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REVIEW ARTICLE

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Effect of upper limb focal muscle vibration on cortical activity: A systematic review with a focus on primary motor cortex

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Abstract

This systematic review aimed to investigate the effects of upper extremity focal muscle vibration (FMV) on cortical activity. A systematic literature search was conducted for articles published in English in the SCOPUS, PEDro, PUBMED, REHABDATA, MEDLINE, and Web of Science databases. Eighteen studies (6 controlled and 12 experimental studies) were included in the systematic review. A total of 264 individuals (20 to 68 years) participated in the studies. The outcome of this review showed that FMV might have contradictory effects on cortical areas: (a) Reduction of cortical activity in the primary motor cortex (M1) and somatosensory cortex (S1), (b) no changes in the cortical activity of M1, and (c) increased cortical activity of M1 and S1. These effects may depend on different factors such as frequency and amplitude of FMV, vibration exposure time, and muscle status. However, no single factor can definitely be accounted for the variance.

KEYWORDS

corticospinal excitability, motor cortex, somatosensory cortex, vibration

Abbreviations: AF, afferent facilitation; APB, abductor pollicis brevis; BBAP, beta band absolute power; Con, control group; CSP, cortical silent period; ECR, m. extensor carpi radialis; EEG, electroencephalogram; Exp, experimental group; FC, functional connectivity; FCR, m. flexor carpi radialis; FDI, first dorsal interosseous; fMRI, functional magnetic resonance imaging; FMV, focal muscle vibration; ICF, intracortical facilitation; ICI, intracortical inhibition; LAI, long-latency afferent inhibition; M1, primary motor cortex; MEP, motor evoked potentials; MRPD, alpha motor-related power desynchronization; MT, motor threshold; NA, not applicable; NIH, National Institutes of Health; NR, not reported; PET, positron emission tomography; PMcx, premotor cortex; rCBF, changes in the regional blood flow; RMT, resting motor threshold; S1, primary somatosensory cortex; S2, secondary somatosensory cortex; SAI, short-latency afferent inhibition; SICI, short intracortical inhibition; SMA, supplementary motor area; TMS, transcranial magnetic stimulation; UE, upper extremity.

1 | INTRODUCTION

Vibration as an intervention method in rehabilitation programs for improving function and neuroplasticity continues to gain popularity (Lai et al., 2018). Focal muscle vibration (FMV) is a technique in which a vibratory stimulus is delivered to a muscle belly or a tendon via a mechanical device (Alashram et al., 2019). Physiologically, vibration applied to a muscle induces the firing of Ia afferent fibres, which leads to an increased representation of the vibrated muscle at the cortical level (Li, Li, Xu, & Ji, 2019).

Whereas a large body of research focused on the effect of FMV on behavioural outcomes such as motor performance, a small number of studies targeted the effects of FMV on cortical activity. Even though the curiosity on this topic was started as early as the 1900s and FMV has been used in the rehabilitation programs for many years for varied purposes (Lai et al., 2018), there is still no consensus on its effects on cortical activity. Furthermore, the optimal FMV application parameters such as frequency, time, amplitude, duration, and so forth for robust results are still unknown.

In fact, ambiguity better defines the current state of the topic, rather than a consensus. For instance; recent studies by Miyara et al. (2021) and Barss et al. (2021) reported that a 30 Hz FMV may lead to both central and peripheral inhibition and therefore could be used for decreasing the spasticity. On the other hand, Solopova et al. (2018) reported that an increase in the motor evoked potentials (MEP) following a 40–60 Hz vibration suggests a cortical excitation. Nevertheless, there has not been any systematic review published to date summarizing these conflicting findings.

In this study, we aimed to review the effects of upper extremity FMV on cortical activity, specifically on the primary motor cortex (M1), and the potential factors that may affect the outcomes.

2 | MATERIALS AND METHODS

This systematic review was conducted following the steps defined by Tawfik et al. (2019). Unfortunately, the authors were unable to register the study in a public registry.

2.1 | Search strategy

A systematic literature search was conducted for articles published in English in the following databases: SCOPUS, PEDro, PUBMED, REHABDATA, MEDLINE, and Web of Science. A manual search for the relevant literature was also performed for a more thorough review. The keywords that were included in the database search were "muscle vibration," "vibration," "cortical activity," and "cortex." The literature search was performed in May 2021, and no time limit was imposed on the date of publication. Additionally, due to the lack of randomized clinical trials on the topic, no restriction on the study design was applied.

2.2 | Study selection criteria

This systematic review includes articles if they were (a) published as a full text in the English language, (b) used FMV in the upper extremity, and (c) assessed cortical activity. We have excluded any studies with (a) samples consisting of populations other than healthy adults (i.e., animals, children, or any specific disease), (b) vibration modalities other than FMV (such as skin vibration, whole-body vibration, etc.), (c) vibration in combination with other modalities (e.g., peripheral or central stimulation), and (d) imprecise vibration frequency such as imperceptible vibration or random frequency vibration. The skin vibration was not included in the review because it produces different spatial excitability patterns than the muscle or tendon vibration (Smith et al., 2013). We have also not included case reports or case series in this review.

2.3 | Quality assessment

Two of the authors (B.E.H. and Z.B.) independently reviewed the studies with control groups (i.e. randomized or non-randomized studies) using the 14 item National Institutes of Health (NIH) Quality Assessment of Controlled Intervention Studies tool (National Institutes of Health, 2013) to determine whether the study was described as randomized, used random sequence generation, concealed allocation, blinding was used, participants had similar baseline characteristics, the overall dropout rate was <20%, high adherence to the treatment protocol was present, similar background treatments received by all participants, valid and reliable outcome measurements was used, the study achieved 80% power, outcomes were identified before analysis, and intention to treat analysis done or not (National Institutes of Health, 2013). Studies without a control group (i.e., before–after studies) were assessed using the 12 item National Institutes of Health (NIH) Quality Assessment Tool for Before-After (Pre-Post) Studies With No Control Group (National Institutes of Health, 2013) to assess whether the study question was clearly stated, eligibility criteria were described, study participants represented the population of interest, the sample size was adequate, intervention delivered consistently, valid and reliable outcome measurements were used, blinding was used, the dropout rate was <20%, the changes in outcome measures were tested before–after and p values reported, use an

TABLE 1 Characteristics of the participants and study design

Study	Characteristics of participants	Parameters	Experiment design
Rosenkranz et al., 2003	Participants: $n = 10$ Gender (F/M): 6/4 Age: 23–27 years Dominant UE: NR	Tested UE: Right Frequency: 80 Hz Amplitude: 0.5 mm Rest interval: 3 s	Target muscle: FCR – muscle belly Status of the muscle: Relaxed Exp: Trains of stimuli in single session Con: Trains of stimuli single session
de Moraes Silva et al., 2015	Participants: $n = 30$ Gender (F/M): 16/14 Age: 22.7 years Dominant UE: Right	Tested UE: Right Frequency: 56 Hz Amplitude: 1.8 mm Rest interval: NA	Target muscle: Hand and forearm muscles Status of the muscle: Relaxed Exp: Single session FMV × 15 min Con: Single session FMV × 15 min
Binder et al., 2009	Participants: $n = 17$ Gender (F/M): 9/8 Age: 39 ± 6.9 years Dominant UE: Right	Tested UE: Right Frequency: 60 Hz Amplitude: NR Rest interval: NA	Target muscle: ECR – muscle-tendon junction Status of the muscle: Relaxed Exp: Single FMV session × 5 s Con: Single FMV session × 5 s
Lopez et al., 2017	Participants: $n = 20$ Gender (F/M): 4/16 Age: 25.2 years Dominant UE: NR	Tested UE: Right Frequency: 100 Hz Amplitude: 0.3 mm Rest interval: NA	Target muscle: FCR – muscle belly Status of the muscle: Contracted Exp: 3 trains of FMV × 10 min Con: Sham FMV × 10 min
Marconi et al., 2008	Participants: $n = 26$ Gender (F/M): 11/15 Age: 35.1 ± 10.1 years Dominant UE: Right	Tested UE: Right Frequency: 100 Hz Amplitude:0.05–0.1 mm Rest interval: NR	Target muscle: FCR – muscle belly Status of the muscle: Contracted and relaxed Exp: FMV × 10 min/3 session per day × 3 days. Con: Sham FMV × 10 min/3 sessions per day × 3 days
Li, Li, Xiang, et al., 2019	Participants: 10 Gender (F/M): NR Age: 36 ± 11.8 years Dominant UE: NR	Tested UE: Right Frequency: 75 Hz Amplitude: 1.2 mm Rest interval: NA	Target muscle: Biceps – muscle belly Status of the muscle: Relaxed Exp: 3 trains of FMV × 3 min Con: Sham FMV × 3 min
Rosenkranz & Rothwell, 2003	Participants: $n = 14$ Gender (F/M): 6/8 Age: 26–48 years Dominant UE: NR	Tested UE: Right Frequency: 80 Hz Amplitude: 0.5 mm Rest interval: 1.5 s	Target muscle: FDI – muscle belly Status of the muscle: Relaxed Exp: Trains of stimuli × single session Con: NA
Rosenkranz & Rothwell, 2006	Participants: $n = 6$ Gender (F/M): 2/4 Age: 30–48 years Dominant UE: Right	Tested UE: Right Frequency: 80 Hz Amplitude: 0.2–0.5 mm Rest interval: 2 s	Target muscle: FDI – muscle belly Status of the muscle: Relaxed Exp: FMV × 15 min Con: NA
Smith & Brouwer, 2005	Participants: $n = 16$ Gender (F/M): 9/7 Age: 23–42 years Dominant UE: NR	Tested UE: Right Frequency: 100 Hz Amplitude: 0.5 mm Rest interval: NA	Target muscle: ECR – muscle belly Status of the muscle: Relaxed Exp: FMV × 15 min or 30 min Con: NA
Kossev et al., 2001	Participants: $n = 10$ Gender (F/M): 5/5 Age: 25–48 years Dominant UE: Right	Tested UE: Right Frequency: 80 Hz Amplitude: 0.5 mm Rest interval: 12–22 s	Target muscle: ECR – NR Status of the muscle: NR Exp: Trains of FMV × 4 s Con: NA
Radovanovic et al., 2002	Participants: $n = 12$ Gender (F/M): 0/12 Age: 23.5 ± 7 years Dominant UE: Right	Tested UE: Left Frequency: 70–80 Hz vs. 20–50 Hz Amplitude: 0.2–2 mm Rest interval: NA	Target muscle: Biceps and Triceps – Tendons Status of the muscle: Relaxed Exp: FMV × 1.5 min Con: NA

(Continues)

TABLE 1 (Continued)

Study	Characteristics of participants	Parameters	Experiment design
Duclos et al., 2007	Participants: $n = 11$ Gender (F/M): 6/5 Age: 33 years Dominant UE: NR	Tested UE: Right Frequency: 80 Hz Amplitude: NR Rest interval: 20 s	Target muscle: Wrist extensors – tendons Status of the muscle: Relaxed Exp: Trains of stimuli × 0.5 min Con: NA
Mancheva et al., 2014	Participants: $n = 19$ Gender (F/M): NR Age: 36.7 ± 9.8 years Dominant UE: Right	Tested UE: Right Frequency: 80 Hz Amplitude:0.5 mm Rest interval: 12–22 s	Target muscle: ECR – NR Status of the muscle: NR Exp: FMV × 4 s Con: NA
Lapole & Tindel, 2015	Participants: $n = 10$ Gender (F/M): 2/8 Age: 27 ± 9 years Dominant UE: NR	Tested UE: Left Frequency: 80 Hz Amplitude:0.8–1 mm Rest interval: NA	Target muscle: APB – muscle belly Status of the muscle: Relaxed Exp: FMV × 15 min Con: NA
Li, Li, Xu, et al., 2019	Participants: $n = 20$ Gender (F/M): 0/20 Age: 26 ± 0.6 years Dominant UE: Right	Tested UE: Left Frequency: 75 Hz Amplitude: 1.2 mm Rest interval: NA	Target muscle: Biceps – muscle belly Status of the muscle: Relaxed Exp: FMV × 3 min Con: NA
Siggelkow et al., 1999	Participants: $n = 10$ Gender (F/M): 4/6 Age: 20–29 years Dominant UE: NR	Tested UE: Right Frequency: 80 vs. 120 vs. 160 Hz Amplitude: 0.5 mm Rest interval: 12–22 s	Target muscle: ECR – NR Status of the muscle: Relaxed Exp: FMV × 4 s Con: NA
Solopova et al., 2018	Participants: $n = 13$ Gender (F/M): 2/11 Age: 20–68 years Dominant UE: NR	Tested UE: Left and right Frequency: 40–60 Hz Amplitude: 0.8 mm Rest interval: NA	Target muscle: Biceps, triceps, deltoid anterior and posterior – NR Status of the muscle: Relaxed Exp: FMV × NR Con: NA
Steyvers et al., 2003	Participants: $n = 10$ Gender (F/M): 6/4 Age: 21 ± 1.32 years Dominant UE: Right	Tested UE: Right Frequency: 20 Hz vs. 75 Hz vs. 120 Hz Amplitude: 0.5 mm Rest interval: NA	Target muscle: FCR – tendon Status of the muscle: Relaxed Exp: FMV × 15 s Con: NA

Abbreviations: Con, control group; ECR, extensor carpi radialis; Exp, experimental group; FCR, flexor carpi radialis; FDI, first dorsal interosseus; FMV, focal muscle vibration; NA, not applicable; NR, not reported; UE, upper extremity.

interrupted time-series design and whether the intervention was conducted at a group level (National Institutes of Health, 2013). Any disagreement is resolved through a discussion with the third author (E.N.K.).

2.4 | Data extraction

One author extracted the data (E.N.K.), and then another author (B.E.H.) checked and confirmed the accuracy of the extraction. Any disagreement is resolved through a discussion with the third author (Z.B.). The parameters extracted from the studies were included (a) study information (year, sample size, and study design), (b) demographics (age, gender, dominant side, and application side), and (c) application-specific parameters (targeted muscle, application area, device and apparatus, status of the muscle and vibration parameters – frequency, duration, and interval), (d) outcome measures and assessment periods, and (e) results and reported effects. All the parameters are presented in Table 1.

2.5 | Outcome measurement

Due to the main goal of this study, we have only focused on the cortical activity differences after a muscle vibration in the upper extremity. Results of activities in different cortical areas such as M1, the primary somatosensory cortex (S1), or secondary somatosensory cortex (S2) that explored using various imaging methods such as functional magnetic resonance imaging (fMRI), electroencephalogram (EEG), and transcranial magnetic stimulation (TMS) were noted. Even if additional outcomes were included in the studies, those were not considered for this systematic review.

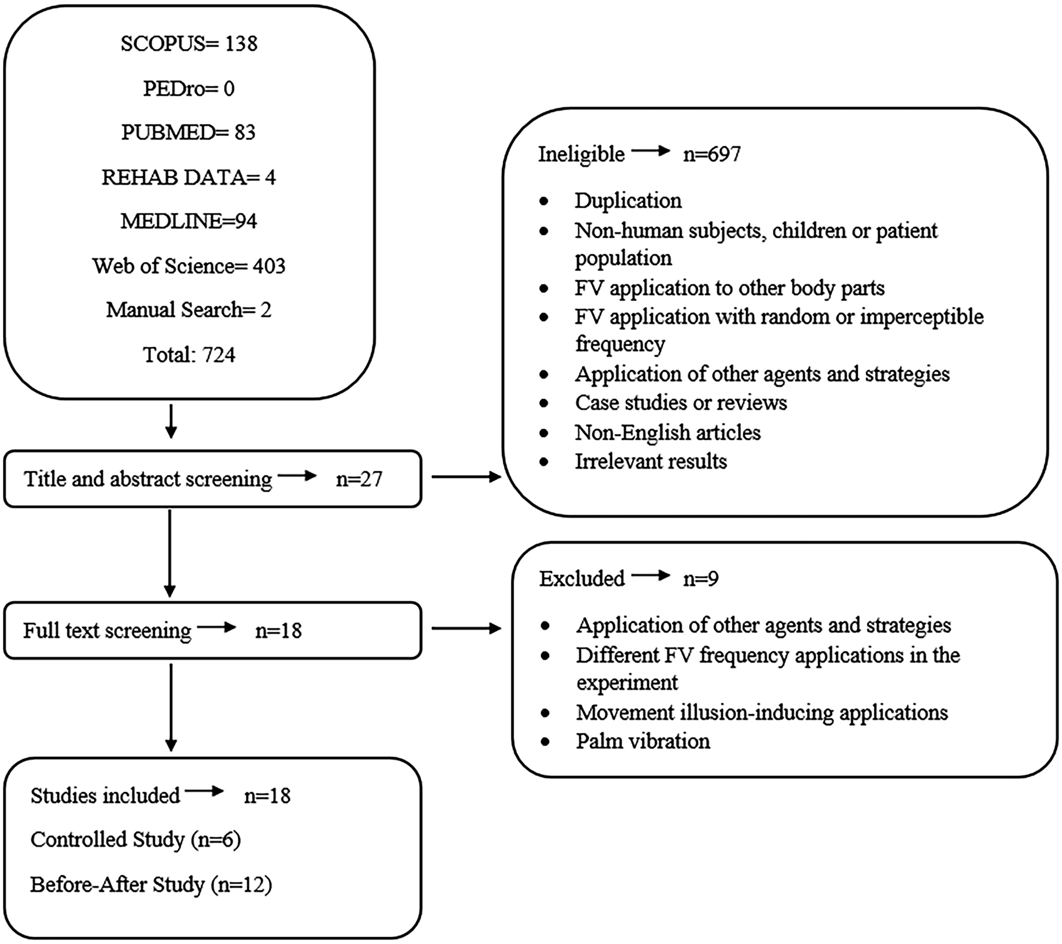

FIGURE 1 Study diagram

3 | RESULTS

3.1 | Study selection

A summary of the search results is presented in Figure 1, and detailed information is provided in Material S1. The studies included in the systematic review ranged from the years 1999–2019.

3.2 | Study designs

Six studies were designed as controlled (randomized or pseudo-randomized) (Binder et al., 2009; de Moraes Silva et al., 2015; Li, Li, Xiang, et al., 2019; Lopez et al., 2017; Marconi et al., 2008; Rosenkranz et al., 2003) whereas 12 studies were before–after (pre–post) experimental trials with no control group (Duclos et al., 2007; Kossev et al., 2001; Lapole & Tindel, 2015; Li, Li, Xu, & Ji, 2019; Mancheva et al., 2014; Radovanovic et al., 2002; Rosenkranz & Rothwell, 2003, 2006; Siggelkow et al., 1999; Smith & Brouwer, 2005; Solopova et al., 2018; Steyvers et al., 2003). The control conditions varied between the studies. For example, the control experiment was a posteriorly directed current induced by TMS in one study (Rosenkranz et al., 2003). In another study (Binder et al., 2009), the control condition was the vibration of dorsal phalanges instead of upper extremity muscles. The other four studies set up the control experiments with no vibration (de Moraes Silva et al., 2015; Li, Li, Xiang, et al., 2019; Lopez et al., 2017; Marconi et al., 2008). FMV was applied to m. biceps brachii (Li, Li, Xiang, et al., 2019; Li, Li, Xu, & Ji, 2019; Radovanovic et al., 2002; Solopova et al., 2018), m. triceps brachii (Radovanovic et al., 2002; Solopova et al., 2018), wrist extensors (Duclos et al., 2007), m. extensor carpi radialis (ECR) (Binder et al., 2009; Kossev et al., 2001; Mancheva et al., 2014; Smith & Brouwer, 2005), m. flexor carpi radialis (FCR) (Lopez et al., 2015; Marconi et al., 2008; Rosenkranz et al., 2003), first dorsal interosseous (FDI) (Rosenkranz & Rothwell, 2003), and abductor pollicis brevis (APB) (Lapole & Tindel, 2015). The vibration frequency ranged from 20 Hz to 100 Hz. The duration of the FMV also ranged from 4 s to 30 min. In terms of the frequency of application, only Marconi et al. (2008) applied FMV for three sessions a day for three consecutive days (nine sessions). Other studies were performed in a single session. The summary of the study designs is demonstrated in Table 1.

TABLE 2 Methodological quality assessment of before–after studies

Study	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Item 12	Quality
Rosenkranz & Rothwell, 2003	Yes	No	Yes	NR	NR	Yes	Yes	NR	Yes	Yes	No	Yes	Good
Rosenkranz & Rothwell, 2006	Yes	No	Yes	NR	NR	Yes	Yes	NR	Yes	Yes	No	Yes	Good
Smith & Brouwer, 2005	Yes	Yes	Yes	CD	Yes	Yes	Yes	NR	NA	Yes	No	Yes	Good
Kossev et al., 2001	Yes	No	Yes	NR	NR	Yes	Yes	NR	NA	Yes	No	No	Fair
Radovanovic et al., 2002	Yes	Yes	Yes	No	NR	Yes	Yes	NR	NA	Yes	No	NA	Fair
Duclos et al., 2007	Yes	No	Yes	No	NR	Yes	Yes	No	NA	Yes	No	Yes	Fair
Mancheva et al., 2014	Yes	No	Yes	NR	NR	Yes	Yes	NR	NA	Yes	No	Yes	Fair
Lapole & Tindel, 2015	Yes	No	Yes	NR	NR	Yes	Yes	NR	NA	Yes	No	No	Fair
Li, Li, Xu, & Ji, 2019	Yes	No	No	NR	NR	Yes	Yes	NR	NA	Yes	No	Yes	Fair
Siggelkow et al., 1999	Yes	No	Yes	NR	NR	Yes	Yes	NR	NA	Yes	No	No	Poor
Solopova et al., 2018	Yes	Yes	Yes	NR	NR	No	Yes	NR	Yes	Yes	No	No	Good
Steyvers et al., 2003	Yes	Yes	Yes	NR	NR	Yes	Yes	No	Yes	Yes	No	No	Good

Abbreviations: CD, cannot determine; NA, not applicable; NR, not reported.

3.3 | Characteristics of the participants

A total of 264 individuals were included in the studies included in this review. One hundred forty-seven of the participants were males and 88 were females; however, two studies did not report the gender distribution of their study population (Li, Li, Xiang, et al., 2019; Mancheva et al., 2014). The age range of the participants was from 22 to 68 years. In eight studies (de Moraes Silva et al., 2015; Kossev et al., 2001; Li, Li, Xu, & Ji, 2019; Mancheva et al., 2014; Marconi et al., 2008; Radovanovic et al., 2002; Rosenkranz & Rothwell, 2006; Steyvers et al., 2003), participants were reportedly right-handed. Table 1 summarizes the characteristics of the study participants.

3.4 | Quality of the studies

Table 2 and Table 3 display the results of the quality assessment. Included studies demonstrated poor to good quality. However, the studies were subject to some level of bias due to a lack of sample size calculation and operator/participant blinding.

3.5 | Outcome measures

Four studies (de Moraes Silva et al., 2015; Li, Li, Xiang, et al., 2019; Li, Li, Xu, & Ji, 2019; Lopez et al., 2017) had used EEG (alpha or beta band absolute power movement-related desynchronization and functional connectivity) for the assessment of the effect of the FMV. Twelve studies (Binder et al., 2009; Kossev et al., 2001; Lapole & Tindel, 2015; Mancheva et al., 2014; Marconi et al., 2008; Rosenkranz et al., 2003; Rosenkranz & Rothwell, 2003, 2006; Siggelkow et al., 1999; Smith & Brouwer, 2005; Solopova et al., 2018; Steyvers et al., 2003) investigated the effects of FMV by using TMS (motor evoked potentials, motor thresholds, short intracortical inhibition-SICI, intracortical facilitation, afferent inhibition, afferent facilitation, silent period, map area, and map volume). Only one study (Radovanovic et al., 2002) used positron emission tomography (PET) (cortical activity), whereas another study (Duclos et al., 2007) used fMRI (BOLD-signal) to assess the FMV effects. The details of the outcome measures were listed in Table 4.

3.6 | Effect of FMV on cortical activity

The effect of FMV on cortical activity is presented in Table 4. The methodologies and outcome measures as

TABLE 3 Methodological quality assessment of controlled studies

Study	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Item 12	Item 13	Item 14	Quality
Rosenkranz et al., 2003	No	No	No	NR	NR	NR	Yes	Yes	Yes	NA	Yes	NR	No	Yes	Poor
de Moraes Silva et al., 2015	Yes	Yes	NR	NR	NR	No	Yes	Yes	Yes	NA	Yes	No	Yes	Yes	Good
Binder et al., 2009	No	CD	No	NR	NR	NR	Yes	Yes	Yes	NA	Yes	No	Yes	Yes	Fair
Lopez et al., 2017	No	Yes	NR	NR	NR	Yes	Yes	Yes	Yes	NA	Yes	No	Yes	Yes	Good
Marconi et al., 2008	Yes	CD	NR	NR	NR	NR	Yes	Yes	Yes	NA	Yes	NR	Yes	Yes	Fair
Li, Li, Xiang, et al., 2019	No	NA	No	NR	NR	NR	Yes	Yes	Yes	No	Yes	No	Yes	NA	Poor

Abbreviations: CD, cannot determine; NA, not applicable; NR, not reported.

well as the results vary among the studies. Nonetheless, this systematic review revealed that there might be three different outcomes of FMV on the primary motor cortex (M1). The first outcome was the reduction of activity in the M1, which was demonstrated by two studies (Li, Li, Xu, & Ji, 2019; Marconi et al., 2008). However, Marconi et al. (2008) stated that there were no changes in some parameters such as resting motor threshold (RMT), intracortical facilitation (ICF), and map areas following FMV with contraction. Similarly, no significant change was found after FMV if performed without contraction. Second, no significant effect after FMV was reported in four studies (Lapole & Tindel, 2015; Rosenkranz & Rothwell, 2006; Siggelkow et al., 1999; Steyvers et al., 2003). However, Siggelkow et al. (1999) and Steyvers et al. (2003) reported that MEP amplitude was increased *during* vibration. It is also worth noting that Lapole and Tindel (2015) reported that four individuals in the experiment responded to the FMV (responders) and FMV induced significant changes in responders compared to non-responders. Interestingly, Smith and Brouwer (2005) reported no significant change in the corticospinal excitability of M1 (i.e., MEP) and the area of corticospinal excitability following a 30 min FMV. The remaining studies found a significant increase in the M1 activity (Binder et al., 2009; de Moraes Silva et al., 2015; Duclos et al., 2007; Kossev et al., 2001; Li, Li, Xiang, et al., 2019; Lopez et al., 2017; Mancheva et al., 2014; Radovanovic et al., 2002; Rosenkranz et al., 2003; Rosenkranz & Rothwell, 2003; Smith & Brouwer, 2005; Solopova et al., 2018). Of note, Radovanovic et al. (2002) stated that the regional cerebral blood flow in M1 was much increased in higher frequency FMV application compared with a lower frequency. In terms of somatosensory cortices (S1 and S2), only de Moraes Silva et al. (2015) reported a decrease in S1 activity contralateral to the tested upper extremity. With regard to cortical areas, it was reported by Duclos et al. (2007) that the right cingulate cortex, putamen, supplementary motor area, and the superior temporal gyrus (i.e., auditory cortex) were activated during FMV. On the other hand, activations in the parietal areas, thalamus, and cerebellar vermis were observed after the offset of FMV.

4 | DISCUSSION

To the best of our knowledge, this is the first systematic review to investigate the effects of FMV on cortical activity, specifically on M1. The initial findings showed that FMV might have different effects on

TABLE 4 Results extracted from the studies

Study	Outcome measures	Assessment times	Findings	Reported effects: M1	S1	Other areas
Rosenkranz et al., 2003	MEP, MT, ICI and ICF	Before FMV During FMV	↑MEPs ↓ MT ↑ICF ↓ICI	↑	NA	NA
de Moraes Silva et al., 2015	BBAP	Before FMV After FMV	↑BBAP in C3, C4 and P4 ↓BBAP in P3	↑	↓	NA
Binder et al., 2009	CSP	Before FMV During FMV	=CSP of ECR ↓CSP of FCR	↑	NA	NA
Lopez et al., 2017	Alpha and Beta MRPD	Before FMV After FMV	↑MRPD of C3	↑	↑	NA
Marconi et al., 2008	RMT, map area, map volume, SICI	Before FMV After FMV 3 weeks after FMV	=RMT, ICF, and map area of FCR and EDC. ↑SICI of FCR ↓SICI of EDC ↑Map volume of FCR	↓	NA	NA
Li, Li, Xiang, et al., 2019	Beta MRPD FC	Before FMV During FMV	↑MRDP in bilateral M1-S1	↑	↑	NA
Rosenkranz & Rothwell, 2003	MEP, SICI, LICI and ICF	Before FMV During FMV	↑MEPs =ICF ↓SICI ↑LICI	↑	NA	NA
Rosenkranz & Rothwell, 2006	MEP, SICI, and sensorimotor organization	Before FMV After FMV	=MEPs =SICI ↑ sensorimotor organization	=	NA	NA
Smith & Brouwer, 2005	MEP and area of corticospinal excitability	Before FMV After FMV	For 15 min FMV: ↑MEPs ↑Area of cortical excitability	↑	NA	NA
			No changes with 30 min FMV	=	NA	NA
Kossev et al., 2001	MEP	Before FMV During FMV After FMV	During FMV: ↑MEPs ↓MEP latency No changes *after* FMV	↑	NA	NA
Radovanovic et al., 2002	rCBF	Before FMV During FMV	↑rCBF in S2 in low and high-frequency FMV ↑ rCBF in M1 in high-frequency FMV	↑	NA	↑S2
Duclos et al., 2007	BOLD-signal	Before FMV During FMV After FMV	During FMV: ↑ left S1, right cingulate cx, putamen and bilateral M1, SMA and superior temporal gyrus After FMV: ↑M1, PMcx, S1, parietal areas, cerebellar vermis, thalamus	↑	↑	↑Cingulate cx, SMA, thalamus, cerebellar vermis

(Continues)

TABLE 4 (Continued)

Study	Outcome measures	Assessment times	Findings	Reported effects M1	S1	Other areas
Mancheva et al., 2014	MEP area, SICI and ICF	Before FMV During FMV	↑MEP area ↓SICI =ICF	↑	NA	NA
Lapole & Tindel, 2015	SAI, LAI, AF	Before FMV After FMV	=SAI =LAI =AF	=	NA	NA
Li, Li, Xu, & Ji, 2019	Relative power, FC	Before FMV During FMV 2 min after FMV	↑Relative power in bilateral M1 ↓Relative power in bilateral S1 ↑FC	↓	↑	NA
Siggelkow et al., 1999	MEP	Before FMV During FMV 1 s after FMV	↑MEP amplitudes and areas *during* 80 Hz and 120 Hz FMV No changes in MEP *after* FMV	↑	NA	NA
Solopova et al., 2018	MEP	Before FMV During FMV	↑MEP	↑	NA	NA
Steyvers et al., 2003	MEP	Before FMV During FMV After FMV	↑MEP *during* 75 and 120 Hz FMV No changes in MEP *after* FMV	↑	NA	NA

Abbreviations: AF, afferent facilitation; BBAP, beta band absolute power; CSP, cortical silent period; ECR, extensor carpi radialis; EDC, extensor digitorum communis; FC, functional connectivity; FCR, flexor carpi radialis; ICF, intracortical facilitation; ICI, intracortical inhibition; LAI, long-latency afferent inhibition; MEP, motor evoked potentials; MRPD, motor-related power desynchronization; MT, motor threshold; M1, primary motor cortex; NA, not applicable; PMcx, premotor cortex; rCBF, changes in the regional blood flow; RMT, resting motor threshold; SAI, short-latency afferent inhibition; SICI, SICI, short intracortical inhibition; SMA, supplementary motor area; S1, primary sensory cortex; S2, secondary sensory cortex; ↑, increase; ↓, decrease; =, $p > 0.05$.

cortical areas. These effects can be classified into three categories:

1. Reduction of cortical activity in M1 and S1
2. No changes in the cortical activity of M1
3. Increased cortical activity of M1 and S1, as well as other areas.

In the next paragraphs, we will try to discuss the factors that may have influenced these diverse results.

4.1 | Timing of assessment

Eleven studies in this systematic review measured the after effects of vibration (de Moraes Silva et al., 2015; Duclos et al., 2007; Kossev et al., 2001; Lapole & Tindel, 2015; Li, Li, Xu, & Ji, 2019; Lopez et al., 2017; Rosenkranz & Rothwell, 2006; Siggelkow et al., 1999; Smith & Brouwer, 2005; Steyvers et al., 2003), while the rest of the studies reported the effects during vibration. The findings were ambiguous. Four studies (de Moraes Silva et al., 2015; Duclos et al., 2007; Lopez et al., 2017; Smith & Brouwer, 2005) showed that the M1 activity was increased *after* the FMV, whereas studies by Marconi et al. (2008) and Li, Li, Xu, et al. (2019) reported that the activity was diminished. The remaining studies stated that there were no changes in cortical activity *after* FMV compared to before condition (Kossev et al., 2001; Lapole & Tindel, 2015; Rosenkranz & Rothwell, 2006; Siggelkow et al., 1999; Steyvers et al., 2003).

It is well-known that FMV excites the Ia afferents from the vibrated muscle. This responsiveness of Ia afferents was decreased *after* the FMV as suggested by a recent study (Nito et al., 2021). On the other hand, two earlier studies (de Moraes Silva et al., 2015; Smith & Brouwer, 2005) included in this systematic review suggested that repeated vibratory sensorial inputs were maintained up to 30 min after FMV. The ambiguous findings of this systematic review may have originated from the varied vibration characteristics in the studies, rather than the timing of the outcome assessment. Nito et al. reported that the vibration exposure period might also be the reason for different findings in studies (Nito et al., 2021).

It is also worth noting that the common feature in the studies that reported no changes after the FMV has been the low vibration amplitude (0.2–1 mm). These findings bring us to the first factor that may influence the effects of FMV on cortical activity: Vibration frequency and amplitude.

4.2 | Vibration frequency and amplitude

Early studies on both animals and human subjects speculated that the frequency and the amplitude of the FMV would affect the outcomes. For instance, two early studies (Bishop, 1974; Cochrane, 2011) reported that high-frequency vibration (>100 Hz) elicited muscle contractions via tonic vibration reflex, whereas low-frequency vibration (2–80 Hz) caused a decrease in the muscle activation. Recent research conducted by Barss et al. (2021) reported similar findings. According to the authors, a 30 Hz palm vibration during a small contraction (i.e. approximately 10% of maximal voluntary contraction) led to significantly reduced H-reflex (by 15.7%) and middle latency cutaneous reflexes (by 20%). Additionally, no significant effect was observed in terms of corticospinal excitability. The authors concluded that the FMV inhibits cutaneous and H-reflexes via increased presynaptic inhibition of afferent transmission and resulting in no change in the corticospinal excitability. Radovanovic et al. (2002) reported that when high frequency, movement illusion inducing FMV (70–80 Hz) contrasted with low-frequency FMV (20–50 Hz), regional blood flow increase was detected in M1.

This result may be supported by the previous findings. Low-frequency MV might have led to a decrease in muscle activity, which in turn, resulted in lesser M1 activity. Additionally, two different studies included in this systematic review (Binder et al., 2009; de Moraes Silva et al., 2015) with 56 and 60 Hz frequency of FMV reported increased cortical excitability. These results may raise the question of whether the 50 Hz may be a threshold for applications of corticospinal excitability. Chung et al. (2013) also suggested that the frequency band around 50 Hz induced the most discriminative cortical activity patterns between somatosensory cortices (i.e., S1 and S2). Authors reported a frequency above 50 Hz mainly activated bilateral S2, whereas flutter stimulation (5–50 Hz) activated contralateral S1 and bilateral S2.

However, one must not forget the results of the studies by Siggelkow et al. (1999), Marconi et al. (2008), Rosenkraz and Rothwell (2006), Smith and Brouwer (2005), Lapole and Tindel (2015) and Li, Li, Xiang, et al. (2019) conducted with frequencies from 75 Hz to 100 Hz. Even though the frequencies were high in these studies, they reported either a decreased cortical activity or no change at all following FMV. However, it is worth noting that the longer vibration exposure periods were a common feature in these studies. All of these studies, except one (Li, Li, Xiang, et al., 2019) had longer vibration exposure periods (i.e., 10–30 min). This brings us to the third factor that may have influenced the results of FMV on cortical activity.

4.3 | Vibration exposure period

Smith and Brouwer (2005) reported that following 15 min of FMV led to a 33% increase in MEP size and enlarged the area of corticospinal excitability; however, no additional changes were found if FMV application was extended to 30 min.

Lopez et al. (2017) speculated that FMV might have a particular dose-dependent effect. In their research, three trains of FMV at 100 Hz and 0.3 mm in amplitude were applied for 10 min while participants were maintaining an isometric contraction at the 10% of maximal voluntary contraction. As a result, they found the first two trains of FMV increased the alpha motor-related power desynchronization (MRPD) at the contralateral C3 electrode location suggesting an increase in the activity of M1 and S1. However, the MRPD returned to the baseline following the third train of FMV. These findings may be the result of a habituation-like phenomenon which is a neurophysiological mechanism that protects neural circuits from excessive sensory input load (Lee et al., 2016).

Marconi et al. (2008) reported that motor map volume, MEPs, and SICI values for the vibrated muscle were significantly reduced following a 10 min FMV compared with baseline values. As very well-known today, there are extensive intrinsic connections within the cortical areas such as M1 and S1 in addition to the horizontal circuits that interconnect cortical regions. The important feature of these intracortical pathways is that they have an either inhibitory or excitatory effect (Mohammed & Hollis, 2018). Prolonged stimulation of somatosensory cortices (≥10 min) may activate the inhibitory intracortical pathways, which in turn may result in reduced functional activity in M1 (Marconi et al., 2008).

These results may be supported by other studies with short vibration exposure periods as well as studies with rest intervals in addition to the short vibration exposure periods. These studies reported increased cortical activity following the FMV (Binder et al., 2009; Duclos et al., 2007; Kossev et al., 2001; Mancheva et al., 2014). For example, a reduction in SICI and increased MEP area was detected following 4 s of FMV in the Mancheva et al.'s (2014) study suggesting that there might be a dose-dependent effect of FMV on cortical activity.

4.4 | Muscle status

There were only two studies in which FMV was applied over a contracted muscle in this systematic review (Lopez et al., 2015; Marconi et al., 2008). Marconi et al. (2008) proposed a decreased activity following a repeated FMV application on, contracted flexor carpi radialis muscle over a 3-day period. The authors also reported that no changes in corticospinal excitability were observed when FMV was applied over a relaxed muscle.

A review (Kilavik et al., 2013) proposed that a beta rebound (inhibition of motor network) in EEG studies may occur upon both somatosensory cortex activation or at the end of a movement. Li, Li, Xiang, et al. (2019) suggested that beta rebound may be in line with the "functional inhibition" hypothesis (Zaepffel et al., 2013). This hypothesis suggests the inhibition of motor cortical activity by somatosensory processes involved in FMV application (Zaepffel et al., 2013). However, the authors reported that even though the M1 activity was reduced, the sensorimotor organization was achieved after FMV (Li, Li, Xiang, et al., 2019).

5 | CONCLUSION

Conclusively, there was no clear effect of FMV on cortical activity. In fact, FMV application may have contradictory effects on cortical areas. Studies reported that FMV may reduce the cortical activity in M1 and S1, lead to no changes in the cortical activity of M1, or increase the cortical activity of M1 and S1, as well as other areas. These findings may be the result of various application parameters in the studies (i.e., frequency and amplitude of FMV, vibration exposure time and muscle status, etc.). The differences in the FMV application may dramatically change the effects of FMV on cortical excitability and promote a shift from facilitation to inhibition or vice versa.

However, this systematic review revealed that no single factor can be accounted for the variance. Thus, we suggest that researchers and clinicians should take into consideration the results of individual studies mentioned in this review by their application parameters when evaluating outcomes and plan a rehabilitation program accordingly, especially in neurorehabilitation.

Besides, the authors would like to underline the potential effect of experimental study designs and the poor-to-good methodological quality of studies included in this systematic review on the results. There were only two randomized-controlled studies included, and only seven studies had good methodological quality. Therefore, we recommend for future studies conduct randomized-controlled studies with a lower risk of bias on the topic, whereas investigating the potential effects of the factors mentioned in this systematic review individually.

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CONFLICT OF INTEREST

Authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Conceptualization: Esma Nur Kolbaşı, Burcu Ersöz Hüseyinsinoğlu and Zübeyir Bayraktaroğlu; Methodology: Esma Nur Kolbaşı, Burcu Ersöz Hüseyinsinoğlu and Zübeyir Bayraktaroğlu; Formal analysis and investigation: Esma Nur Kolbaşı; Writing - original draft preparation: Esma Nur Kolbaşı, Burcu Ersöz Hüseyinsinoğlu and Zübeyir Bayraktaroğlu; Writing - review and editing: Burcu Ersöz Hüseyinsinoğlu and Zübeyir Bayraktaroğlu; Supervision: Burcu Ersöz Hüseyinsinoğlu and Zübeyir Bayraktaroğlu.

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DATA AVAILABILITY STATEMENT

There are no linked data sets for this paper.

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