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Effects of vibration therapy on neuromuscular efficiency & features of the EMG signal based on endurance test

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ABSTRACT

Background: Vibration Therapy (VT) stimulate the muscle spindles, which in turn enhances its afferent activities.

Objective: The present study was designed to investigate the effect of VT at 23 and 35 Hz on muscle performance. The EMG features (six time-domain (TD) and four frequency-domain (FD)) and a new formula for computing neuromuscular performance were used as dependent variables to evaluate the effect of VT.

Method: The EMG recording was performed at 50% MVC during grip endurance test before and after VT. The EMG features were extracted out of raw EMG signals acquired from four forearm muscles, viz., flexor digitorum superficialis (FDS); flexor carpi ulnaris (FCU); extensor carpi radialis brevis (ECRB); and extensor carpi ulnaris (ECU) in supine position. Fatigue assessments were evaluated based on the pattern of TD and FD features.

Results: Statistical analysis showed a significant difference in the effect of vibration exposure frequency on IEMG ($p < 0.001$), MAV ($p = 0.041$), SSI ($p = 0.032$), and WL ($p < 0.001$) of FCU muscle. In addition, the greatest increase in neuromuscular efficiency (NME) was observed in the performance of ECRB after 35 Hz of VT and ECU muscles after 23 Hz of VT.

Conclusions: The features of EMG signals could be used for fatigue analysis. However, the slope based on the median frequency regression line may be the best feature for fatigue assessment.

1. Introduction

The vibration therapy (VT) stimulates the muscle spindles, thereby enhancing their afferent activities and thus allowing the motor units (MUs) to be synchronised, in turn resulting in the generation of more force (De Gail et al., 1966; Rittweger, 2010; Cochrane, 2011a; Souron et al., 2017). VT has been used to increase EMG, strength, flexibility, and power in various populations (Rittweger, 2010; Alam et al 2016, 2018; Morel et al., 2018; Sousa-Gonçalves et al., 2019; Paiva et al., 2019) including patients with neurological disorders (Eftekhari et al., 2012; Tankisheva et al., 2014). Many investigators have used fixed frequencies for VT: 18 Hz (Rittweger et al., 2002), 26 Hz (Bosco et al 1999b, 2000; Rittweger et al., 2003), 30 Hz (Jackson and Turner, 2003; Hazell et al., 2007; Mischi et al., 2010) and 35 Hz (Torvinen et al., 2003; Roelants et al., 2006; Fagnani et al., 2006; Rhea and Kenn, 2009; Osawa and Oguma, 2011; Di Giminiani et al., 2013; Moawd et al., 2014). However, there has been no agreement on determining the optimal vibration frequency, which has been confounded by the different protocols used in research. Vibratory massage therapy (VMT) may reduce the pressure or tension of muscles belly, which may affect the viscoelastic aspect of the muscle tissue and thus lead to an increase in force generating capability/flexibility (Weerapong et al., 2005). However, muscle fatigue is also a parameter to know about the muscle performance. Many approaches have been used to evaluate muscle fatigue: isometric strength tests; endurance tests; muscle imaging; surface electromyography (sEMG); and muscle biopsy (Greig and Jones, 2013; Cifrek et al., 2009) for comparing muscle performance before and after therapies.

Amplitude measurements and spectral parameters of EMG signal reveal variations in the sEMG signal during isometric, fatiguing and dynamic contractions; where force generating capacity varied over time (Rogers and MacIsaac, 2011). Spectral

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parameters, namely mean frequency, median frequency (Cifrek et al., 2009) and total power (Khanam and Ahmad, 2015) are widely considered as a means to continue the evolution of muscle fibre fatigue over time (De Luca, 1984). Further, while measuring sub-maximal contractions, it was found that measurements of the amplitude of EMG signal (mean absolute value (MAV) and root mean square (RMS)) increased with fatigue due to improved MUs firing rate, MUs recruitment and synchronization within muscle fibres (Lowery and O'Malley, 2003; McManus et al., 2017). Amplitude features are also used for fatigue assessment: root mean square, mean absolute value, and integrated EMG (Soylu and Arpinar-Avsar, 2010); simple square integral (Phinyomark and Phukpattaranont, 2009; Phinyomark et al., 2013); variance of EMG (Zardoshti et al., 1995; Phinyomark et al., 2013); and waveform length (Kiguchi et al., 2001; Phinyomark et al., 2013). However, the above-mentioned amplitude measures and spectral parameters may show increased inconsistency in values over time (Rogers and MacIsaac, 2011). However, due to the non-stationary nature of the surface EMG signal, an increase in these parameters were reported (Farina and Merletti, 2000). A multivariable approach to fatigue assessment has recently been recommended (Rogers and MacIsaac, 2011) and it was suggested that multiple features provide more information than anyone.

Researchers suggested that the gradual increase in EMG activity is due to the increased recruitment of additional MUs (Griffin et al., 2001; Lowery and O'Malley, 2003; Cardinale and Bosco, 2003; Cochrane, 2011b). In addition, the amount of neural energy from electrical signal directed from the central nervous system to muscle fibres is also assessed by integrated EMG (IEMG) (Enoka, 1988; Gabriel et al., 2006). Milner-Brown et al. (1986) used the term neuromuscular efficiency (NME) to evaluate the muscle performance based on Force/IEMG ratio.

The aims of the present research was to investigate the influence of vibration therapy on forearm muscle neuromuscular output and also to understand its influence on different EMG signal features. With the expected results of the study, guidelines can be introduced to help physiotherapists. Therefore, this study proposes a procedure to compare neuromuscular performance and also studies the effects of VT on muscle performance (in the form of muscle fatigue) with respect to EMG features (six time-domain (TD) and four frequency-domain (FD) features) and neuromuscular efficiency. The null hypothesis assumed for the study was as follows:

“there were no significant differences in the effects of vibrational exposure frequency on forearm muscle neuromuscular output and on different EMG signal features.”

2. Methods

2.1. Experiment design

A full factorial design (7 days × 3 levels (before vibration exposure (BVE); after vibration exposure at 23Hz; and at 35Hz) x 10 subjects) was used in the present study. The EMG features were used as dependent variables: integrated EMG (IEMG); mean absolute value (MAV); simple square integral (SSI); variance (VAR); root mean square (RMS); waveform length (WL); mean frequency (MNF); median frequency (MDF); total power (TP); slope based on regression line of median frequency (SMDF); and neuromuscular efficiency.

2.2. Experimental rig

To give VT and to record EMG activities an experimental rig was fabricated in-house to support the forearm in the supine posture (Fig. 1). The vibratory massager (Max JS113; M/s Manipol Massager Medicare Products Inc. India) was attached to the experimental rig, consisting a small D.C. motor. The vibrator had the capacity to produce a frequency ranging from 15Hz to 65Hz. The slightly curved plastic disc 5 cm in diameter was attached to the head of the massager. The grip Jammer dynamometer (Model: G100; M/s Biometrics Ltd. UK) was also attached to the rig.

2.3. Participants

Ten healthy right-handed male participants (including college students/staff) volunteered in the study, having mean age of 29.2 (S.D. ± 5.3) years, mean height of 175.4 (S.D. ± 4.5) cm, and mean weight of 72.8 (S.D. ± 7.9) kg. Participants were included if they did not report a history of hand, wrist, or forearm dysfunction and other neuromuscular problems. Participants were called from the university campus through notices, and were explained in detail about the experimental protocol and the risks (negligible chances of allergies by sticky tapes, the level of muscular fatigue etc.) involved therein. All the participants gave their written consent and examined with the help of Physician from J N Medical College, AMU, Aligarh. The protocol of the experiment was approved by the ethics committee of the department of Mechanical Engineering, AMU, Aligarh (Ref. No. EC/60/2017). Participants were also allowed to terminate the experiment at any stage, if they wished.

2.4. Protocol and procedure for the experiment

In this study, the participants were asked to sit on a fixed-height chair with the supine forearm laid horizontally on the wooden platform with an adjustable support at the wrist (Fig. 1). The height of the platform was adjusted to the postures of the elbow, shoulder, and trunk postures. The participant's upper right arm was in the coronal plane with 0° abduction ensuring an elbow angle of 90°. However, due to inconsistency in the height of some participants and the fixed chair height, shorter participants could not sit with their elbows flexed at 90°; therefore, they were allowed to further flex their forearm up to an estimated 30° (Nicolay and Walker, 2005).

The following steps were followed for the vibration exposure to forearm and for the assessment of the muscle performance:

1. Identifying the muscles for placement of EMG sensors and then marking the positions with permanent marker.
2. Attaching the EMG sensors to the selected muscles and asking the participants to squeeze the grip meter, in supine posture at the beginning of the experiment before vibration exposure (BVE) with a fixed grip span.
3. Taking initial recording of grip MVC and after 5 min of rest measuring the grip endurance time at 50% MVC (taking reference as maximum value of both trials) along with the EMG recordings (*see* sections 2.4.2 & 2*.4.3*).
4. The detaching of the EMG sensors and the grip meter.
5. Applying VT at 23 Hz frequency for a duration of 10 min (see section 2.4.1).
6. A rest period of 15 min.
7. Repeat point No. 2 & 3.
8. The detaching of EMG sensors and grip meter.
9. Applying VT at a frequency of 35 Hz for a period of 10 min (see section 2.4.1).
10. Repeat point No. 6 & 7.

2.4.1. Exposure to vibratory massage therapy (VMT)

The following steps were taken to apply VMT:

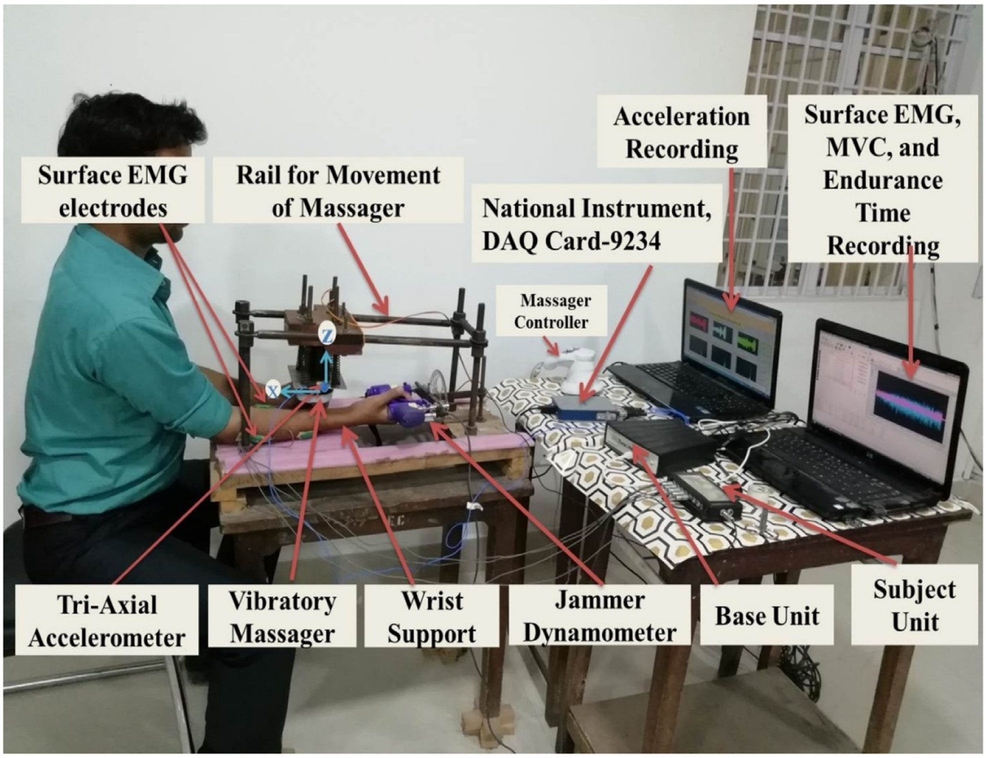

Fig. 1. Experimental rig (consisting of vibratory massager mounted vertically on the rail, hand grip Jammer dynamometer, base and data acquisition unit, sEMG electrodes placed over the forearm muscles, Tri-Accelerometer, and NI DAQ card).

1. A VMT was given for a duration of 10 min based on the usual duration of the massage therapy (Weerapong et al., 2005; Pournot et al., 2016)
2. VMT was applied directly on the flexor side of forearm muscles in supine posture, resting horizontally, as shown in Fig. 1. During the VMT ten back-and-forth movements (Eklund and Hagbarth, 1966) were given between the tip of the olecranon process to the styloid process of the ulna.
3. A small amount of mustard oil (M/s: Fortune mustard oil, Adani Wilmar Ltd., India) was placed on the skin of the forearm to reduce the friction and heat produced between the head of the massager and the skin.

2.4.2. Grip MVC and grip endurance time recording

Participants were asked to squeeze the grip jammer dynamometer (Model: G100; M/s Biometrics Ltd. UK) to maximum capacity (twice, with a 2-min rest to record MVC (Alam et al., 2016; Khan et al., 2009) until they feet intolerable discomfort and are unable to maintain exertion at a target level. The grip dynamometer was directly interfaced with laptop using Data LINK. Thereafter, endurance time at 50% MVC was recorded, and simultaneously the EMG signals were obtained using Data LINK (M/s Biometrics Ltd. UK) for further analyses.

2.4.3. EMG recording

Active differential surface EMG electrodes (SX230, M/s Biometrics Ltd. UK) were used to record the surface EMG signals at a sampling rate of 1024 Hz. For referencing and de-noising the EMG signals, a ground electrode was attached to the wrist of the non-dominant hand of the subject. In accordance with the protocol of SENIAM (Hermens et al., 1999), the electrodes were placed over flexor carpi ulnaris (FCU), flexor digitorum superficialis (FDS), extensor carpi radialis brevis (ECRB), and extensor carpi ulnaris (ECU) muscles of the right forearm. In addition, the electrodes were placed as follows: FCU - two finger widths from the ulnar edge to the proximal third of the forearm; FDS - in the middle third of the forearm along a line drawn from the middle of the wrist to the tendon of the biceps; ECRB— two finger widths distal to the lateral epicondyle; ECU - just lateral to the ulnar border on the middle forearm (Mogk and Keir, 2003). These muscles were selected based on functional importance in gripping (Roman-liu and Bartuzi, 2013). Before the electrodes placement, the skin and electrodes were cleaned with a cotton swab dipped in alcohol (the skin may be shaved prior to cleaning, if necessary) (Delagi et al., 1980).

2.4.4. Recording of vibration levels

On the trail run, the minimum frequency of the vibrating massager can be controlled at 23 Hz. In addition, the exposure frequencies have been selected on the basis of other studies (Kihlberg, 1995; Dong et al., 2008). Finally, the VT exposure level was maintained at 23 Hz and 35 Hz. In order to verify the reliability and the precision of the experimental setup (in terms of VT frequency), a tri-axial accelerometer (Model: SEN041F, Manufacturer: Piezo Electronic PCB, New York, USA) was attached to the massage plate (Fig. 1). The acceleration signal recordings were acquired via a data acquisition card (National Instrument, DAQ Card-9234) connected to a laptop (Samsung Core i3 processor) via a USB cable. The LabVIEW 12.0 program was written to acquire, record and analyse the vibration signal. Several trail runs were performed at the frequency of interest and the reliability of the experimental setup was found to be approximately (97 ± 1.27%).

In addition, the average RMS values of the vibration exposure at 23 Hz were $\mu = 4.75$ with $\sigma = 0.51$ m/s^2 in X-direction, $\mu = 3.77$ with $\sigma = 0.37$ m/s^2 in Y-direction and $\mu = 5.21$ with $\sigma = 0.51$ m/s^2 in Z-direction; while at 35 Hz the RMS values were $\mu = 8.789$ with

$\sigma = 0.64$ m/s^2 in X-direction, $\mu = 6.79$ with $\sigma = 0.47$ m/s^2 in Y-direction and $\mu = 8.13$ with $\sigma = 0.72$ m/s^2 in Z-direction.

2.5. Feature extraction

The EMG features listed in Table 1 have earlier been used in the investigation of EMG signal (Phinyomark et al., 2013).

3. Neuromuscular efficiency

Milner-Brown et al. (1986) used NME to quantify the changes in neuromuscular performance over time. The changes were attributed due to reduction in force generating capacity, which indicated fatigue in the muscle fibres. However, the present study was aimed to provide strength training by applying VT with respect to endurance. The previous formula given by Milner-Brown et al. (1986) was slightly modified and a new approach was introduced to calculate the neuromuscular efficiency (η_{NME}) in which ‘endurance time’ was taken into account. The effort was calculated according to the force exerted over the endurance time and effort of muscle was calculated according to the integration of EMG signal over endurance time. Therefore, the modified formula for evaluating NME was introduced as below:

$$\eta_{NME} = \frac{\frac{F_{after} \times Time_{after}}{IEMG_{after}} - \frac{F_{before} \times Time_{before}}{IEMG_{before}}}{\frac{F_{before} \times Time_{before}}{IEMG_{before}}} \times 100$$

where, η_{NME}- neuromuscular efficiency, F_{after}-maximum force at 50% MVC after day 7 of exposure, F_{before}-maximum force at 50% MVC after day 1 of exposure $Time_{after}$-endurance time after day 7 of exposure, $Time_{before}$-endurance time after day 1 of exposure, $IEMG_{after}$- IEMG value of EMG signal after day 7 of exposure, $IEMG_{before}$ - IEMG value of EMG signal after day 1 of exposure.

4. Results

Analyses of the recorded raw EMG signals were executed in Data LINK software (M/s Biometrics Ltd. UK). Further, a LABVIEW 12.0 program was written to extract EMG features. MANOVA was performed, using SPSS 20.0, on the data of dependent variables, which were obtained by extracting the EMG features (Table 2). Moreover, Pearson's correlation coefficients (r) between dependent variables (EMG features) vs. independent variables (days of exposure and frequency of exposure) were calculated and are presented in Table 3. In addition, Fig. 2(a–j) showed a systematic representation of the muscular configuration of all EMG features with respect to the frequency of vibration exposure.

4.1. Neuromuscular performance

The summary of the mean values of NME (using the modified formula) with respect to frequency of vibration exposure is presented in Table 4. The results showed that the greatest increase in neuromuscular efficiency (NME) was about 60.15% in both ECRB and ECU muscles after 35 Hz and 23 Hz of VT respectively. There was not much improvement in NME after 23 Hz of VT in flexor muscles, but after 35 Hz of VT, there was a substantial increase in NME of FDS (25.76%) and FCU (17.07%) muscles. Interestingly, present results revealed the increase in mean MVC strength and endurance time after VT (Fig. 3).

4.2. Integrated EMG (IEMG)

Days of exposure had a significant effect on the IEMG value of FCU, ECRB and ECU muscles; while the frequency of VT had only significant effect on FCU muscle (Table 2). Further, Pearson correlation test (Table 3) showed significant correlation between days of exposure with IEMG of muscles FDS, FCU, and ECU; and also for frequency, IEMG of muscles FCU and ECU. In addition, significant positive correlation of MVC was reported with IEMG of FDS, FCU, ECRB, and ECU muscles (Table 3).

Furthermore, post hoc Student-Newmen-Keuls (SNK) test showed that on day 7, IEMG of FCU, ECRB, and ECU muscles were on higher side and were significantly different ($p < 0.05$) from day 1 to day 6. Also, FCU muscle showed the greatest increase in IEMG followed by ECU, ECRB, and FDS muscles after vibration therapy (highest increase at 35 Hz) (Fig. 2(a)). Fig. 4 showed that FDS (except Day 2), FCU, and ECU (except Day 4) muscles demonstrated an increase in mean IEMG after vibration therapy from day 1 to day 7 (highest increase at 35 Hz). ECRB muscle also showed an increasing trend after VT at 35 Hz until day 3; however, after day 4,

Table 1
Representation of time domain and frequency domain features.

S. No	EMG Features	Formula	Explanation
1	Integrated EMG (IEMG)	$\sum_{i=1}^{N} \lvert x_i \rvert$	Used as identifying index in EMG non-pattern recognition (Huang and Chen, 1999).
2.	Mean Absolute Value (MAV)	$\frac{1}{N}\sum_{i=1}^{N} \lvert x_i \rvert$	Used in investigation of EMG signal as identifying index for pattern recognition (Hudgins et al., 1993).
3.	Simple square integral (SSI)	$\sum_{i=1}^{N} x_i^2$	Used as energy index and uses energy of the EMG signal (Du and Vuskovic, 2004).
4.	Variance (VAR)	$\frac{1}{N-1}\sum_{i=1}^{N} x_i^2$	Used as power index feature for pattern recognition (Zardoshti et al., 1995).
5.	Root mean square (RMS)	$\sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2}$	Most common feature used during analysis of the EMG signal (Boostani and Moradi, 2003; Kim et al., 2011).
6.	Waveform length (WL)	$\sum_{i=1}^{N-1} \lvert x_{i+1} - x_i \rvert$	Measure of the complexity of the EMG signal acquired from the raw signal (Hudgins et al., 1993; Oskoei and Hu, 2008).
7.	Mean Frequency (MNF)	$\sum_{j=1}^{M} f_j P_j \Big/ \sum_{j=1}^{M} P_j$	Summation of product of power spectrum of EMG signal and the frequency and then divided by summation of the intensity of the spectrum (Oskoei and Hu, 2008)
8.	Median Frequency (MDF)	$\sum_{j=1}^{MDF} P_j = \sum_{j=MDF}^{M} P_j = \frac{1}{2}\sum_{j=1}^{M} P_j$	Frequency at which the spectrum of EMG signal is divided into two regions with equal amplitude (Oskoei and Hu, 2008).
9.	Total Power (TP)	$\sum_{j=1}^{M} P_j$	Also called as zero spectral moment (SM0) and energy (Du and Vuskovic, 2004).
10.	Slope based on regression line of median frequency (SMDF)	$Y = mx + c$ m is the slope of the line.	Used as an index to measure fatigue in muscles fibers.

Note: x_i denotes the surface EMG signal in a segment i and N represents length of the sEMG signal, f_j is frequency of the spectrum at frequency bin j, P_j is the EMG power spectrum at frequency bin j, and M is length of the frequency bin.

Table 2
Result of multivariate- analysis of variance (MANOVA).

			Independent Variables											
			Days of Exposure				Frequency of Vibration Exposure				Days of Exposure X Frequency of Vibration Exposure			
			FDS	FCU	ECRB	ECU	FDS	FCU	ECRB	ECU	FDS	FCU	ECRB	ECU
Dependent Variables	Time Domain Features	IEMG	#	<0.001**	0.007*	0.021*	#	<0.001**	#	#	#	#	#	#
		MAV	#	#	#	#	#	0.041*	#	#	#	#	#	#
		VAR	#	#	#	#	#	#	#	#	#	#	#	#
		SSI	#	#	0.033*	#	#	0.032*	#	#	#	#	#	#
		WL	#	0.003*	#	#	#	<0.001**	#	#	#	#	#	#
		RMS	#	#	#	#	#	#	#	#	#	#	#	#
	Frequency Domain Features	MDF	#	#	#	#	#	#	#	#	#	#	#	#
		MNF	#	#	#	#	#	#	#	#	#	#	#	#
		SMDF	#	0.03*	#	#	#	#	#	#	#	#	#	#
		TP	#	#	#	#	#	#	#	#	#	#	#	#

Note: **p < 0.001,*p<0.05, **#** p>0.05 (not significant).
IEMG- Integrated Electromyography, MAV-mean absolute value, VAR-variance, SSI- simple square Integral, WL-waveform length, RMS-root mean square, MDF- median frequency, MNF- mean frequency, SMDF- slope based on regression line of median frequency, TP- total power, FDS- flexor digitorum superficialis, FCU-flexor carpi ulnaris, ECRB-extensor carpi radialis brevis, ECU-extensor carpi ulnaris.

Table 3
Pearson's correlation coefficient (r) between dependent variables and independent variables.

			Independent Variables							
			Days of Exposure				Frequency of Vibration Exposure			
			FDS	FCU	ECRB	ECU	FDS	FCU	ECRB	ECU
Dependent Variables	Time Domain Features	IEMG	0.153* (p = 0.027)	0.248** (p < 0.001)	#	0.189* (p = 0.006)	#	0.222** (p = 0.001)	#	0.135* (p = 0.05)
		MAV	#	#	#	#	#	0.145* (p = 0.036)	#	#
		VAR	#	#	#	#	#	#	#	#
		SSI	0.142* (p = 0.04)	0.155* (p = 0.024)	#	0.147* (p = 0.034)	#	0.160* (p = 0.02)	#	#
		WL	#	0.236** (p = 0.001)	#	#	#	0.233** (p = 0.001)	#	#
		RMS	#	#	#	#	#	#	#	#
	Frequency Domain Features	MDF	#	#	#	#	#	#	#	#
		MNF	#	#	#	#	#	#	#	#
		SMDF	#	−0.190* (p = 0.006)	#	#	#	#	#	#
		TP	#	#	#	#	#	0.143* (p = 0.038)	#	#

Note: **p < 0.001,*p<0.05, **#** p>0.05 (not significant).
IEMG- Integrated Electromyography, MAV-mean absolute value, VAR-variance, SSI- simple square Integral, WL-waveform length, RMS-root mean square, MDF- median frequency, MNF- mean frequency, SMDF- slope based on regression line of median frequency, TP- total power, FDS- flexor digitorum superficialis, FCU-flexor carpi ulnaris, ECRB-extensor carpi radialis brevis, ECU-extensor carpi ulnaris.

this increase was more at 23 Hz until day 6, thereafter increased on day 7 at 35 Hz (Fig. 4).

4.3. Mean absolute value (MAV)

There was only a significant effect of frequency on the MAV for FCU muscle. In addition, Pearson correlation test (Table 3) showed significant correlation between the frequency of VT and MAV of muscle FCU (Table 2). The increase in MAV was also found for all the muscles after vibration exposure at 23 Hz (except for FDS muscle); but when VT was administered at 35 Hz there was a slight decrease in the MAV for all the muscles (expect for FCU muscle) as shown in Fig. 2(b). Fig. 5 showed a decreasing pattern of the MAV for FDS muscle after VT from day 1 to day 6 (except Day 2 and Day 3) as compared with BVE; whereas FCU muscle showed an increasing pattern after VT from day 1 to day 7 (maximum increase at 35 Hz). The MAV of ECRB muscle also showed an increasing pattern after VT till day 3 (highest increase at 35 Hz), thereafter decreased on day 4 and day 5, then again increased till day 7 (more increase at 23 Hz as compared to BVE). ECU muscle showed an increase in MAV after VT till day 4; however, on day 5, its value suddenly decreased, and then again it increased on day 6 and day 7 of VT (highest increase at 23 Hz) compared to BVE as shown in Fig. 5.

4.4. Simple square integral (SSI)

The results (Table 2) showed a significant effect of the days of exposure on the SSI for ECRB muscle and of frequency of VT on the SSI for FCU muscle. In addition, Pearson correlation test showed significant correlation between the days of exposure and the SSI of muscles FDS, FCU, and ECU; and also for frequency of vibration exposure with SSI of muscle FCU (Table 3). In addition, SNK test showed that on day 7, the SSI of ECRB muscle was on higher side and was significantly different ($p = 0.033$) from day 1 to day 6.

Fig. 2(c) showed the increase in SSI for all the muscles after VT (with the exception for FDS muscle that shows a decrease in SSI after VT at 23 Hz) and the greatest increase in SSI was for FCU muscle followed by ECU and ECRB muscles. FDS muscle showed a

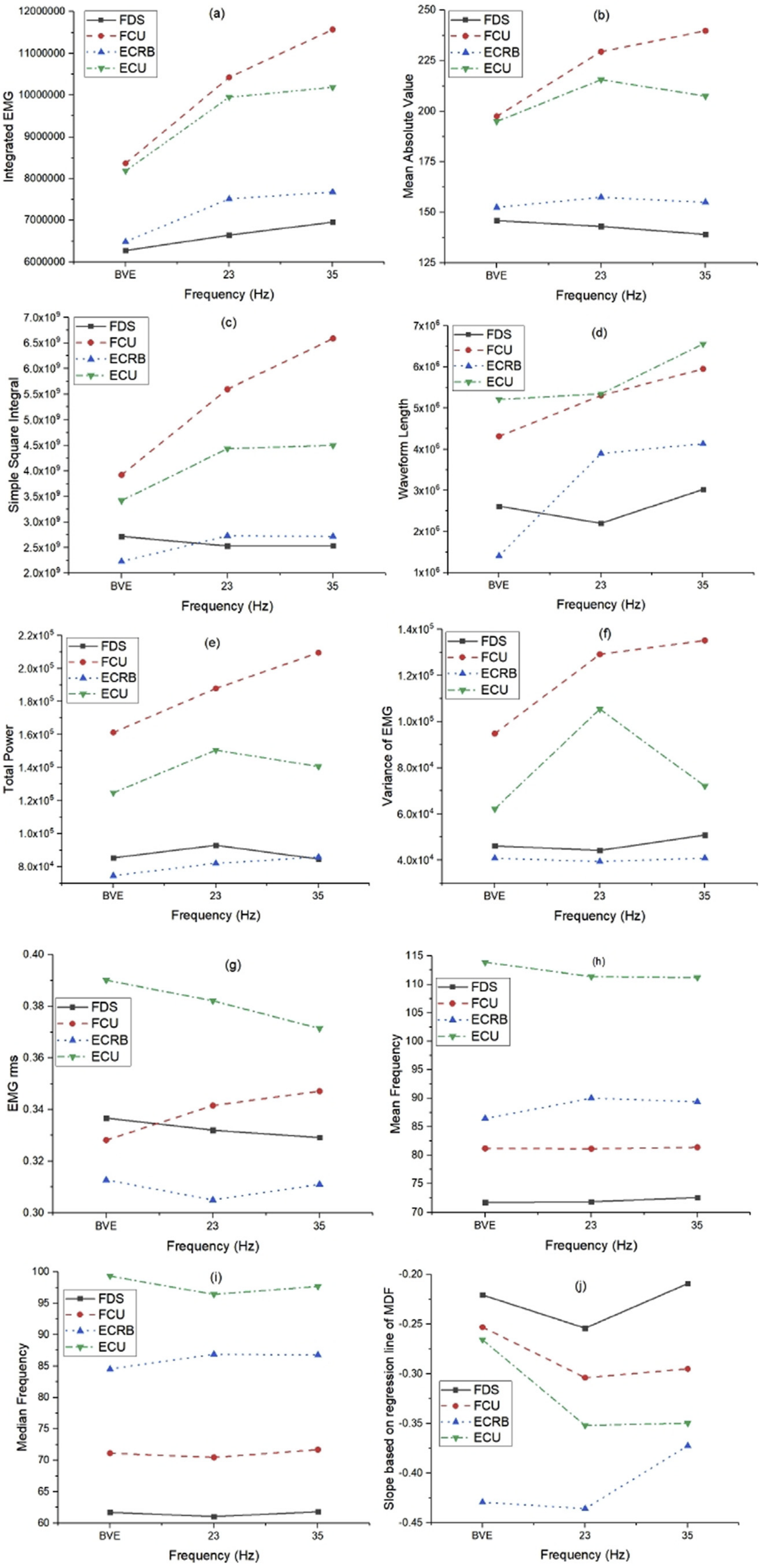

Fig. 2. Systematic representation of muscles-wise pattern of all EMG features with respect to the frequency of vibration exposure-a) integrated EMG, b) mean absolute value, c) simple square integral, d) waveform length, e) total power, f)variance of EMG signal, g) root mean square, h) mean frequency, i) median frequency, j) slope based on regression line of median frequency.

Table 4
Summary of mean Neuromuscular Efficiency using proposed modified formula.

Frequency of Vibration Exposure	Neuromuscular Efficiency (% Increase in the ratio N-s/mV)			
	FDS	FCU	ECRB	ECU
23 Hz	5.46	4.52	39.17	60.15
35 Hz	25.76	17.07	60.15	55.77

Note: FDS- flexor digitorum superficialis, FCU-flexor carpi ulnaris, ECRB-extensor carpi radialis brevis, ECU-extensor carpi ulnaris.

decreasing trend in SSI after VT from day 3 to day 6 (Fig. 6). However, FCU and ECU muscle showed an increasing trend in SSI after VT from day 1 to day 7 as compared with BVE. Further, ECRB muscle also showed increasing trend in SSI after VT from day 1 to days 7; however, this increase was maximal at 35 Hz until day 3 and thereafter the increase was more at 23 Hz.

4.5. *Waveform length (WL)*

The effect of days of exposure and frequency of VT was significant on the WL for FCU muscle (Table 2). In addition, FCU showed significant correlation (Table 3) between the days of exposure and the frequency of vibration exposure with WL. In addition, SNK test showed that the WL of only FCU muscle was on higher side on day 7 and was significantly different (p = 0.003) from day 1 to day 6. Fig. 2(d) showed an increase in the WL for all the muscles after VT (except for FDS muscle which showed decrease in WL after 23 Hz of VT). However, the greatest increase in WL was observed after 35 Hz of VT in ECU muscle followed by FCU, ECRB, and FDS muscles. Further, FDS, FCU, ECRB, and ECU muscles showed an increasing trend in WL after VT from day 1 to day 7 as compared to BVE (highest increase at 35 Hz except for ECRB on day 6) as shown in Fig. 7.

4.6. *Slope based on regression line of median frequency (SMDF)*

There was a significant effect of days of exposure on FCU muscle ($p = 0.03$), whereas no significant effect of frequency of vibration as well as their interaction on SMDF for any of the muscles (Table 2). Further, Pearson correlation test (Table 3) showed a significant negative correlation between the days of exposure and the SMDF of muscle FCU.

Fig. 2(j) showed an increase in the SMDF for all the muscles after VT at 23 Hz; however, when VT was given at 35 Hz it showed a decreasing pattern. Furthermore, the pattern of the SMDF (Fig. 8) showed an increase in fatigue after VT at 23 Hz from day 1 to day 7 for all the muscles; however, there was a decreasing trend at 35 Hz from day 1 to day 7 (except for ECU muscle which showed increase in fatigue on day 1, day 3, and day 7; and FDS and FCU muscles which showed increased fatigue on day 3). Fig. 2(j) also suggests that there was more fatigue in the extensor muscle, i.e., ECRB after 23 Hz of VT followed by ECU muscle than the flexor muscles.

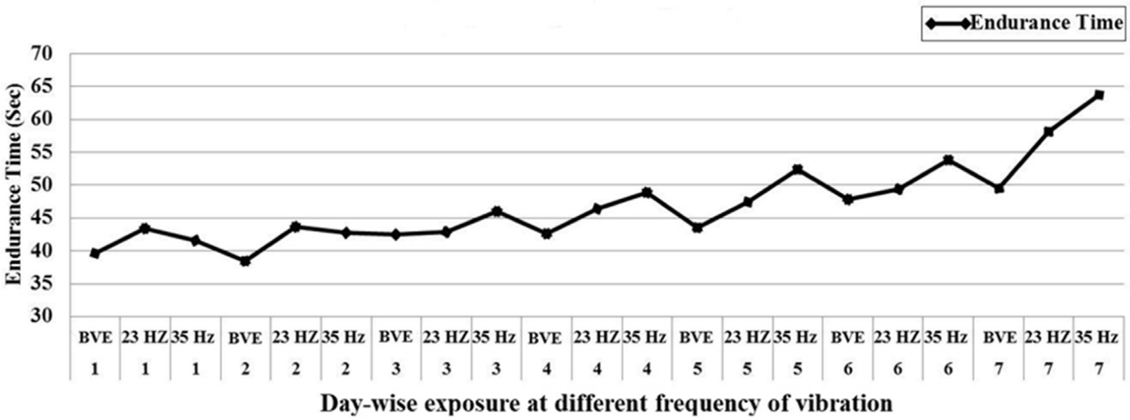

Fig. 3. Day-wise exposure value of endurance time with respect to the frequency of vibration exposure.

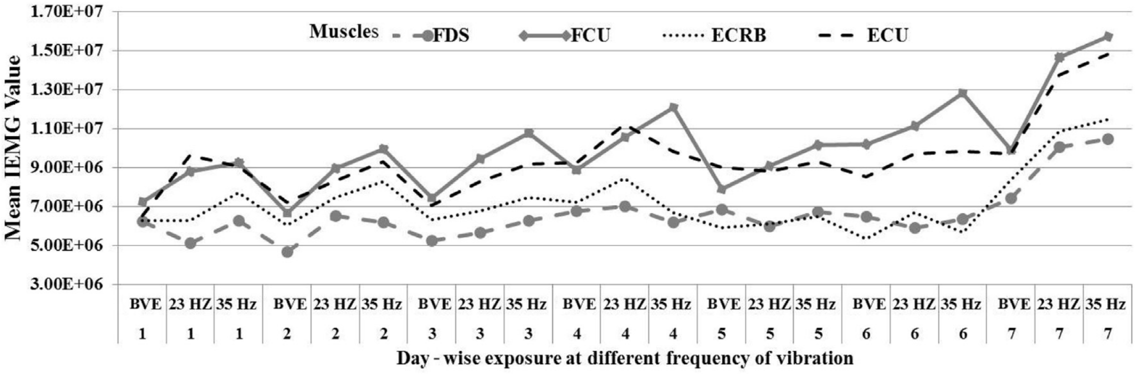

Fig. 4. Day-wise exposure value of Integrated EMG of the respective muscles with respect to the frequency of vibration exposure.

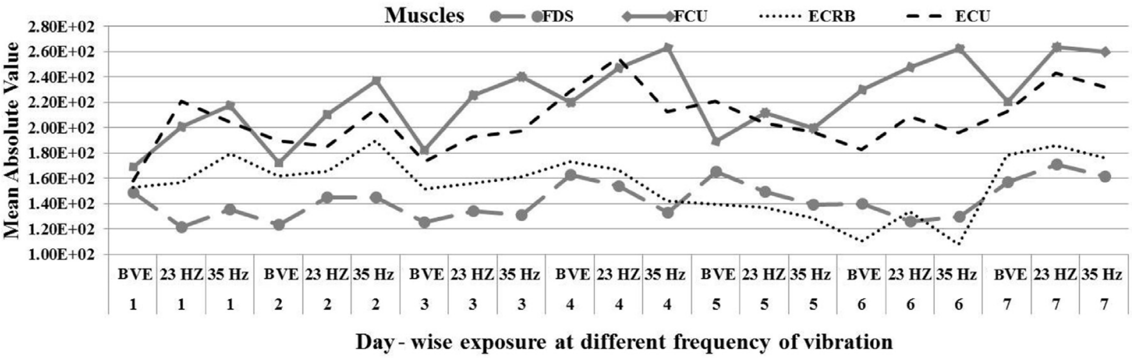

Fig. 5. Day-wise exposure value of MAV of the respective muscles with respect to the frequency of vibration exposure.

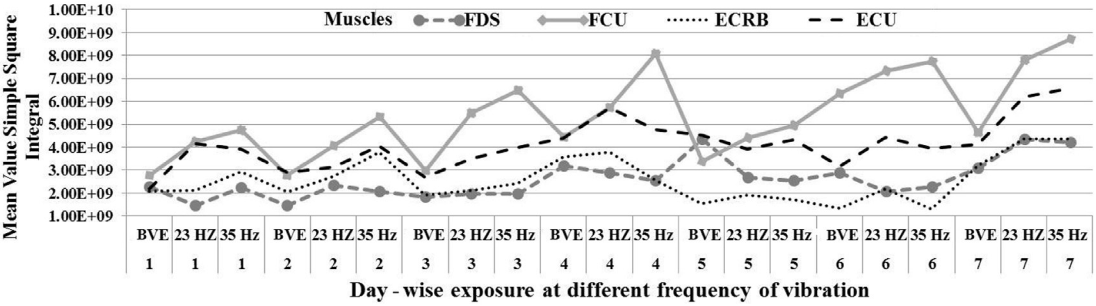

Fig. 6. Day-wise exposure value of SSI of the respective muscles with respect to the frequency of vibration exposure.

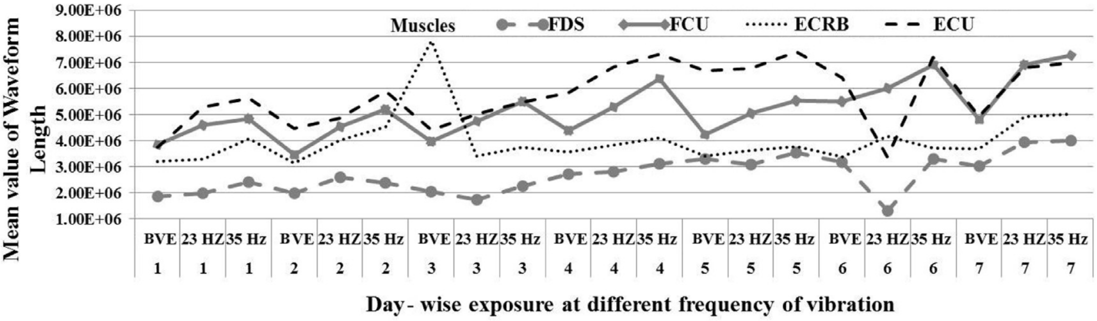

Fig. 7. Day-wise exposure value of WL of the respective muscles with respect to the frequency of vibration exposure.

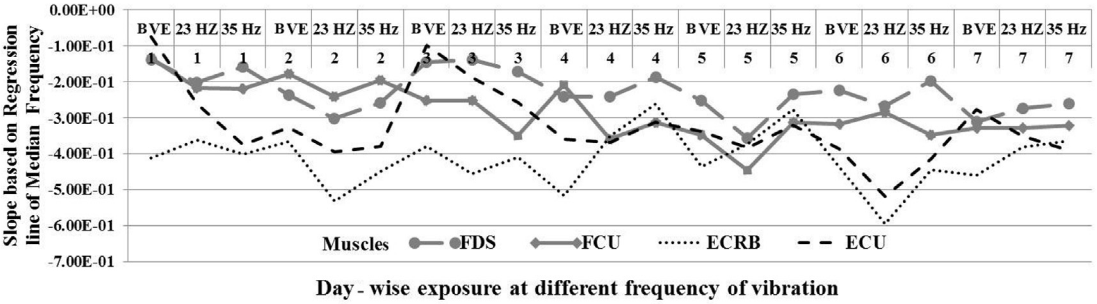

Fig. 8. Day-wise exposure value of slope based on regression line of median frequency of the respective muscles with respect to the frequency of vibration exposure.

5. Discussion

5.1. Neuromuscular efficiency

It is hypothesized that there were no significant differences in the effects of vibrational exposure frequency on forearm muscle neuromuscular output. However, using the formula given by the authors, a significant increase in neuromuscular performance was found after giving a VT (Table 4). More than 50% increase in neuromuscular performance was noticed temporarily after giving VT at 35 Hz. VT improved the motor-evoked potentials (Kossev et al., 2001) along with EMG signal (Ritzmann et al., 2010) signifying excitability of the motor cortex associated with muscle adaptations and improvement of the neuromuscular efficiency (Bosco et al 1999a, 2000). In contrast, Milner-Brown et al. (1986) showed decrease in the NME of flexor muscles (49 ± 15%). They used NME to quantify the time-course of recovery in neuromuscular performance and found decrease in its value during each treatment, which was attributed due to reduction in force generating capacity, thereby indicating the fatigue in muscles fibres. It may be said that the improvement in neuromuscular efficiency as found was due to the positive effect of VMT.

5.2. Muscular performance change based on individual features

The results of linear relationship between Integrated EMG and force needs further examination, because, the slope of this relationship depends on the level of fatigue. The progressive enhancement in EMG activity during sustained contractions was possibly due to the increased recruitment of MUs as evident in a study (Enoka, 1988). Integrated EMG values significantly increased ($p < 0.05$) by vibration intervention (Kihlberg et al., 1995), along with an increase in sub-maximal contraction force (De Luca, 1997). Similarly, present study also showed a significant increase ($p < 0.05$) in the IEMG of FCU muscle due to VT, along with an increase in MVC strength and endurance time (Fig. 3).

Luo et al. (2005) reported an increase in the muscle activity during submaximal dynamic and isometric contractions due to vibration intervention. However, they also concluded that prolonged exposure to vibration induces more fatigue. The present study also found the increase in MVC and total power after VT. Although, there was more fatigue after VT at 23 Hz, but this fatigue did not affect much the force generating capacity and total power of the muscles, hence, there was increase in the endurance time, force generating capacity, and total power (better at 35 Hz for FDS and ECRB muscles as compared to 23 Hz and BVE). Therefore, one can suggest an increase in muscle strength as a result of strength training due to vibration intervention using 35Hz.

Further, an increase in MAV indicates increase in the amplitude of EMG signal, which in turn results in an increase in the level of fatigue in the muscle fibres (Kiran and Uma Rani, 2017). Similarly, the present study revealed an increase in MAV for all the selected muscles after VT at 23 Hz (except for FDS muscle); but when VT was given at 35 Hz, there was a small decrease in MAV for all the muscles (expect for FCU muscle). Therefore, it can be said that fatigue had occurred in the muscle fibres after vibration exposure at 23 Hz.

All muscles showed increase in WL, after vibration exposure (except for FDS muscles which showed decrease in WL after 23 Hz of VT); wherein the greatest increase in WL was found for ECU muscle followed by FCU, ECRB, and FDS muscles after 35 Hz of VT (Fig. 2(d)). Thus, an increase in WL after VT indicates the increase in EMG amplitude and hence fatigue in the muscles.

FDS and ECU muscles showed the decrease in mean RMS value after VT (highest decrease after 35 Hz). However, there was an increase in the mean RMS value for FCU and ECRB muscles after 35 Hz of VT (Fig. 2(g)). Nevertheless, the changes in the amplitude characteristics of surface EMG signal could increase (Sogaard et al., 2006), decreases (Bigland- Ritchie, 1981), or remain unchanged (Thomas et al., 1989) with fatigue.

The decrease in the MNF and the MDF for FDS, FCU, and ECU muscles after VT at 23 Hz was resulted in the increased firing frequency of the motor units (MUs) in the endurance test after VT at 23 Hz. Similarly, Griffin et al. (2001) reported an increase in the firing rate of triceps brachii muscle during sustained contractions after vibration exposure. In addition, the present study revealed a small increase in the MNF and the MDF for all the muscles after VT at 35 Hz. However, for the ECRB muscle, the MNF and the MDF increased after 23 Hz of VT and decreased after 35 Hz as compared to BVE as shown in Fig. 2(h) and (i) respectively. A significant enhancement in the MDF of the vastus lateralis (VL) muscle after vibration intervention at 26 Hz was found thereby suggesting the recruitment of type I MUs during fatigue (Rittweger et al., 2003). Doheny et al. (2008), also reported an increase in median frequency with an enhanced force generating capacity of muscle. Jackson and Turner (2003) also suggested that low frequency vibration exposure provoke more neuromuscular fatigue similar to the present findings. It was also exhibited that the extensor muscles had more fatigue (highest fatigue in ECRB followed by ECU muscle) than the flexor muscles during the endurance task after vibration exposure at 23 Hz (Fig. 2(j)). However, the fatigue in the extensor muscles were found to set in more rapidly than the flexor muscles during gripping (Bystrom et al., 1991; Hagg and Milerad, 1997): having less fatigue in flexor muscles.

A decrease in fatigue response when VT was given at 35 Hz was found, but this response occurred more predominantly after day 4 of the vibration exposure. The main reason behind this response might be the decrease in the pressure or tension on muscles belly or tendon unit after giving VMT at a higher frequency, which may affect the viscoelastic factor of the muscular tissue. Therefore, it helps in the enhancement of the muscle force generating capability and the reduction in fatigue along with improvement in the muscles flexibility by reducing muscle stiffness: a result of strength training.

6. Limitations and future scope

Only a short term (7 days) effect of VMT was studied. The effect of the surface or the shape of massager was not considered. During the experiments the reported low level of discomfort was neglected, which may have inhibited improvement in muscles performance. Further investigations are required to define the parameters microscopically for: indicating the optimal frequency; intensity and amplitude parameters.

7. Conclusions

The pattern of EMG signal TD and FD features represented the signal amplitude and spectral parameters and could achieve fatigue analysis in real time. In addition, slope based on the median frequency regression line and EMG signal median frequency were the best features to evaluate muscle fatigue after exposure to vibration therapy. The modified formula to calculate neuromuscular performance changes showed a significant increase in muscle performance after VT with significantly increased in both ECRB and ECU muscles.

Clinical relevance

1. The present finding is a sample guideline for the professional sports, clinic, rehabilitation, medical use and may be useful for the therapists.
2. VMT is found to be a safe modality at lower frequencies (i.e. 23 Hz and/or 35 Hz for a duration of 10 min) to enhance muscle performance of upper extermitites for sports persons, workers, aged person and person with weak muscles.
3. VMT at 35 Hz for a duration of 10 min on forearms had significant posituve effect on their neuromuscular performance and can be used as optimal range for investigation the effect of VT.

CRediT authorship contribution statement

Mohd Mukhtar Alam: Formal analysis. **Abid Ali Khan:** Supervision. **Mohd Farooq:** Supervision.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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