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One session of whole body vibration increases voluntary muscle strength transiently in patients with stroke

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Objective: To determine the effect of whole body vibration on isometric and eccentric torque and electromyography (EMG) variables of knee extensors on the affected side of stroke patients.

Design: A randomized controlled study.

Setting: A rehabilitation centre.

Subjects: Sixteen patients (age 58.2 ± 9.4 years) were enrolled in an inpatient rehabilitation programme 27.2 ± 10.4 days after a stroke.

Interventions: Eight patients were randomly assigned to the vibration group and received 20 Hz vibration (5 mm amplitude) while standing on a vibration platform for 1 minute six times in one session. Patients in the control group also stood on the platform but did not receive vibration.

Main measures: Maximum isometric and eccentric torque, rate of torque development, root-mean-squared EMG, median frequency of vastus lateralis, and co-activation of knee flexors.

Results: Isometric and eccentric knee extension torque increased 36.6% and 22.2%, respectively, after vibration ($P < 0.05$) and 8.4% and 5.3% in the control group. Vibration increased EMG amplitude 44.9% and the median frequency in the vastus lateralis by 13.1% (all $P < 0.05$) without changes in the control group (10.6% and 3.9%). Vibration improved the ability to generate mechanical work during eccentric contraction (17.5%). Vibration reduced biceps femoris co-activation during isometric (8.4%, ns) and eccentric (22.5%, $P < 0.05$) contraction.

Conclusion: These results suggest that one bout of whole body vibration can transiently increase voluntary force and muscle activation of the quadriceps muscle affected by a stroke.

Introduction

A stroke can critically impair motor function, including manipulative abilities in the upper

extremities and balance and gait in the lower extremities. There is a well-established relationship between the reduction in voluntary strength in the affected muscles of the lower extremities and the ability to execute activities of daily living.^{1,2} For example, decrease in voluntary strength of the knee extensors in the affected limb is closely linked to reductions in walking speed,¹⁻⁴ impaired stability and increased postural sway.³

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Although there is growing support for the use of resistance training in stroke rehabilitation,^{5–7} there are several factors that still limit its incorporation in a rehabilitation programme. After a stroke many patients have low motivation, attention and tolerance to discomfort, and an increased vulnerability to stress.⁸ In addition, activation of hemiparetic muscles is reduced due to changes in motor unit number, recruitment, discharge rates, and in balance between agonist and antagonist muscles.⁹ Therefore, exertion of high voluntary force may not be an ideal rehabilitation option for stroke patients. Strokes predominantly occur in older adults who, in the process of ageing, become unaccustomed to using high levels of voluntary effort in activities of daily living, leading to disuse and inability to recruit high threshold motor units.¹⁰

We thus explored an alternative method to conventional resistance training to restore voluntary muscle force in stroke patients. Several recent studies in healthy volunteers showed that mechanical vibration of skeletal muscles increased maximal voluntary force of upper and lower extremity muscles.^{11–13} A few studies reported decreases in isometric strength after whole body vibration in previously exercise-trained and untrained healthy subjects,^{14–16} possibly due to fatigue related to the frequency of vibration, as 40 versus 20 Hz of whole body vibration decreased joint flexibility and dynamic strength in young adults.¹³ Whole body vibration seems to improve postural stability¹¹ and reduce the risk of falls¹⁷ in older adults.

The effects of whole body vibration on posture and motor symptoms was also examined in a few clinical conditions including patients with Parkinson's disease^{20,21} and multiple sclerosis.²² There is limited information available on the use of whole body vibration in stroke patients. van Nes *et al.*¹⁸ showed that four bouts of 45-second whole body vibration at 30 Hz decreased the centre-of-pressure velocity in the anteroposterior direction in stroke patients who stood on a vibrating platform with eyes closed. However, no specific effect of whole body vibration was reported after six weeks of daily treatment. Therefore, the purpose of this study was to examine the transient effects of whole body vibration on

maximal voluntary force and agonist and antagonist muscle activation in stroke patients.

Methods

Subjects

Having inspected the medical charts of 88 acute post-stroke patients hospitalized in the National Institute of Medical Rehabilitation Centre, 26 patients met the inclusion criteria. Eight patients refused to participate in the study (Figure 1).

Inclusion criteria were first-time stroke from infarction and haemorrhage, onset of stroke from 14 to 50 days before study entry, and a Functional Independence Measure (FIM)²³ score at admission of 60–110. Patients were excluded if they had unstable angina pectoris, congestive heart failure, peripheral arterial disease, severe dementia, language problems that precluded following simple commands consistently, painful orthopaedic conditions involving the pelvis, hips, knees or ankles having vibration treatment.

Eligible ($n = 18$) patients (9 men and 9 women, average age 58.2 (9.4) years, range 42–67) were randomly assigned to a vibration ($n = 9$) and a control ($n = 9$) group. After inclusion, subjects

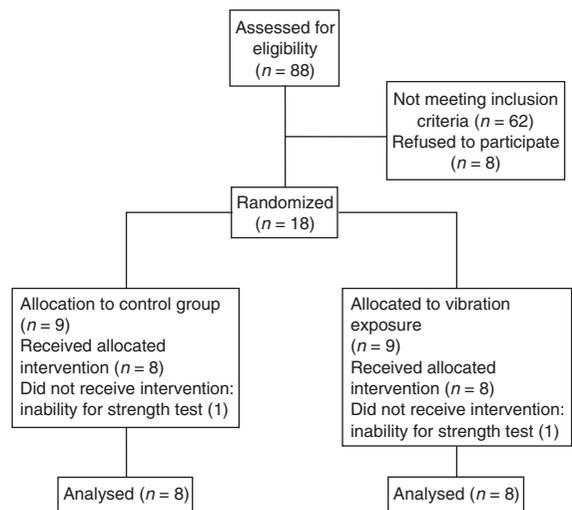


Figure 1 Flowchart of participants through each stage of study.

were stratified by age and randomized into vibration or control group. Sealed envelopes were used for randomization. The envelopes containing letters either VG (vibration group) or CG (control group) were prepared by the primary investigator. The envelopes were given to the chief physician who wrote the names of the selected patients on the envelopes. After the baseline measurement two patients (one from the vibration group and one from the control group) were lost because of their inability to perform strength tests (Figure 1). The Research and Ethics Committee of Semmelweis University, Budapest approved the study methods, and all patients gave their written informed consent according to the Declaration of Helsinki. The Hospital's Ethics Committee also approved the study.

Familiarization

Patients were familiarized with the dynamometer and practised the knee extension task to reduce the influence of learning on the ability to generate maximal voluntary torque. Eighteen patients participated in three familiarization sessions separated by two days. The three familiarization sessions occurred over the third week of the rehabilitation programme and the experiment was conducted at the beginning of the fourth week of the programme. During these sessions the patients were familiarized with the dynamometer and the procedure to execute knee extensions. At the end of each session subjects performed one set of three isometric and one set of three eccentric contractions with the knee extensor muscle group of the affected leg. There were 2 minutes of rest between sets. By the end of the third familiarization session, two patients were excluded from the study because they were not able to execute the knee extension properly.

Vibration intervention

Patients received whole body vibration using the Nemes-Bosco vibration platform (OMP, Rieti, Italy). The peak-to-peak amplitude of the vibration was 5 mm and the vibration frequency could be adjusted between 0 and 100 Hz in increments of 1 Hz. The patients in vibration group were

familiarized with the vibration treatment three days prior to the experiment (during the third familiarization session). During this session, patients received 1 minute of 20 Hz vibration followed by 1 minute of rest, and 1 minute of vibration again. Subjects sat on a chair and pressed the sole of the shoe of the affected leg on the platform surface. Next, patients stood on the platform with both knees flexed 40 degrees, grasped the railing in front of them, and received whole body vibration five times for 1 minute with 1 minute of rest between bouts.

In the present study, patients received whole body vibration in one session. First, patients in the vibration group received the usual, daily, conventional physiotherapy. Next, vibration group patients were tested for knee extension strength on the dynamometer (MultiCont II, Mediagnost, Budapest and Mechatronic Ltd, Szeged, Hungary). Finally, patients stood on the vibration platform with both knees flexed 40 degrees, grasped the handlebar, shifted their body mass over the affected leg, and 20 Hz whole body vibration was turned on for six, 1-minute-long bouts separated 2 minutes of rest. During the rest period patients sat on a chair placed next to the vibration platform. Immediately after the last bout of whole body vibration, patients were retested for voluntary torque production on the dynamometer. The preparation for test took 3.2 ± 0.4 minutes after finishing the last whole body vibration session and the test lasted 5.3 ± 0.8 minutes. Patients in the control group performed exactly the same procedures: they stood on the platform six times for 1 minute with knees flexed 40 degrees, shifted the centre of mass over the afflicted leg, and sat on a chair during the 2-minute-long rest intervals. However, the vibration was not turned on. These patients were also tested for knee extension strength immediately after the last bout of sham intervention. The duration of the preparation for the test and the tests of voluntary contraction were similar to those in the vibration group.

Strength testing

We used the conventional daily rehabilitation session as a warm-up for strength testing.

Subjects sat on the seat of a computerized dynamometer (MultiCont II, Mediagnost, Budapest and Mechatronic Ltd, Szeged, Hungary) that was described in detail elsewhere.²⁴ The affected leg was attached to the dynamometer's lever arm at the ankle with a padded cuff. The apparent knee joint centre of rotation was aligned with the lever arm's centre of rotation. Crossover shoulder straps, a lap belt, and a wide strap across the thigh stabilized the trunk and prevented hip extension. The torque was measured by four strain gauges glued to the flexible ribs of the load cell (sensitivity 0.5 Nm, maximum torque 500 Nm). Joint position was measured with a potentiometer built into the lever arm driver. The resolution was 0.01 rad. A preprogrammed electrical servomotor controlled velocity. Torque, angular displacement and velocity were recorded by a personal computer following analogue-to-digital conversion at 0.5 kHz and were stored for offline analysis.

Maximum isometric and eccentric torque of the knee extensors in the affected leg were measured before and after whole body vibration and sham. Patients performed maximal voluntary isometric contractions using the affected leg at 60 degrees knee flexion. They performed four efforts with 1 minute of rest between efforts. In efforts 1 and 2 patients were instructed to extend the knee with maximal effort against the fixed lever arm for 3–4 seconds. In efforts 3 and 4 patients were asked to execute isometric contractions as fast as possible. From efforts 1–2, maximum isometric torque was extracted from the torque–time curves (Figure 2) and from efforts 3–4 we determined the maximum rate of torque development (dM/dt) as the steepest part of the torque–time curves. The highest maximum isometric torque and rate of torque development values were averaged and used in the statistical analyses (Figure 3).

Patients performed maximal voluntary eccentric contractions with the affected leg by starting the efforts with an isometric contraction at 30 degrees knee flexion. After reaching 20 Nm of torque the electrical motor was activated and flexed the knee at 60 degrees/s by rotating the lever arm for a range of motion of 60 degrees. The patients were asked to resist the rotating lever arm as hard as they could. Patients performed three eccentric

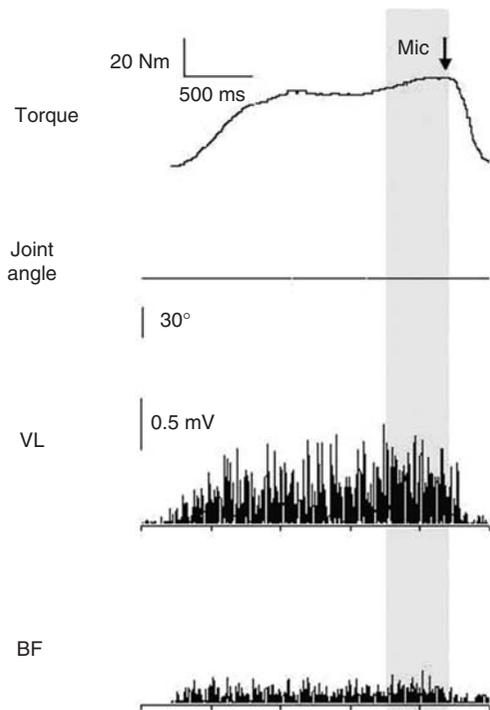


Figure 2 Representative isometric knee extension torque, knee joint angle and rectified EMG data for vastus lateralis (VL) and biceps femoris (BF) performed without time constraint by one of the patients. The arrow indicates the location at which the maximum isometric torque (MIT) was determined. The shaded area represents 400 ms window used for computation of root mean square EMG (EMG_{rms}) values for VL and BF.

contractions with 1 minute of rest between efforts. Torque, angular displacement and angular velocity were recorded as a function of time and stored for later analysis. Peak torque was measured as the highest torque anywhere in the range of motion and torque was also determined at 60 degrees knee flexion (Figure 4). Mechanical work was calculated as the area under the torque–angular displacement curve using the following equation:

$$W = \int_{\theta_1}^{\theta_n} M(\theta) \cdot d\theta$$

where M is the torque measured at θ joint angle.

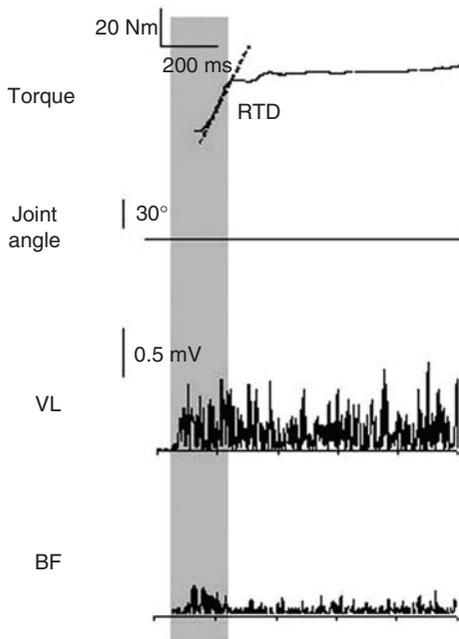


Figure 3 Representative isometric knee extension torque, knee joint angle and rectified EMG data for vastus lateralis (VL) and biceps femoris (BF) performed without time constraint by one of the patients. The dashed line drawn to the curve indicates the maximum rate of torque development (RTD) which is the tangent (dM/dt) fitted to the steepest part of the curve. The 200 ms window (shaded region), which began at the onset of EMG activity of VL, was used to compute EMG_{rms} for VL and BF.

Myoelectrical activity

Myoelectrical activity (EMG) was recorded using bipolar, 8-mm-diameter, silver–silver chloride electrodes. The centre-to-centre interelectrode distance was 2.5 cm. The electrodes were placed over the vastus lateralis and biceps femoris (long head) of the affected leg. The skin surface over the belly of the muscles was palpated, shaved and washed with alcohol. The skin over the patella was similarly prepared for the ground electrode. EMG data were collected with the TeleMyo telemetric hardware system (Noraxon U.S., Inc., Scottsdale, AZ, USA). All signals were digitized at 1 kHz using the Myosoft software (Noraxon Myoclinical 2.10). EMG data reduction consisted of the full-wave rectification

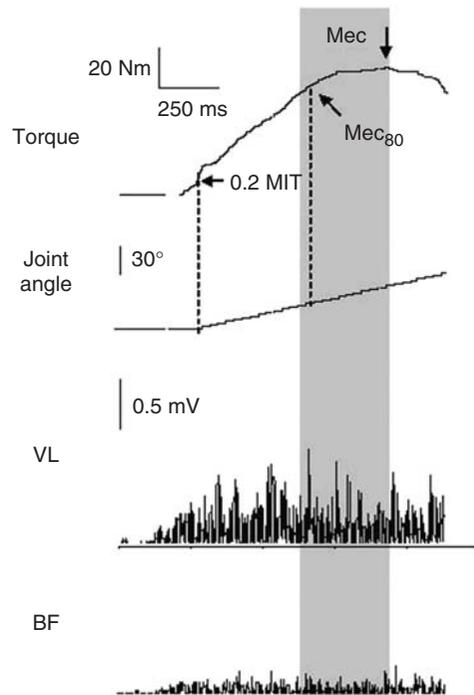


Figure 4 Representative knee extension torque, knee joint angle and rectified EMG data for vastus lateralis (VL) and biceps femoris (BF) performed under eccentric contraction by one of the patients. The first dashed line and arrow show the threshold level necessary to activate the dynamometer servo-motor and initiate the muscle stretch. The second dashed line and arrow indicate the location on the torque-time curve at which eccentric torque (Mec_{60}) was estimated for a knee joint angle of 60 degrees. The third arrow shows the maximum eccentric torque (Mec) produced during the whole eccentric contraction. The 400 ms window (shaded region) was used to determine EMG_{rms} for VL and BF.

and root-mean-square (rms) conversion of the raw EMG data by a 20 ms smoothing window. Maximum torque was identified and the corresponding EMG_{rms} activity digitized. Across all channels, marker 1 was placed at peak torque and marker 2 was inserted 400 ms before marker 1 (Figures 2 and 4). Within this 400 ms window the highest EMG_{rms} value was taken as peak EMG (μV) activity. In fast isometric contractions, marker 1 was placed at the onset of EMG activity and marker 2 at 200 ms (Figure 3).

Fast Fourier transform analysis was also performed for the calculation of the median frequency of the power spectrum by using Noraxon Myoclinical 2.10 software. Median frequency was determined for vastus lateralis during maximum isometric and eccentric contraction in the windows indicated in Figures 2 and 4. Biceps femoris co-activity during the quadriceps contraction was computed as the quotient of peak EMG_{rms} amplitude of biceps femoris divided by the peak EMG_{rms} amplitude of the vastus lateralis.

Statistical analysis

Mean and standard deviation (SD) were computed for the measured and calculated variables. Because of the limited sample size and according to the requirements of using parametric statistical procedures all variables were tested with Shapiro–Wilk’s *W*-test for normality. Because the variables were not normally distributed the effect of whole body vibration (independent variable) on strength and EMG variables (dependent variables) was statistically analysed by means of the Friedman test. Significant overall differences–values were followed by a Wilcoxon test for within groups and the Mann–Whitney *U*-test for between-groups comparisons. All analyses were executed using the SPSS package (version 12). The probability level for statistical significance in all tests was set at $P < 0.05$.

Results

Eighteen patients were recruited in the study. Two subjects were excluded at the baseline tests because they were not able to execute the strength measurement properly. From the remaining 16 subjects (6 female (37.5%) and 10 male (62.5%)) 10 (62.5%) had a stroke in the left hemisphere and six patients (37.5%) had a right hemisphere cerebral accident (11 infarcts (68.7%) and 5 haemorrhages (31.3%)). All patients were enrolled in an inpatient rehabilitation programme 27.2 ± 10.4 days after their stroke. Patients were able to stand, keep their balance at least for 3 minutes, and walk without or with an aid (stick). Patients underwent a medical and neurological evaluation

at baseline. The Barthel²⁵ disability index and FIM²³ score ranged from 25 to 85, and 63–110, respectively (Table 1).

Sixteen subjects were randomized to either the vibration group or the control group. Table 1 shows the baseline characteristics of the participants enrolled in the groups. No significant differences existed across the groups in demographic or stroke history characteristics. The two groups were similar at baseline in the dependent variables with the largest percentage difference of 24% ($P=0.1282$) in biceps femoris co-activation during eccentric contraction (Table 2).

Isometric contraction

Vibration significantly increased maximal voluntary isometric torque by 36.6% in the vibration group ($P=0.0391$) but not in the control group (8.4%) (Table 2). The 19.0% increase in rate of torque development was significant in the vibration group ($P=0.0458$) but not in the control group (10.9%).

Eccentric contraction

Vibration significantly increased 22.2% maximal voluntary eccentric torque in the vibration group ($P=0.013$) but not in the control group (5.3%). Vibration also significantly increased peak eccentric torque measured at 60 degrees 23.1% in the vibration group ($P=0.0107$) but not in the control group (5.3%). Finally, mechanical work during eccentric contraction increased 15.7% ($P=0.0724$) and 9.2% in the vibration and control groups, but the changes were not significant in either group (Table 2).

Myoelectrical activity

EMG_{rms} in the vastus lateralis increased significantly 44.9% ($P=0.0122$) in the vibration group after vibration during isometric knee extension without changes in the EMG_{rms} in the control group (Figure 5). Whole body vibration did not affect the EMG activity in the biceps femoris in either group. Whole body vibration did not influence EMG during fast isometric contractions (Table 2).

Table 1 Clinical features and clinical assessment of patients. Main characteristics (age, start of rehabilitation after stroke in days (duration), type of stroke, side affected, score of Barthel Index and Functional Independence Measure) of the patients randomly assigned to vibration (V) and control (C) groups

Subjects	Sex	Age (years)	Duration (days)	Type of stroke	Side affected	Barthel Index	FIM
V1	F	54	24	Infarction	L	40	80
V2	F	60	22	Infarction	L	45	76
V3	M	55	47	Infarction	R	30	72
V4	M	62	30	Infarction	R	45	93
V5	M	54	32	Haemorrhage	R	39	73
V6	M	62	30	Haemorrhage	R	55	86
V7	M	66	18	Infarction	R	85	110
V8	F	51	22	Infarction	L	48	84
C1	M	46	26	Infarction	L	47	83
C2	M	66	18	Infarction	R	40	70
C3	M	68	19	Infarction	R	75	96
C4	F	48	14	Infarction	L	60	101
C5	M	54	14	Haemorrhage	R	35	63
C6	F	62	41	Haemorrhage	R	48	84
C7	F	76	38	Infarction	R	25	85
C8	M	42	32	Haemorrhage	L	50	86

F, female; M, male; L, left; R, right.

The EMG_{rms} associated with maximum eccentric torque increased significantly 33.2% in the vastus lateralis and decreased 22.5% in the biceps femoris in the vibration group after whole body vibration ($P=0.0013$). In this condition the EMG_{rms} in the control group remained unchanged (Table 2). The co-activation quotient during isometric contraction and eccentric contraction decreased significantly from 23.0 (8.9) to 15.0 (4.0) (31.5%) and from 35.7 (13.3) to 14.5 (11.3) (37.0%), respectively, in the vibration group after whole body vibration ($P=0.0334$ and $P=0.0181$). Other changes in the quotient were not significant.

Median frequency associated with maximum isometric torque increased significantly 13.1% in the vibration group ($P=0.0295$) without significant changes in the control group. Under eccentric conditions, whole body vibration increased median frequency 7.3% in the vibration group ($P=0.0646$) but not in the control group (Table 2).

Discussion

The key findings of this study were that whole body vibration transiently but significantly

increased maximal voluntary strength and reduced the antagonistic hamstring muscle activity during eccentric contraction of the quadriceps muscle. There is now a growing interest in using strength training in stroke rehabilitation.^{5-7,27} Muscle strength is a key contributor to balance and ambulation.^{4,5} Even healthy old adults execute activities of daily living such as walking and stepping at a relatively high percentage of the maximal available voluntary joint torques,²⁶ improving maximal voluntary force of major muscle groups especially in the lower extremities used in locomotion is important. Individuals with a disability, including stroke patients, tend to avoid or minimize efforts that require high intensity. It is thus desirable to consider alternative methods to conventional resistance training that also improve stroke patients' ability to exert high levels of force.²⁷

Mechanical vibration of skeletal muscle to improve maximal voluntary force has recently received considerable attention among rehabilitation experts and fitness practitioners.^{12,17-19}

The potential benefits of mechanical vibration are being exploited in patients with Parkinson's disease and multiple sclerosis.^{20,21} For example, whole body vibration at 2.0-4.4 Hz using 3 mm oscillations positively influenced the postural control and mobility of patients with

Table 2 Group data for torque and EMG variables before and after whole body vibration in the vibration (VG) and control (CG) groups

Variable	Group	Before	After	Change, abs	Change, %	P-value
MIT, Nm	VG	41.0 (23.8)	53.1 (29.0)	10.9 (12.5)	36.6 (40.6)	0.0391
	CG	42.9 (32.8)	45.8 (38.0)	2.9 (17.4)	8.4 (35.6)	
RTD, Nm/s	VG	144.4 (74.2)	162.2 (70.4)	17.8 (27.8)	19.0 (24.8)	0.0458
	CG	123.2 (87.1)	138.9 (105.0)	15.6 (25.4)	10.9 (19.2)	
Mec, Nm	VG	76.7 (60.9)	88.7 (63.9)	12.0 (11.3)	22.2 (28.9)	0.013
	CG	67.5 (52.0)	69.9 (56.6)	2.4 (25.2)	5.3 (36.9)	
Mec60, Nm	VG	69.3 (55.0)	80.7 (58.1)	11.5 (10.4)	23.1 (29.2)	0.0107
	CG	63.5 (48.9)	65.2 (52.4)	1.8 (23.7)	5.3 (36.0)	
Wec, J	VG	48.3 (34.5)	55.3 (39.7)	7.0 (10.2)	15.7 (27.6)	0.0770
	CG	50.5 (34.2)	55.0 (38.1)	4.5 (9.5)	9.2 (21.0)	
VL MIT EMG, μ V	VG	197.8 (113.5)	270.1 (150.9)	72.3 (67.3)	44.9 (38.5)	0.0112
	CG	195.3 (146.0)	219.9 (182.5)	24.6 (62.7)	10.6 (32.7)	
BF MIT EMG, μ V	VG	41.9 (19.0)	40.04 (23.2)	-1.5 (6.7)	-8.4 (20.2)	0.5815
	CG	41.9 (28.4)	43.4 (32.5)	2.0 (10.7)	6.1 (23.7)	
VL ICf EMG, μ V	VG	185.2 (102.1)	204.3 (99.3)	19.1 (20.5)	6.3 (15.2)	0.435
	CG	175.3 (135.2)	189.4 (143.3)	14.1 (20.4)	7.6 (13.4)	
BL ICf EMG, μ V	VG	39.8 (18.1)	39.6 (20.2)	-0.2 (6.2)	-0.5 (6.5)	0.873
	CG	39.2 (22.2)	40.5 (24.7)	1.3 (7.2)	3.3 (10.2)	
VL EC EMG, μ V	VG	172.1 (98.7)	216.1 (120.7)	44.0 (51.6)	33.2 (35.4)	0.0333
	CG	67.5 (51.4)	69.9 (53.7)	2.4 (22.7)	9.0 (33.6)	
BF EC EMG, μ V	VG	54.5 (24.7)	44.4 (25.5)	-10.1 (6.3)	-22.5 (17.1)	0.0013
	CG	62.1 (42.6)	60.8 (45.4)	-1.3 (14.6)	-1.0 (22.1)	
Co-activity-MIT, %	VG	23.0 (8.9)	15.0 (4.0)	-8.9 (10.4)	-31.5 (25.5)	0.0334
	CG	21.9 (5.0)	21.8 (7.1)	-0.1 (9.9)	6.8 (53.4)	
Co-activity-Mec, %	VG	35.7 (13.3)	14.5 (11.3)	-15.1 (15.3)	-37.0 (15.1)	0.0181
	CG	89.1 (29.7)	77.9 (12.9)	-11.2 (28.3)	-0.6 (43.7)	
MF-Isometric, Hz	VG	36.4 (7.9)	40.6 (6.4)	4.2 (4.8)	13.1 (12.4)	0.0275
	CG	35.9 (10.1)	37.5 (12.3)	1.7 (3.6)	3.9 (10.3)	
MF-Eccentric, Hz	VG	34.6 (7.7)	37.4 (9.4)	2.7 (3.8)	7.3 (11.7)	0.0646
	CG	34.1 (11.4)	35.4 (7.7)	1.3 (2.6)	3.1 (7.7)	

Values are mean (\pm SD).

Change, absolute change: MIT, maximal voluntary isometric torque; RTD, rate of torque development; ICf, fast isometric contraction; Mec, maximal voluntary eccentric torque; Mec60, maximal voluntary eccentric torque at 60 degrees of knee flexion; Wec, mechanical work during maximal eccentric voluntary contraction; VL, vastus lateralis; BF, biceps femoris; MF, median frequency of the surface electromyogram.

P-value refers to the unpaired two-tailed *t*-test on absolute change.

multiple sclerosis.²² Whole body vibration also improved postural stability, rigidity and tremor in patients with Parkinson's disease.^{20,21} In stroke patients Whole body vibration or vibration delivered to specific muscle groups produced favourable transient effects on postural control and the ability to walk,^{18,28} but chronic exposure to whole body vibration in this patient population was no more effective than exercise therapy.²⁹

In exploring an appropriate adjunct to resistance training in stroke patients, one must select carefully the parameters of mechanical vibration

such as frequency, amplitude and duration (for review see Luo *et al.*²⁹). Because high-frequency (30–40 Hz) and small-amplitude (1 mm) vibration of muscle can cause fatigue,^{13,15} we applied whole body vibration at 20 Hz and 5 mm amplitude. Indeed, recent studies using such vibration parameters in healthy young adults reported an increase in voluntary force^{12,13,15} without fatigue³⁰ and a reduction in producing finely graded forces.³¹ All in all, whole body vibration at 20 Hz and 5 mm amplitude appears to be safe and effective to produce

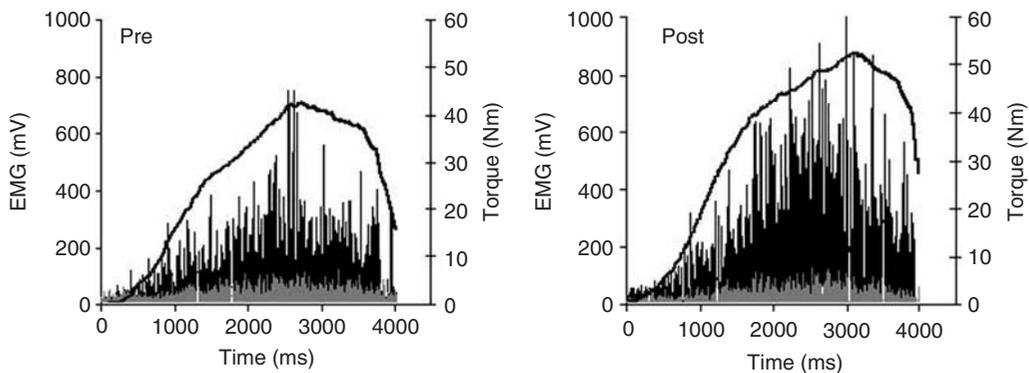


Figure 5 Torque (solid line) and electrical activity of vastus lateralis (black signal) and biceps femoris (grey signal) prior (pre) and after (post) vibration treatment for one of the patients in group VG. The figure clearly shows improvement in MIT and increased electrical activity of VL.

adaptations in the neuromuscular system in stroke patients as well.

A stroke can impair individual leg muscles to a different extent. However, instead of vibrating individual leg muscles²⁸ we exposed our patients to whole body vibration while standing on a vibrating platform in a crouched position. While vibrating individual muscles would permit more specific targeting of affected muscles,²⁹ whole body vibration used in its current form actively involves the patient, requires balance and activates several lower extremity muscles, including the quadriceps that is in a mildly stretched position. The crouched posture emphasizes the quadriceps muscle's involvement and dampens the propagation of acceleration waves to the head through the skeletal system.

We also evaluated the effects of whole body vibration on rate of torque development, a property of the neuromuscular system associated with rapid force generation and explosive muscle actions. Because mechanical vibration of a tendon and muscle modulates the ascending sensory input to motor cortical areas³² and selectively activates Ia afferents,³³ we anticipated that whole body vibration could acutely increase rate of rate of torque development in the paretic muscles of stroke patients. Indeed, whole body vibration significantly improved rate of torque development 19.0% but the associated EMG activity increased only 6.3% (not significant). This dissociation suggests that the improvement in rate of torque

development was mediated by mechanical rather than neural factors. That is, the rate of torque development increased because the maximum isometric torque increased with little contribution from early recruitment of high threshold motor units. This means that the tangent (dM/dt) fitted to the steepest part of torque–time curve was greater after than before whole body vibration, because the torque improvement was higher during the same period of time, but not because the time decreased to reach the same torque. However, the change in rate of torque development after one session of whole body vibration may have implications for rehabilitation because Pohl *et al.*³³ reported that rate of torque development, more so than peak torque, was a good predictor of gait speed in stroke patients. Our patients anecdotally reported that they felt more confident and stable walking after whole body vibration.

In addition to isometric force production, human movements also involve eccentric muscle contractions. The new finding was that whole body vibration significantly increased voluntary eccentric torque in stroke patients. We suspect that this increased force production is related to increased muscle activation, reflected by the higher EMG activity during the test contraction, especially through the involvement high threshold motor units.³⁴ The increase in median frequency may indicate that new motor units were recruited during the eccentric test contraction after whole

body vibration. In addition, the elevated eccentric torque can be attributed to the significantly decreased EMG activity of biceps femoris (−22.5%) and the lower co-activation quotient (−37.0%). Our results agree with previous data³⁵ suggesting that vibration provides an effective source of excitatory input to motor neurons because Ia terminals are subjected to less presynaptic inhibition and post-activation depression in patients with spasticity than in healthy subjects.³⁶

In the present study the surface EMG activity of the vastus lateralis muscle increased 44.9% during a maximal voluntary isometric contraction performed after whole body vibration. The elevated EMG activity after whole body vibration may indicate that patients were able to recruit more motor units than before. The EMG activity and maximal voluntary torque did not change in the control group. These data suggest that the stretched position and whole body vibration may have an additive effect on voluntary strength because control patients also assumed the crouched position for the same time period, did not receive vibration, and did not reveal increased voluntary torque. The additive effect may be because vibration of 20 Hz or lower is known to maintain or even increase the stretch-related afferent input to the motoneuron.³⁷

The present study has several limitations. It is unclear how long the beneficial effects last after one bout of whole body vibration. Torvinen *et al.*¹¹ found that knee extensor strength and performance in vertical jump measured 2 minutes after whole body vibration improved, but the benefits of vibration disappeared in 1 hour. We tested our patients 5–10 minutes after whole body vibration and observed significant increase in voluntary muscle strength and EMG activity. It seems that the residual effects of whole body vibration peak between 2 and 60 minutes after whole body vibration. It is also unclear if simple increases in muscle strength would improve function such as gait or manipulative tasks. Also, the use of whole body vibration is limited because it can only be applied to those patients who can stand in a crouched position. Another weakness of the present study is that we had small sample size ($n=8$ for each group) preventing us from dividing the sample into subgroups on the basis

Clinical messages

- One bout of whole body vibration (20 Hz frequency, 5 mm amplitude) transiently increases isometric and eccentric strength of knee extensors at the affected side.
- Whole body vibration may help to increase the effectiveness of the subsequent functional rehabilitation programme.

of severity and type of the stroke. Larger sample size may allow selection of individual vibration frequency that may result in more pronounced improvement in strength. Finally, this study did not examine the mechanisms by which whole body vibration increases maximal voluntary muscle strength, which can include neural,^{35–38} metabolic³⁹ and hormonal^{40,41} factors.

In summary, one bout of low-frequency (20 Hz) and small-amplitude (5 mm) whole body vibration increased maximal isometric and eccentric voluntary knee extension torque in stroke patients. The surface EMG activity of the vastus lateralis during these efforts also increased with selective reductions in antagonist hamstring muscle co-activity. Future studies will determine if chronic exposure to whole body vibration can improve function in this patient population.

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