per minute Peak amplitude of acceleration (PAA)	Vibration of ipsilateral neck muscles increased sEMG power, whereas vibration of contralateral neck muscles decreased sEMG power Vibration of contralateral neck muscles reduced the frequency of dystonic movements per minute Vibration of contralateral neck muscles decreased PAA during dystonic episodes

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TABLE 1 Continued

Authors	Study design	Participant characteristics	VTS protocol	Outcomes measures	Effect of vibration
Zhu et al. [68]	Quasi-experimental (pretest/posttest)	Clinical population: Adult-onset, isolated focal cervical dystonia n = 44 Age (year): 61.8 years Sex (M/F): 15/29 Disease duration: 13.6 ± 12.8 years BoNT: 39/44 treated ±2w before/±1w after injection	Frequency: 100 Hz Amplitude: 1.7 G Muscles or sites: sternocleidomastoid and trapezius muscles Duration: 45 min	Perceived pain Score (PPS) (0–100 scale of neck pain)	During VTS: Vibration of neck muscles reduced PPS in 66% (≥10%) and 39% (≥50%) of participants After VTS: Vibration of neck muscles reduced PPS immediately after treatment in 57% of participants (≥10%), p = 0.02) Pain was significantly reduced at 20 min post-treatment (p < 0.01)

SICI, short interval intracortical inhibition. Relative amplitude of an MEP, generated by subthreshold conditioning stimulus followed by a suprathreshold test stimulus at interstimulus interval of 1–6 ms.
ICF, intracortical facilitation. Relative amplitude of an MEP generated by subthreshold conditioning stimulus followed by a suprathreshold test stimulus at interstimulus interval of 8–30 ms.
BoNT, botulinum neurotoxin injection; CD, cervical dystonia; LD, laryngeal dystonia; ICF, intracortical facilitation; MD, musician's dystonia; MCV, maximal voluntary contraction; SICI, short interval cortical inhibition; WC, writer's cramp; VTS, vibrotactile stimulation.

Inclusion and exclusion criteria

Inclusion criteria were: 1) Inclusion of participants who presented with a form of focal dystonia (FD), 2) application of superficial VTS adjacent or directly to dystonic muscles or regions, 3) reporting of at least one biomechanical and/or electrophysiological outcome measure reflecting possible VTS effects.

Exclusion criteria were: 1) Application of VTS for assessing an unrelated experimental effect, 2) not reporting selected parameters of VTS such as frequency, amplitude or duration, 3) not constituting an original, empirical investigation (e.g., review, comment or opinion article), 4) not written in English.

Study selection

Search results were exported to Covidence systematic review software (Veritas Health Innovation, Melbourne, Australia). After duplicate studies were removed, two reviewers (CO, SR) independently screened titles, abstracts and then the full-texts against the inclusion-exclusion criteria. The third reviewer (JK) was consulted to resolve any disagreements where required.

Quality assessment

Two reviewers (CO, SR) independently assessed the quality of the included articles according to the Joanna Briggs Institute (JBI) critical appraisal checklists [43]. The case-control studies, case reports, quasi-experimental studies, and crossover studies were assessed using the 10-item case-control study checklist, 8-item case report checklist, 9-item quasi-experimental study checklist, and 13-item randomized controlled trials checklist, respectively [44]. The overall risk of study bias ranked into one of the four levels (High, Moderate, Low, Very Low) in line with the recommendation from the JBI reviewer manual [43]. Any disparities in the quality assessment were resolved through consensus with a third reviewer (JK) if necessary. No studies were excluded based on the results of the quality assessment. The methodological quality of the selected studies is presented in Supplementary Table S2.

Data extraction

Two reviewers (CO, SA) extracted data and entered these into a standard data extraction table (Table 1). Extracted data related to 1) study details (author names, year of publication, and study design), 2) participant characteristics (i.e., population, age, sex, disease duration, Botulinum neurotoxin history, controls), 3) VTS protocol information (i.e., type of vibration device,

frequency, amplitude, vibrated muscles or sites, duration), 4) outcomes measures and results.

Data synthesis

The heterogeneity of dystonia types and outcome measures across articles meant that a meta-analysis was not possible. Therefore, a narrative synthesis of the data was conducted, detailing the findings, the VTS protocol, and the measured outcomes for each study. For each included study, the intervention effect was determined by extracting reported outcome data. Specifically, we focused on the primary biomechanical, neurophysiological or electrophysiological outcome measures. Where available, we included secondary outcomes or subgroup analyses to provide a broader understanding of the intervention's effect across different dystonia populations. The intervention effect was inferred from pre- and post-VTS comparisons and statistical significance. In case reports, the intervention effect was determined based on the pre- to post-VTS percentage change in the reported outcome measure [53, 68]. For case-control studies that focused on comparing pre- to post-VTS changes between people with FD and healthy individuals, we considered the statistical significance of the difference in the intervention effect between groups [49, 50, 57, 64].

Risk of bias

A Joanna Briggs Institute (JBI) bias risk analysis was performed [69]. The risk of bias was categorized as high when a study had up to 49% of "yes" responses, moderate when it ranged from 50% to 69%, and low when it exceeded 70% [69]. Based on these criteria, 6 studies were classified as having a high risk of bias, 7 as moderate, and 11 as low. None of the studies were excluded based on the quality assessment results. A summary of the applied risk analysis can be found in Supplementary Table S2.

Results

Search results

A search of the PUBMED (n = 73), MEDLINE (n = 68), CINAHL (n = 28), and Cochrane Library databases (n = 16) identified a total of 185 studies. After removing 93 duplicate studies, 92 studies were reviewed through title-abstract assessment. A total of 66 records were excluded, because they did not meet the inclusion criteria. Of the 26 records sought for retrieval, one full text of one study was unavailable, another study was not published in English. Thus, 24 studies were included in this review. The process of study selection for this review is presented in Figure 1.

Study characteristics

Thirteen studies (54%) applied a case-control study design [47–50, 52, 57, 58, 60, 61, 63–66] focusing on elucidating possible neurophysiological mechanisms of VTS as a form of neuromodulation that influences motor output. These studies were not designed as clinical trials that attempted to determine if VTS can reduce dystonic symptoms. The remaining 11 studies (46%) investigated VTS as a possible treatment for focal dystonia [45, 46, 51, 53–56, 59, 62, 67, 68]. Two of these studies (8%) were case reports [53, 68], 7 (29%) were quasi-experimental studies [45, 46, 51, 54, 56, 59, 62], and 2 (8%) were randomized controlled trials [55, 67].

Participant characteristics

The included studies reported a total of 587 participants (sample size: min = 1; max = 67; median = 7.5), among whom 235 presented with adult-onset, isolated focal cervical dystonia (CD), 100 with adult-onset, isolated laryngeal dystonia (LD), 10 with adult-onset, non-task-specific upper limb dystonia, 48 with adult-onset, task-specific focal hand dystonia (30 = writer's cramp, 18 = musician dystonia), 2 with adult-onset, task specific dystonia of the face, jaw or mouth (musician embouchure dystonia), 7 with adult-onset, isolated focal cranial dystonia affecting the eyelids (blepharospasm), 10 with adult-onset segmental dystonia involving cervical and upper limb (n = 7) or the lower limb (n = 3) and 175 participants served as neurologically normal controls.

The mean age was 50.9 (SD ± 11.8) years for the dystonia participants and 43.1 (SD ± 12.0) years for the healthy controls. Of the 23 studies that reported sex, 61% of the participants were females [45–59, 61–68]. Nineteen studies reported disease duration (mean: 10.1 years; range: 2–21 years) [45–50, 52–57, 59–62, 64, 65, 67]. See Table 1 for an overview of all reviewed studies.

Devices employed for VTS application

The majority of studies used a variety of commercially available vibratory motors [47–50, 52–58, 60–68]. Considering all vibratory motors, the applied frequencies of VTS ranged from 70–150 Hz (mean: 95 Hz, median: 90 Hz) with a vibration amplitude between 0.2–3 mm (mean: 0.85 mm, median: 0.5 mm). VTS was applied for a minimum of 5 s [53] up to a maximum of 54 min [55] and longitudinally for up to 11 weeks [55]. The application sites were generally on or near the clinically

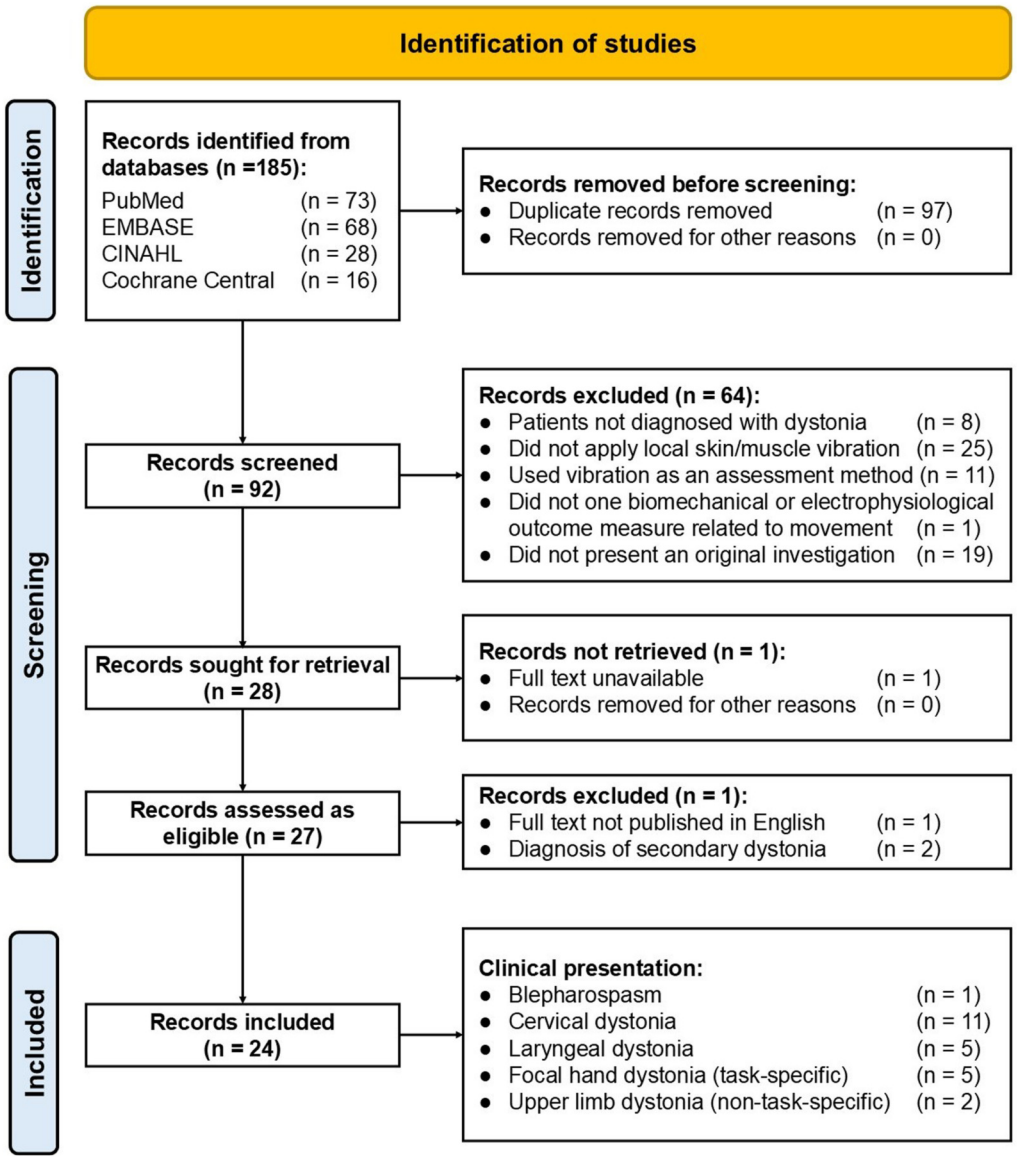

FIGURE 1
PRISMA diagram summarizing the study selection procedure.

identified dystonic muscles. Across the included studies, the VTS targets varied by dystonia subtype. In blepharospasm, stimulation was applied to the region around the mouth [52]. In cervical dystonia, the application sites were the sternocleidomastoid in 5 studies [46–48, 67, 68], trapezius in 6 studies [46, 49, 50, 57, 67], right extensor carpi radialis in one study [64], splenius in one study [53], and broader regions, such as the forehead, occiput, cervical spine, paraspinal and shoulder girdle muscles, masseter, suprahyoid muscles, neck flexors and extensors in one study [56]. For laryngeal dystonia, all studies consistently targeted the lateral aspect of the thyroid cartilage bilaterally [45, 51, 54, 55, 59]. In musician's dystonia, writer's cramp and upper-limb dystonia studies, stimulation was applied to the finger muscle [58, 60–62, 65, 66].

Biomechanical and neurophysiological effects of VTS in focal dystonia

Because a possible link between somatosensory stimulation and the motor manifestations of dystonia have long been recognized, several studies examined the effects of vibration in focal dystonia to elucidate the underlying pathomechanisms of the disease and to understand how the nervous system responds

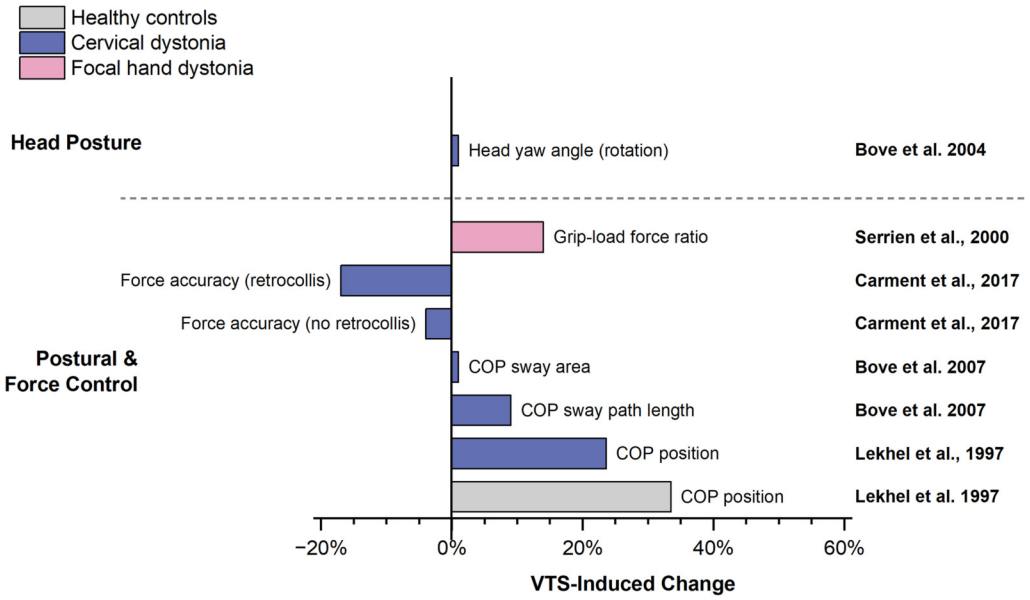

FIGURE 2
Behavioral responses to short-duration VTS (<1 min). Shown is the mean VTS-induced change relative to a reported baseline measure prior to VTS for a particular group. Depending on the dystonia subtype different measures reflecting changes in head/neck, or postural and force control. COP, center of pressure. Head yaw angle refers to the left/right rotation (turning) of the head.

to vibration in people with focal dystonia. These studies applied VTS in short bursts between 4 and 50 s.

Effects of VTS on the control of posture and force

Four case control studies evaluated whole-body postural responses in CD patients during the vibration of neck muscles (trapezius, sternocleidomastoid). In two of these studies, neck vibration induced postural responses in people with CD, particularly in those with an effective sensory trick (57% patients with effective sensory tricks, 43% patients without effective sensory tricks) [49, 57]. CD participants responded similarly to healthy controls with an initial forward sway of the body around the ankle that slowly increased during prolonged vibration. Those without an effective sensory trick exhibited a significantly reduced initial anterior-posterior sway. In contrast, two studies by Bove and colleagues evaluated postural sway in people with CD during quiet standing or stepping in place in response to vibration while they had their eyes closed. Results showed that CD participants exhibited little or no postural responses to vibration [47, 48] or showed inconsistent responses with some CD patients exhibiting orienting responses only unilaterally and not bilaterally as seen in healthy controls [47].

Two studies examined effect of vibration on force regulation in patients with cervical dystonia or writer's cramp [50, 63]. One study investigated sense of force effort in CD patients with and without retrocollis [50]. Participants performed neck extension force matching and force maintenance tasks at 5% and 20% of maximum voluntary contraction (MVC) of both trapezius muscles while providing visual cues of generated force as feedback. Both CD groups performed similar to healthy controls when visual feedback was present. There was no difference between the groups in terms of mean force at 20% MVC in any condition. However, when relying on somatosensory cues (force effort) at 5% MVC without visual feedback, CD patients with retrocollis tended to produce lower and more variable levels of force, and the applied force decreased significantly in this group when VTS was added. In contrast, the CD group without retrocollis overshot desired force targets. Serrien and colleagues investigated grip force regulation in patients with writer's cramp while performing a drawer opening task [63]. Participants with WC generated higher grip force levels during grasping when compared to controls, and this force was higher in the symptomatic hand than in the asymptomatic hand. When vibration was applied to hand muscles, grip force increased in both hands of WC patients, but not in healthy controls.

In summary, the results of these studies indicate that force control of dystonic muscles is altered in FD. VTS can modulate force control in people with FD. However, its effect depends on which muscle groups are stimulated (e.g., non-dystonic vs. dystonic). In addition, the fact that vibration of dystonic neck muscles has no or only minor effects on whole body postural control indicates that possible VTS effects seem to be local and not generalized. For an overview of the effects on head, postural and force control due to VTS, see Figure 2.

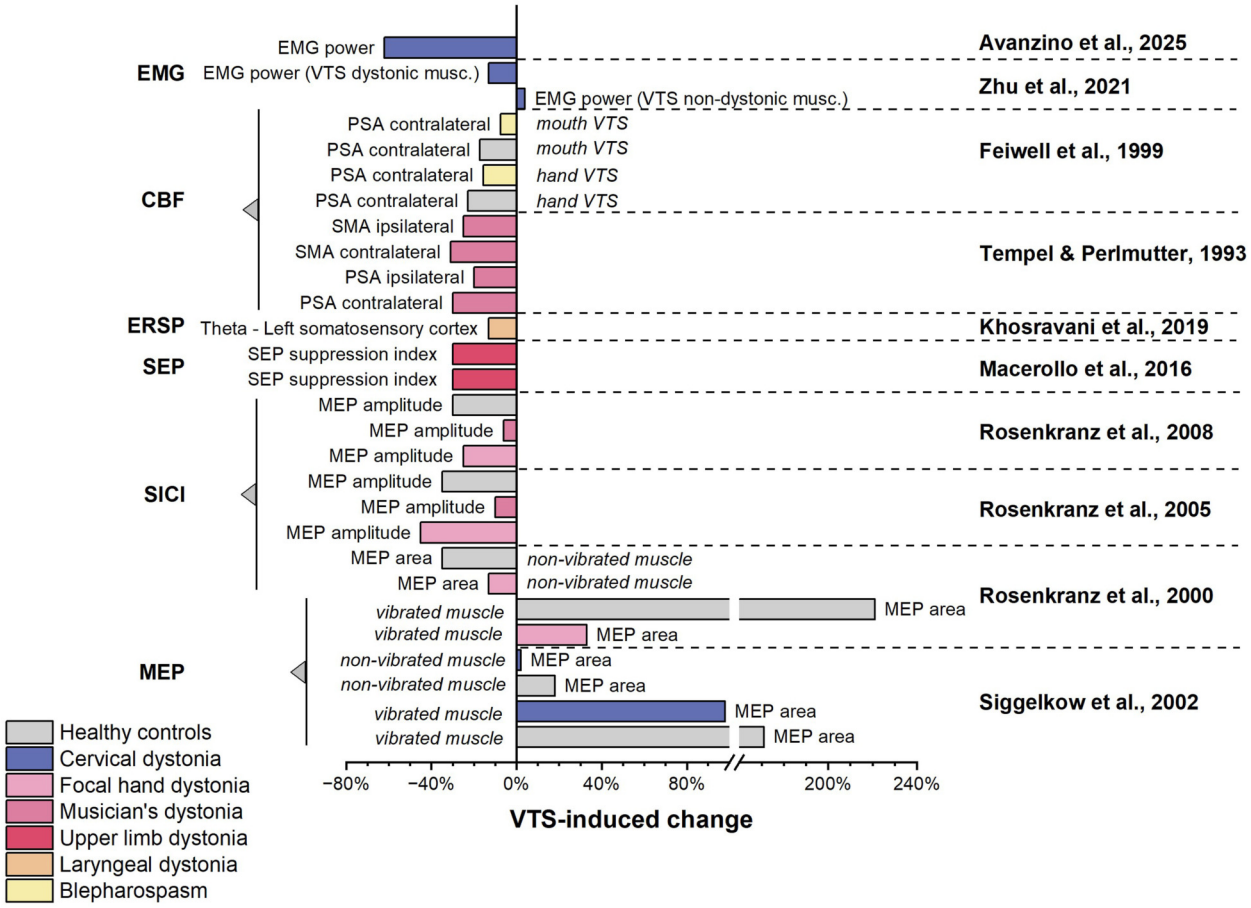

FIGURE 3
Neurophysiological responses to VTS. Shown is the mean VTS-induced change relative to a reported baseline measure prior to VTS for a particular group. CBF, cerebral blood flow; ERSP, event-related spectral power; MEP, motor-evoked potential; PSA, primary sensorimotor area; SEP, somatosensory-evoked potential; SICI, short-interval cortical inhibition. Following the updated dystonia classification, clinical presentations labelled as musician's dystonia correspond to isolated focal task-specific upper-limb dystonia, writer's cramp includes both isolated focal task-specific and non–task-specific upper-limb dystonia, and blepharospasm corresponds to isolated focal cranial dystonia affecting the eyelids.

Effects of VTS on neural markers of sensorimotor processing

Over the last four decades, a series of studies examined the neural responses to VTS. Two studies investigated the effect of hand or wrist muscle vibration in people with MD, WC [60, 61] and another study in participants with CD [64]. Transcranial magnetic stimulation (TMS) was applied over motor cortex and the elicited motor evoked potentials (MEPs) were recorded in the vibrated and non-vibrated antagonistic muscles. In healthy musicians and non-musicians, VTS increased MEP amplitude and decreased the *short-latency intracortical inhibition* (SICI) – the relative reduction of MEP amplitude - in the vibrated muscle but showed the opposite effect on the non-vibrated hand muscles. Muscle vibration strongly reduced SICI in all hand muscles and reduced *intracortical facilitation* (ICF) in MD [60, 61], but had little effect on cortical excitability in WC [61, 62]. Applying VTS to non-dystonic forearm extensor muscles in people with CD significantly increased intracortical facilitation when compared to healthy controls [64] (for a summary of all MEP-based results, see Figure 3).

Using positron emission tomography to measure cerebral blood flow (CBF) in dystonia patients, two studies reported that hand vibration was associated with a 25% reduction in regional blood flow of the contralateral primary sensorimotor hand area in patients with unilateral dystonia [65] and writer's cramp [66]. Moreover, in patients with blepharospasm, a dystonia associated with involuntary spasms of the *orbicularis oculi* muscles, lower face VTS produced a localized and robust bilateral activation of the sensorimotor cortical area in healthy controls, but this response was significantly decreased in the blepharospasm group [52].

Electrocortical responses to VTS were recorded by EEG in people with laryngeal dystonia (LD) in two recent studies [54,

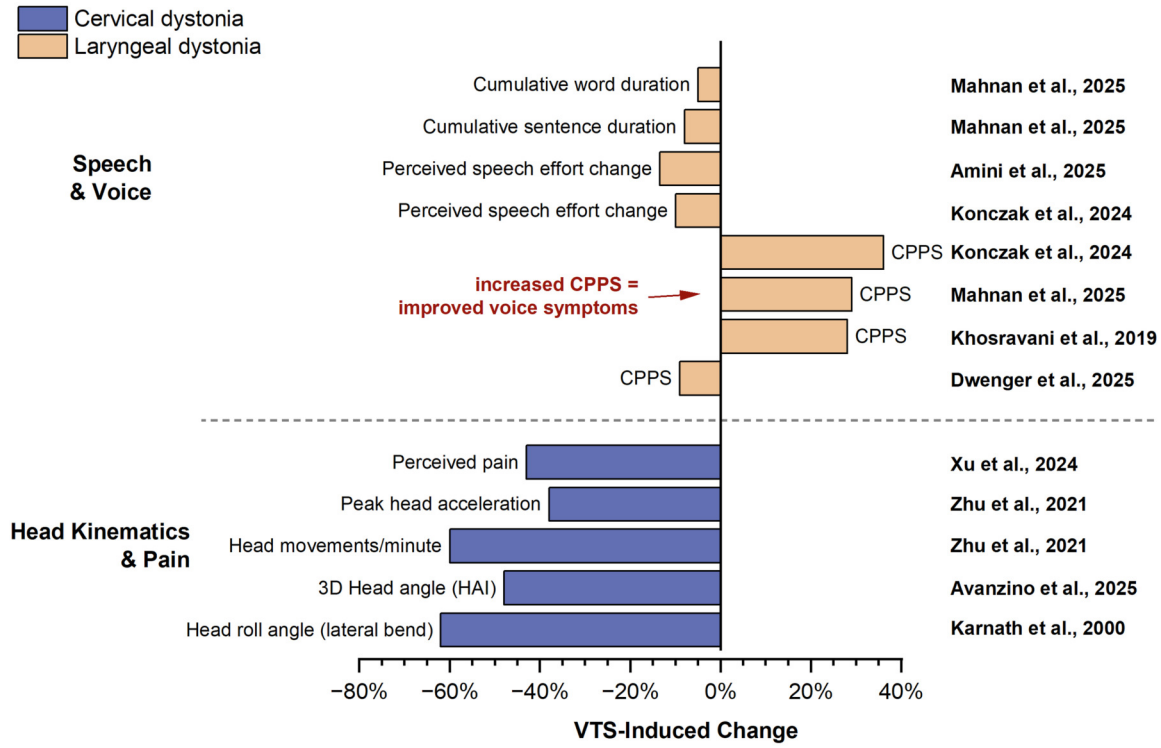

FIGURE 4
Behavioral effects to prolonged VTS on head kinematics, pain and measures of speech/voice quality. Shown is the mean VTS-induced change relative to a reported baseline measure prior to VTS for a particular group. CPPS, smoothed cepstral peak prominence; HAI, head angle index indicating three-dimensional (3D) head posture; ST, sensory trick. Head roll angle refers to left/right bending of the head.

59]. During vocalization, both healthy controls and participants with adductor- or abductor-type LD exhibited characteristic movement-related depression of cortical activity over left sensorimotor cortex. The cortical response to VTS was a reduced event-related spectral power (ERSP) in theta, alpha, and beta bands over left and right somatosensory-motor cortical areas that was most prominent over the left premotor cortex. The VTS-induced suppression of theta band power over the left somatosensory-motor cortex was found in both clinical presentations (adductor- or abductor-type LD). This is noteworthy, because such suppression of theta oscillations is observed in patients with cervical dystonia who apply effective sensory tricks [25], suggesting that VTS in LD may activate a similar neurophysiological mechanism.

In summary, the application of VTS to people with various forms of FD revealed that cortical processing is altered regardless of clinical phenotype as evidenced by characteristic changes in MEP responses of dystonic muscles and their antagonists. Importantly, the neuromodulation effect of VTS can be seen in the rapid changes in cortical ERSP over bilateral sensorimotor cortex in people with the laryngeal presentation of FD. For an overview of the neurophysiological findings, see Figure 3.

Effectiveness of VTS as a clinical intervention by dystonia phenotype

Cervical dystonia

Several single case and quasi-experimental studies examined the effects of neck muscle vibration in patients with CD [46, 53, 56, 67, 68]. The case report by Karnath et al. documented that *trapezius* muscle vibration can induce head righting in a person with right torticollis [53] and, compared to baseline prior to VTS, the frequency of dystonic neck movements decreased by 60% post VTS in a juvenile patient with CD [68]. Short 5-s bursts of VTS led to fast changes in head position, but the head returned within seconds to the initial pathological position after each burst [56]. Applying VTS over longer time periods (15–45 min) could lead to prolonged normalization of head posture that would decay slowly within 20 min after VTS was turned off [46, 53, 68] (for a summary of the effects on head kinematics due to VTS, see Figure 4).

The most comprehensive and systematic evidence that cervical VTS can induce head righting in CD comes from a multi-center study that examined 67 CD patients [46]. Three-dimensional head angle kinematics and surface EMG for bilateral *sternocleidomastoid* and *trapezius* muscles were recorded while VTS was applied to these muscles under 9 different stimulation

conditions (e.g., single muscle, bilateral trapezius). Nearly half of participants exhibited large changes in abnormal head posture as measured by a head angle index that expressed 3D head position relative to a normal upright head posture (see Figure 5A). Responsiveness to VTS was widespread with 85% of participants showing head righting responses (see Figure 5B).

Studies applying VTS to the neck and head in CD documented that VTS induces fast changes in muscle activation within seconds. In one study [56], VTS was applied for short 10-second bursts to bony parts of the skull (forehead, occiput), cervical spine and several facial, neck and arm muscles. The corresponding analysis of neck muscle activity recorded by EMG showed that VTS applied to both bony landmarks and muscles could affect EMG amplitude. VTS applied to neck muscles resulted in the largest reduction (up to 84% on average) [56]. Assessing EMG responses to longer applications of VTS (up to 45 min) [46, 68] revealed that VTS applied to a single neck muscle reduced average EMG power by up to 15% in a juvenile patient with CD [68]. The more comprehensive study of 67 CD patients by Avanzino and colleagues (2025) confirmed that VTS can substantially reduce EMG activity in dystonic muscles [46] (see Figure 6).

Neck muscle vibration may also have therapeutic effect on pain that is frequently associated with CD. A case report [68] reported pain relief after vibration to sternocleidomastoid and trapezius muscles in a patient with juvenile CD. A compendium study [67] to Avanzino et al. (2025) that examined those participants who presented with pain (n = 44) found that 29/44 (66%) of participants experienced a reduction in pain of at least 10% with 17/44 (39%) reporting a reduction in pain of 50% or higher. After VTS cessation, 57% of participants still reported a pain reduction at retention 20 min past VTS. Factors like disease severity, and, duration did not differentiate between VTS responders and non-responders. Also, the sensory trick did not clearly differentiate responders (82%) from nonresponders (60%).

Laryngeal dystonia

To better understand the contribution and nature of sensory tricks in LD, a pilot study compared voice symptoms across varied sensory conditions in five participants with laryngeal dystonia to an equal sample presenting with essential vocal tremor [51]. The altered sensory conditions included delayed auditory feedback, reduced somatosensory feedback from the nasal and pharyngeal/laryngeal mucosa due to topical anesthesia, and VTS. Ratings of auditory recordings of speech by naïve listeners indicated that delayed auditory feedback and VTS worsened perceived speech quality in both the LD and essential vocal tremor groups. The results did not allow to differentiate between both patient populations on the basis of their susceptibility to sensory cues.

Four studies conducted by the same laboratory examined potential therapeutic effects of VTS in patients with LD [45, 54, 55, 59]. Vibratory motors were positioned above the skin of the voice box (Figure 7). A single session of laryngeal vibration (24–29 min VTS) improved objective markers of voice quality such as the number of voice breaks and/or reduced perceived speech effort (PSE) as rated by participants with adductor- and abductor-type of LD [54, 59]. In response to VTS, 64% of participants with abductor-type LD rated their improvement in voice quality as noticeable to very noticeable [59] and 69% of participants with adductor-type LD exhibited a reduction in voice breaks and/or a meaningful increase in cepstral peak prominence–an acoustic marker indicating improved voice quality [54]. Note that there was nearly no

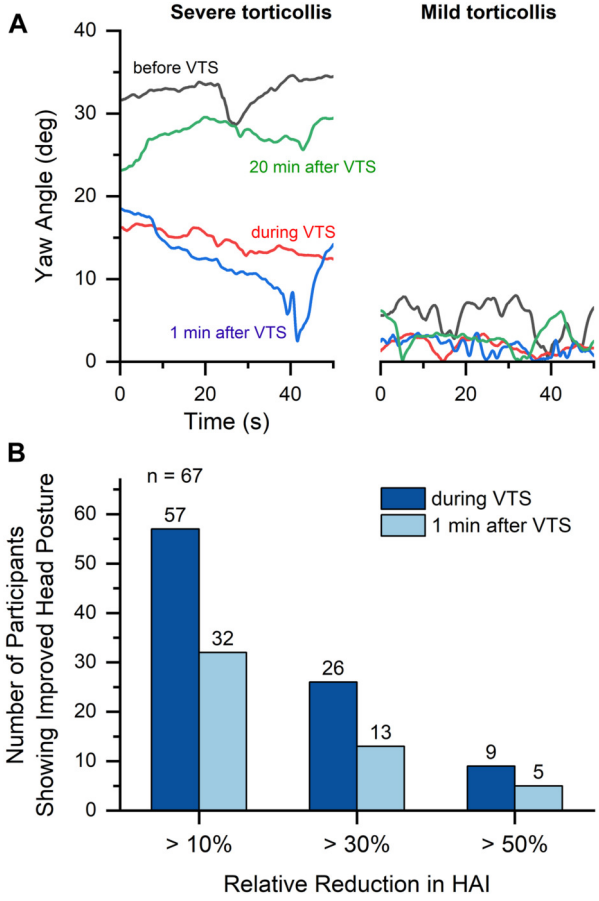

FIGURE 5
Changes in head posture due to cervical VTS. **(A)** Exemplar time series data of the yaw head angle (rotation to the left or right) in two patients with torticollis. Note that the large and fast change in head angle in the more severely affected participant. The effect decayed slowly but was still visible 20 min past VTS. The more mildly affected participant also showed an effect but given the smaller deviation from the neutral head position, the magnitude of head angle change was smaller. An angle of 0° indicates a straight-ahead position. **(B)** Magnitude and frequency of improvement in abnormal head posture due to VTS. Shown is the relative change in HAI during VTS-ON and post-VTS relative to the pre-VTS baseline for each participant at the most effective stimulation condition. Reproduced from "Changes in head posture due to cervical VTS" by Laura Avanzinoa, Jiapeng Xuc, Davide Martinod, Antonella Contee, Stephanie Standalg, Parisa Salehig, Sara Terranova, Gaia Bonassib, Parisa Alizadehd, Janet Adesewa Adeotid, Daniele Belvisie, Matteo Costanzof, Jinseok Ohc and Jürgen Konczakc, licensed under CC BY 4.0.

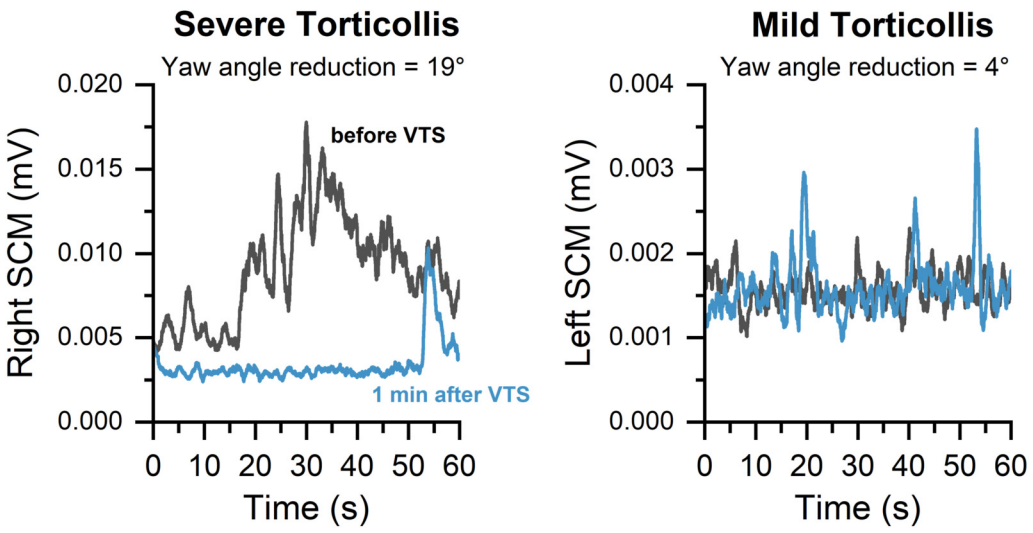

FIGURE 6
Exemplar EMG time-series data before and immediately after the application of the VTS. For the more affected participant presenting with left torticollis, right SCM activity decreased by 62% as the yaw angle was reduced by 19° due to the VTS applied to right trapezius and sternocleidomastoid. For the less affected participant with right torticollis, the left dystonic SCM muscle did not show obvious change in EMG activity although the yaw angle was reduced to 4°. See the respective angle time-series data for each participant in Figure 4. Reproduced from "Muscle-specific responses to VTS". A. Exemplar time-series data of SCM muscle activity of two participants presenting with left and right torticollis before and immediately after the application of VTS" by Laura Avanzinoa, Jiapeng Xuc, Davide Martinod, Antonella Contee, Stephanie Standalg, Parisa Salehig, Sara Terranova, Gaia Bonassib, Parisa Alizadehd, Janet Adesewa Adeotid, Daniele Belvisie, Matteo Costanzof, Jinseok Ohc and Jürgen Konczakc, licensed under CC BY 4.0.

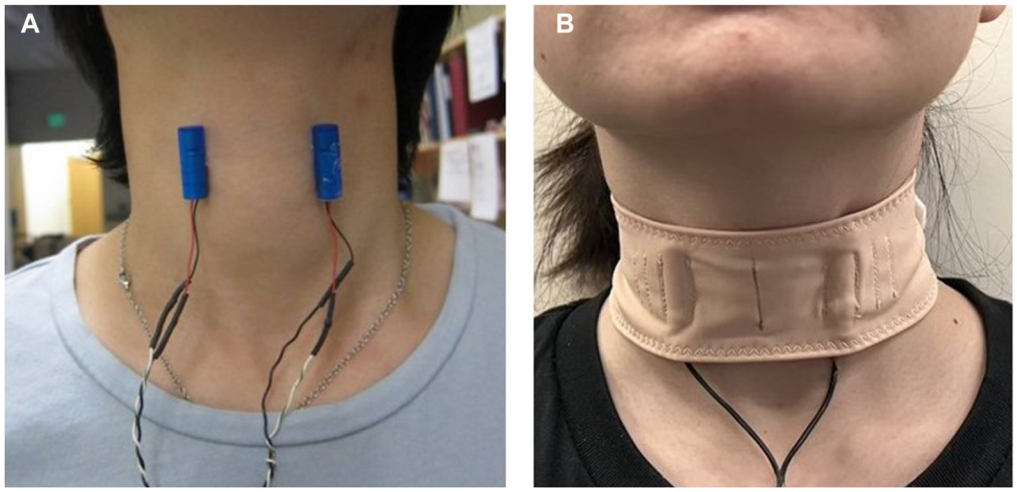

FIGURE 7
Examples of laryngeal VTS application. **(A)** Placement of the encapsulated vibrators on the skin above the larynx at the level of the hyoid bone with double-sided tape (vibrator diameter: 9 mm, length 25 mm) or **(B)** with the use of a collar. Reproduced from "Study design and procedure". A. Placement of the encapsulated vibrators on the skin above the larynx at the level of the hyoid bone with double-sided tape (vibrator diameter: 9 mm, length 25 mm) or (B) with the use of a collar" by Shima Amini, Naveen Elangovan, Cagla Özkul and Jürgen Konczak, licensed under "CC BY".

overlap in the samples studied - only one participant enrolled in two studies [45, 55]. That is, the results are not explained by having tested the same patients in multiple studies.

Two longitudinal clinical trials examined the effect of repeated VTS on voice symptoms in LD [45, 55]. A randomized clinical trial tested differences in dosage (1 or 3 times/week for 20 min each session) or VTS frequency (40 Hz vs. 100 Hz) over an 11-week period in a sample of 32 participants with adductor-type of LD [55]. VTS at the lower 40 Hz frequency was coupled with a lower vibration amplitude, meaning that vibration likely did not

penetrate beyond the thyroid cartilage and only stimulated tactile mechanoreceptors (e.g., Meissner's corpuscles). Results showed VTS improved voice quality (median CPPS increase: 0.41 dB) and/or reduced speech effort (PSE) by at least 30% in up to 57% of participants. Effects lasted from less than 30 min to several days. There was no significant effect of weekly dosage and no evidence that the acute therapeutic effects of VTS increased or decreased longitudinally over the 11-week study period. In addition, both 100 and 40 Hz VTS induced measurable improvements in voice quality and speech effort. Finally, participants not receiving Botulinum neurotoxin (BoNT) treatment responded to VTS and those receiving BoNT showed an additional benefit to VTS. In a follow-up longitudinal study, a cohort of 32 patients with adductor-, abductor, or mixed type of LD applied VTS at home over a period of 2 months [45]. Weekly dosage started at 3 days/week (at 20 min VTS per day applied in a single session), increased to 6 days/week by week 4, with participants following a self-selected dosage plan in weeks 5–8. Over the first 4 weeks of using VTS, 63% (20/32) of participants exhibited a reduction in speech effort in at least half their daily sessions and reduced mean PSE by 14% (range: −9%–44%). For those who responded to VTS, 18 (56%) participants exhibited a consistent immediate change in PSE every time when using VTS, while 4 (12%) demonstrated a longitudinal effect, where PSE decreased longitudinally over time. A total of 10 (31%) participants experienced no change in PSE. Over the 2-month period, 17 participants reported an improved *Voice Quality Score* with a mean increase from 2.9 (neutral) to 3.8 (noticeable). The effects of VTS lasted between 0.5–24 h in 53% and >1 day in 16% of participants.

While the above studies documented the effectiveness of repeated VTS use for people with LD, one pilot study [51] comparing voice symptomatology in adductor-type LD versus those with essential vocal tremor in a sample of 10 participants (n = 5 per group) found that a short application of VTS (7 min) did not improve CPPS or voice quality ratings assessed by naïve listeners.

In summary, there is increasing empirical evidence from clinical studies in people with CD and LD that the short-term or prolonged use of VTS can reduce dystonic symptoms in these two populations with the majority of participants (63%–85%) responding to VTS with measurable improvements as indicated by objective and subjective measures of speech and voice quality in LD and head posture in CD. For a summary of the VTS-induced effects on speech or voice quality, see Figure 4.

Adverse effects or side effects

One study by Tempel and Perlmutter (1990) reported that vibration at 130 Hz induced a dystonic cramp in the stimulated arm/hand in about half (6/11) of patients with upper limb dystonia [65]. None of the other studies that applied vibration between 80 and 100 Hz to people with blepharospasm, laryngeal dystonia, or focal hand dystonia reported adverse events [45, 52, 54, 55, 59, 60, 65]. Some participants with LD experienced mild skin irritations from taping the vibratory motors to the skin above the larynx [45].

Discussion

This systematic review summarizes empirical evidence on the effects and use of VTS in people with FD. Over the last four decades researchers applied VTS as an experimental tool to advance our understanding on the pathophysiology of the various clinical presentations of focal dystonia, and more lately, to determine its potential as a non-invasive neuromodulation method to treat dystonic symptoms.

VTS as a method to manipulate or augment somatosensory input

Abnormalities in somatosensory function affecting the central processing of tactile, proprioceptive and nociceptive afferent signals have long been recognized in patients with focal dystonias [17]. In addition, many people affected by FD apply some form of sensory trick by touching the skin over dystonic body regions to alleviate symptoms indicating that the underlying physiology is susceptible to the manipulation of somatosensory inputs [70, 71]. The pioneering early work reviewed here focused on using VTS as a form of controlled somatosensory input and mostly applied short bursts of VTS. This research obtained a range of neurophysiological parameters to determine VTS response differences of people with FD compared to healthy controls or between different phenotypes of FD.

Using positron emission tomography to measure cerebral blood flow showed that VTS produced a consistently localized and robust peak response in primary sensorimotor cortex contralateral to hand vibration in healthy participants, but this response was reduced in patients with unilateral dystonia [65], writer's cramp [66] and blepharospasm [52]. Moreover, regardless of whether the vibration was applied to the affected or unaffected side, the studies showed a reduction in cerebral blood flow in both ipsilateral and contralateral primary sensorimotor cortex. This research established for the first time that cortical processing of mechanical vibration signals is affected in FD.

Subsequently, TMS-based studies reported that MEP-derived markers indicating intracortical inhibition and/or facilitation (ICF) are altered in FD. For example, in healthy musicians and non-musicians, VTS decreased short-interval cortical inhibition (SICI) in the vibrated muscle increased in the non-vibrated hand muscles. In contrast, VTS strongly reduced SICI and ICF in all hand muscles in people with MD [60, 61] but had little effect on cortical excitability in task-specific upper limb dystonia [61, 62]. Applying VTS to non-dystonic forearm extensor muscles in people with CD significantly increased ICF compared to healthy controls [64] (see Figure 3). This

body of research corroborated previous evidence by showing that people with FD respond to VTS, but the MEPs of the target muscles, their synergists or antagonists is reduced or altered when compared to the MEPs of healthy controls. This is important, because it means that the cortical and myoelectric response to VTS is not restricted to the vibrated dystonic or non-dystonic muscle, but that the underlying functional muscle synergies are modulated by VTS. It further suggests that VTS-induced changes in cortical function extend beyond the projection areas of the clinically affected dystonic muscles.

Another complementary set of studies investigating the effects of VTS on postural and force control demonstrated that force control of dystonic muscles is impaired, but that VTS can modulate force control in people with FD [47–50, 57, 63] (see Figure 2). Importantly, its effect depends on which muscle groups are stimulated (e.g., non-dystonic vs. dystonic), again underlining the notion that VTS affects synergistic muscle control. In addition, the fact that VTS of dystonic neck muscles has no or only minor effects on whole body postural control indicates that VTS effects are regional and not generalized.

Given that the application of sensory tricks to alleviate symptoms and the increasing empirical evidence that FD is associated with deficits in somatosensory processing, there has been an interest in understanding whether people with a sensory trick react differently to VTS than those without it. One study reported that for CD patients who could apply a successful sensory trick, neck muscle VTS vibration led to an initial forward sway of the body that slowly increased during prolonged vibration [49]. In contrast, for patients without a sensory trick, the initial sagittal sway was significantly reduced and the slow increase in forward sway was absent [49]. In addition, neck vibration improved backward head tilt in CD patients, particularly those with sensory tricks (see Figure 3). However, two larger sample clinical trials found that the use of an effective sensory trick did not clearly differentiate between responders and non-responders to VTS and the effect on perceived pain and head righting in CD [46, 67]. Thus, current empirical evidence shows that the presence of an effective sensory trick is associated with a higher susceptibility to somatosensory stimulation (e.g., as a signal to regulate body posture), but such susceptibility does not automatically translate to larger or more effective dystonic symptom relief. Yet, one also needs to recognize that the available evidence is limited. No clinical trials have systematically investigated the efficacy of VTS as a function of the presence or absence of a sensory trick.

VTS as a non-invasive intervention to treat dystonic symptoms

A set of phase 1 and phase 2 clinical trials examined the effectiveness and response rates to VTS in a combined sample of 194 participants with CD and LD [45, 46, 54, 55, 59, 67]. These studies applied VTS over longer periods (up 45 min per session) in a single session with two trials examining VTS effects longitudinally for up to 2 months [45, 55]. Depending on the outcome measure, between 57% and 85% of participants responded to VTS and exhibited improvements in voice and speech quality, in head posture and/or reductions in pain. In approximately 40% of CD participants, 3D head posture and/or pain levels acutely improved by 50% or higher [46, 67]. The studies on people with LD demonstrated that typical voice and speech symptoms such as voice breaks, prolonged speech or reduced loudness can be ameliorated by VTS [54, 55, 59] (see Figure 4). However, a recent pilot study reported that a short 7-min application of VTS did not induce reductions in voice and speech symptoms in LD participants [51], indicating that short-duration VTS may be not or less effective than longer applications exceeding 20 min or more.

A cortical correlate to the observed symptoms in CD and LD is the excessive synchronization of motor cortical neurons [54, 72]. The empirical evidence reviewed here indicates that the effect of VTS on cortical oscillatory activity over somatosensory and premotor cortex is an almost immediate suppression of low-frequency oscillations, which reduces the excessive somatosensory-motor cortical activity and corresponds to the observed fast occurring behavioral changes such as increased loudness of voice, reduced number of voice breaks and sentence durations [54, 59]. Invasive neuromodulation techniques, such as deep brain stimulation, attempt to normalize the irregular neuronal discharge patterns by applying high-frequency impulses to targeted subcortical nuclei [73] with the aim to restore the activity of upstream motor cortical networks. The results from the reviewed studies as well recent recordings from basal ganglia output nuclei showing that neck muscle VTS normalized firing of neck-sensitive neurons in globus pallidus internus [74] indicate that non-invasive high-frequency peripheral stimulation via VTS may modulate the discharge patterns of neurons in the somatosensory-motor network in a similar way.

There is inconclusive evidence on the long-term effects of VTS on dystonic symptoms. In two longitudinal studies, participants with LD applied VTS at home for up to 2 months [45, 55]. They confirmed that the repeated use of laryngeal VTS was safe and feasible at home. The majority of responders to VTS showed a consistent, repeatable response over weeks to a daily 20-minute application of VTS with approximately 20% of those reporting that overall speech effort decreased slowly over the 2-month period [45]. From a clinical and patient perspective, it is important to know for how long a VTS will last. Based on the available research reviewed here, the therapeutic effects after 20–45 min of VTS vary widely from less than 30 min to several days.

Limitations

Several important limitations should be considered when interpreting the findings of this review. First, the applied VTS

protocols and the reported outcome measures varied largely across studies. This limited the interpretation of the evidence, because it was not possible to perform a rigorous meta-analysis. Second, most studies had relatively small sample sizes and besides a single study [55], no randomized clinical trials are yet available. Third, few studies considered the influence of confounding variables in clinical characteristics (e.g., disease duration, BoNT injection history) on VTS effects. Fourth, no fully sham-controlled randomized clinical trials have been conducted. While the available neurophysiological evidence on the afferent pathways and the brain areas activated by VTS is inconsistent with an unspecific placebo response, one cannot exclude the possibility that, at least in a subset of participants, the observed symptom reductions were due to a placebo effect. In addition, the evidence of VTS-induced symptom relief was also based on objective markers (e.g., head righting in CD, CPPS in LD), which is also inconsistent with a placebo response. Lastly, most studies examined the short-term effects of VTS, and the long-term results of VTS in patients with dystonia are unknown and an effective protocol cannot yet be recommended. At present, two longitudinal studies [45, 55] showed that people with LD may receive consistent, repeatable symptom relief over time with some showing an increased magnitude of symptom relief over time.

Conclusion

This review documents a long line of research spanning over nearly four decades that applied VTS to various presentations of FD. What have we learnt from this research and how can it be applied to clinical practice? In summary, there is converging evidence that VTS to dystonic regions can provide temporary symptom relief of varying duration for people affected with FD. There is no evidence that one form of FD is more susceptible to VTS compared to others–VTS has been applied to numerous subtypes of FD and they mostly showed a measurable, repeatable response based on the reviewed neurophysiological and behavioral data (see Figures 2, 3). While the reported response rates are high, indicating that well over half of FD patients may benefit from VTS, there is no clear understanding what determines the susceptibility to VTS in FD. Moreover, most studies applied VTS in a single session and, depending on the reported outcome measures, approximately 15%–42% of FD participants did not respond to a single dose of VTS. Yet, there is initial evidence that continued VTS use over weeks reduces overall symptoms severity in people with LD [45]. Nevertheless, there is still a paucity of longitudinal data on the effects of VTS on dystonic symptoms.

From a clinical perspective one needs to ask whether VTS is a practical strategy to manage patients with dystonia. Why is VTS still not an established treatment for FD? Part of the reason why VTS was not employed earlier stems from the fact that earlier vibration technology was too heavy, too cumbersome and not wearable. Today small vibrators with enough vibration amplitude and a variable range of frequencies are available to build wearable VTS devices for clinical and in-home use. From a practical perspective, there is initial evidence available from two longitudinal studies [45, 55] that one significant advantage of VTS is that it can be easily and safely applied at home. Adverse events due to VTS appear to be rare, with only one study reporting that VTS induced dystonic cramps in patients with unilateral dystonia [65]. Research has already documented that direct skin contact of the vibrators is not necessary to be effective [45]. Thus, wearable VTS devices in the form of collars (see Figure 7B) or arm braces that are rechargeable and wirelessly controlled are a realistic scenario for future use.

What is the path forward? Besides advancing wearable vibration technology, the next necessary steps are the following: First, to delineate the VTS-induced changes in somatosensory-motor networks affected by FD, such as determining short-term and long-term plasticity due to VTS in cortical as well as subcortical regions of the network. This work would further solidify the neurophysiological basis for any future VTS therapy and address the criticism that VTS is mainly a placebo treatment. Second, to conduct rigorous randomized clinical trials to establish treatment efficacy against various sham conditions or other non-invasive treatments (e.g., acupuncture, transcranial magnetic stimulation). These studies would further address the issue of VTS as a placebo treatment. Third, to conduct the necessary clinical trials to determine the optimal VTS frequency, amplitude, duration, number of sessions, and relevant body parts to be stimulated for the various FD subtypes. This work will establish guidelines for the standardization of VTS therapy for treating FD.

In closing, the current empirical knowledge on VTS as a possible non-invasive neuromodulation treatment for FD is incomplete but the present results document that VTS has the potential to reduce dystonic symptoms in people with FD. Given the current limited treatment options for people with FD, VTS could enlarge the available therapeutic arsenal.

Ethics statement

Written informed consent was obtained from the individuals for the publication of any potentially identifiable images or data included in this article.

Author contributions

JK: Project conception, project execution, manuscript writing and review, tables and figures compilation; CO: Project

conception, writing of the first draft, manuscript review, data collection, tables compilation; SR: Manuscript writing and review, data collection; SA: Manuscript review, tables and figures compilation. All authors contributed to the article and approved the submitted version.

Funding

The author(s) declared that financial support was received for this work and/or its publication. CO was supported by the 2219-International Post-Doctoral Research Grant Program of the Scientific and Technological Research Council of Türkiye. JK was supported by a grant from Dysphonia International.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontierspartnerships.org/articles/10.3389/dyst.2026.15695/full#supplementary-material

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