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A Novel Vibration Device for Neuromuscular Stimulation for Sports and Rehabilitation Applications

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***Abstract*— Vibration has been increasingly sought after as new technique, due to its potential to increase muscle strength and positively affect bone remodeling. Currently, there are many vibration devices on the market advertised for different applications, in particular in sports and rehabilitation. All the available devices have two major drawbacks; firstly, they are not sufficiently adaptive to the individual user's needs and secondly, they do not require any force input from the user. Our novel vibration device addresses these drawbacks with new mechanical design and bringing innovative approach to 'how it operates'.**

I. INTRODUCTION

Mechanical vibration is an oscillatory stimulus. Vibration is characterized by its parameters; distance covered by oscillatory motion determines its amplitude (in mm), number of repetitive cycles of the oscillation gives frequency (in Hz) and magnitude is derived from acceleration of these oscillations.

Vibration is broadly categorized into two types 'whole body vibration (WBV)' and 'local vibration (LV)'. WBV occurs when the complete body is undergoing vibration and effect is not limited locally, whereas LV takes place when one or more limbs or parts of a body are undergoing vibration and the effect is local.

Vibration has been studied in depth in occupational medicine, mostly for its ill effects. However, recently there is renewed interest in positive effects of vibration in applications ranging from sports to rehabilitation.

In sports, the use of vibration as an exercise intervention is an increasingly researched topic. In one study, local vibratory stimulation at 44 Hz was shown to increase explosive muscle strength in arm muscles of both elite and amateur athletes [1]. Exposure to 26 Hz WBV training increases the power and force of muscles in female volleyball players [2]. In another study, 5 minutes of WBV at 20 Hz increased the hamstring's flexibility and squat jump performance by 10.1% and 4% respectively [3]. 30 Hz exposure to local vibration resulted in a significant increase in the power of arm flexor muscles of professional boxers [4]. In one comparative study, application of 35-40 Hz WBV on 67 untrained females led to strength gains in knee extensor muscles to the same extent as resistance training at moderate intensity would have lead [5]. Another study involving 30 Hz application of WBV concluded that WBV can be used as a warm up procedure to increase strength gains in muscles [6]. Four months of WBV training enhanced jumping power in young adults, the frequency was varying from 25 to 40 Hz [7].

The effects of vibration therapy in rehabilitation and therapeutics have also been widely reported, illustrating its positive effects. A recent study has shown, an increase in knee extension strength and speed of movement, in older women [8]. The study involved 24 weeks of WBV intervention on 89 postmenopausal women. Elsewhere, the effect of 6 months of WBV therapy on postmenopausal women indicated an improvement in muscle strength and significant increase in bone mass density (BMD) [9]. WBV therapy is also suggested as a potential treatment in treating body balance and mobility in the elderly [10]. 6 months WBV treatment has been effective in reducing chronic lower back pain [11]. Vibration also seems to be promising option in tackling bone disorders, especially osteopenia and osteoporosis [12], [13]. Vibration, a mechanical stimulus, has been put forward as a non-pharmacological intervention for osteoporosis [13]. A one year study on sheep, with application of 30 Hz and 0.3g vibration, for 20 min per day for 5 days a week, resulted in significant increase in bone density [14]. A similar type of study on young osteoporotic females, with the application of 30 Hz, 0.3g vibration, 3 times a week for 8 weeks showed a significant increase in cancellous and cortical bone density [15]. Another year-long study on Postmenopausal women, with the application of 30 Hz, 0.2g vibration for 10 minute treatment twice a day, demonstrated effective inhibition of bone loss in the spine and femur [16]. Low magnitude vibration has also been proven osteogenic in disabled children [17]. A 6 months study on disabled children, with 0.3g and 90 Hz vibration, for 10 min per day, 5 days per week, resulted in significant increase in the trabecular bone of the weight bearing regions of the skeleton.

These mentioned studies were undertaken with variety of commercially available and custom made vibration devices. Existing WBV devices are capable of delivering, frequencies ranging from 5-60 Hz, amplitudes from less than 1 mm to 10 mm and accelerations ranging from less than 1g to 15g (where 1g is the acceleration due to the gravity ≈ 9.81 m/s^2). These vibration devices currently available on the market, deliver vibration to the whole body generally through oscillating plates. These oscillating plates are of two types

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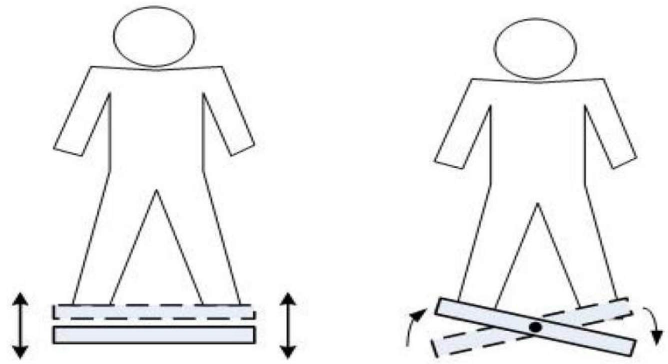

(a) (b)

Fig. 1. (a) Platform moving up and down. (b) Platform moving left and right

(a) the whole plate moves uniformly up and down, (b) plate rocks oscillating to the left and right side of the fulcrum, see Figure 1.

Considering the possibility of large variations in frequency, amplitude and acceleration, and the different devices on offer, it is difficult to decide which vibration protocol is most suitable for a particular application. Besides this uncertainty, all the vibration devices currently available on the market have two main drawbacks that they do not require any input or physical exertion from the user and they offer very limited options in varying vibration stimulus (i.e. frequency, amplitude, etc). With current (WBV) machines, the user stands passively on the vibrating platform and has no active involvement of the muscles in the whole process except for maintaining balance while standing. This expends little energy, hence contributing little to the fitness of the user. Also, the limited variability in vibration stimulus (i.e. frequency, amplitude, etc) limits the benefits of the training, by not being adaptive enough to an individual's needs and therefore being less effective than it might be. Considering the complexity and wide variety of effects of vibrations, it is crucial that vibration delivery is tailored to the individual's need.

Recent work from Mischi and Cardinale [18] have indicated that the benefits of vibration are apparent only if superimposed to high levels of muscle tension in the biceps brachii muscle. Cardinale and Wakeling [19] also suggested that muscle tuning should be taken into consideration when prescribing vibration training programs, as the most effective stimulus may be a combination of vibration input and muscle tension. Considering the limitations of the current equipments on the market, we aimed to design a novel device which would allow users to exercise with vibration stimulation superimposed to various levels of muscle tension. In this work we aimed to validate the technology with preliminary investigations on the ability of such approach to increase muscle activity.

The device presented in this paper overcomes the drawbacks of existing machines by introducing novelty in 'How the device delivers the vibrations?' and 'How much vibration is delivered?' This approach further adapts the vibration delivery according to the individual's needs.

II. Materials and Methods

A. The Concept

The principle difference in comparison with existing vibration devices is that the user has to expend a certain amount of energy, i.e. apply a threshold level of force/pressure, in order to trigger application of the vibration. Here we hypothesize; active neuromuscular involvement of the user in receiving vibration stimulation will be more beneficial as compared to passive reception of vibrations. Moreover, as the user has to spend energy (force applied) in order to receive energy (vibration stimulation); the extent of vibration the user receives is relative to the extent of force he/she applies. Also, the user has fine control over the frequency and duration of the vibration. Thus the vibration stimulation can be closely tailored to the individual's capacity and need (selection of parameters).

B. System Overview

The vibration device presented in this paper consists of (1) Vibrating motors, (2) Sensors attached to the moving parts of the device, (3) Sensors attached to the body of the user, see Figure 2.

1) Vibrating motors: Two contra-rotating motors (Vibratechniques Ltd., UK, Model: MVSI- S90) attached to a spring mounted plate generates sinusoidal vibrations. As the motors contra-rotate they cancel out forces in all directions except in one axis where the forces add up (see positions 1 and 3 in Figure 3). This results in a sinusoidal force in one direction; as the motors are attached to the plate, this ultimately leads to the vibration of the plate in a direction towards and away from the user.

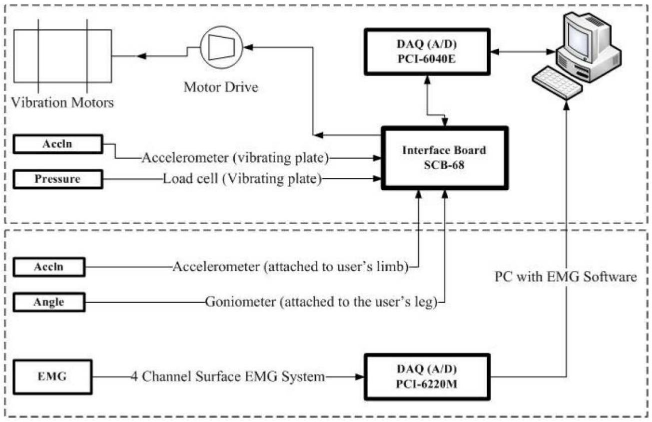

Fig. 2. Block diagram of device's components and their interface with the PC.

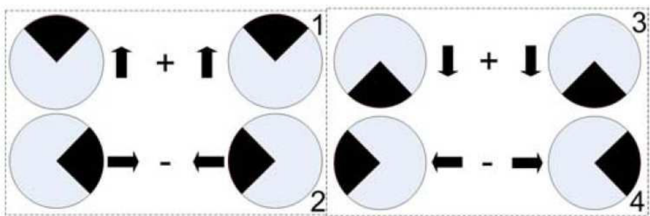

Fig. 3. Schematic of cancellation and addition of the motor forces

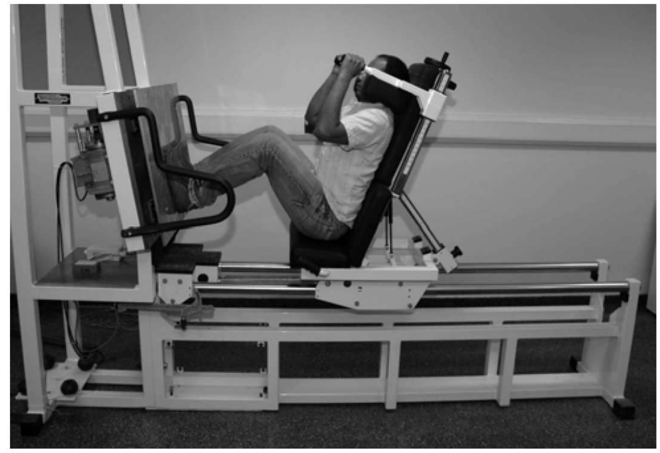

Fig. 4. Side view photograph of the vibration device

2) Sensors attached to the chassis of the device: An accelerometer (Kistler Instrument Corp., Model: K-Shear-8704B25) attached to the vibration plate senses the real time acceleration at which the plate is vibrating. A pancake type load cell (Procter & Chester Measurements Ltd., UK, Model: BD-PLC-C) sandwiched between vibration plate and the foot plate measures real time load applied by the user. The Foot plate is the plate attached immediately to the vibration plate, against which user pushes to receive vibrations.
3) Sensors attached to the body of the user: Three sensors are attached to the body of the user. Four, single differential surface Electromyography (sEMG) electrodes (Delsys Inc., USA, Model: Bagnoli DE-2.1) are attached to the lower limbs of the user to sense the real time muscle activity resulting from vibration delivery. A Goniometer (Measurand Inc., Canada, Model: S700, Shape Sensor) for knee angle measurement is mounted on the knee of the user and a miniature tri-axial accelerometer (Analog Devices Inc., Model: ADXL330) is attached to the upper limb of the user to sense the acceleration transmitted to the upper limb through the legs.

C. Interfacing of the vibration device

Vibration motors, the associated sensors and sensors attached to the body of the user, are all interfaced to a Personal Computer (PC), see Figure 2. The vibration motors are interfaced with the PC so be able to control their speed. The motors are driven by a motor drive (Vibratechniques Ltd., UK, Model: VSC) which is connected to the PC via an interface board (NI, USA, Model: SCB-68). Drive is connected to the interface board through small circuitry to electrically isolate the drive and PC, to prevent any power line and noise interference between the two. The accelerometer and load cell attached to the foot plate are both connected to the PC through the same interface board (SCB-68). Interface board is interfaced with the PC with PCI data acquisition (DAQ) card (NI, USA, Model: PCI-6040E).

The accelerometer and goniometer attached to the body of the user are connected to the PC via the same interface board and DAQ card. A standard, ready to use EMG system (Delsys Inc., USA, Model: Bagnoli) with four surface electrodes is connected to the PC via a shielded cable (NI, USA, Model: SH68-68-EP) and a separate DAQ card (NI, USA, Model: PCI-6220M).

D. Software

Motors were controlled from the PC with a program written in NI LabVIEW 8.5. Data from the sensors i.e. from accelerometer (plate attached, body mounted) and load cell are acquired, stored and analyzed with LabVIEW program. The EMG and goniometer signals are acquired, stored and analyzed with readymade EMGworks software, Version 3.6 supplied by Delsys Inc.

III. Experimental Setup

A. The device and user's position

The user sits on the device seat with backrest; with his/her leg half flexed (90° knee angles) and pushes against the vibrating foot plate, as opposed to current WBV devices where the user stands on vibrating platform, see Figure 4. As mentioned above, the knee angle while exercising is kept close to 90°. This is continuously monitored through the goniometer. The position of the seat and backrest can be manually adjusted towards and away from the foot plate, to accommodate users of different height. This also helps in-turn to keep knee angle of 90°.

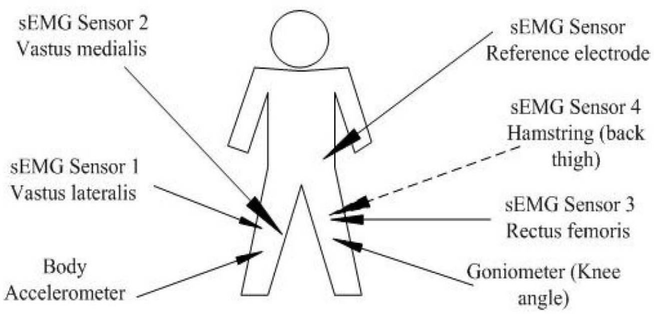

Fig. 5. Body sensors' location map

B. Sensor placements

A pictorial view of the sensor placement used in this study is shown in Figure 5.

1) EMG electrodes: The four sEMG electrodes are placed on the lower limbs of the user while using the vibration machine. Three electrodes are placed on the front thigh (Vastus Lateralis, Vastus Medialis and Rectus Femoris) muscles and one on the back thigh (Hamstrings) muscle. A reference electrode is placed on a bony prominence area to minimize the EMG activity detection by the reference. The surface electrodes are placed in the centre of the muscle belly with proper orientation with respect to the muscle fibers underneath, so as to maximize quality signal detection. Surface electrodes are fixed to the skin with mono-use, medical grade adhesive sensor interfaces. This adhesive interface insures good electrical connection between the electrodes and skin, and minimizes motion artifacts.
2) Accelerometer (body mounted): The miniature accelerometer is mounted on the lower limb of the user. The accelerometer is affixed to a Velcro strap for ease of use which is then tied around a limb.
3) Goniometer: This sensor is mounted on either leg of the user to measure the knee angle while using the device. The sensor consists of two plastic enclosures attached by a vinyl -covered metal cantilever and offers single degree of freedom. The two plastic enclosures are mounted on the skin with the double sided adhesive tape. Care is taken that cantilever part does not come in contact with the skin, so as to achieve accurate angle measurement.

IV. Maximum Voluntary Contraction (MVC)

As aforementioned, the novelty of this device lies in the 'delivery' and 'control over the parameters' of the vibration. This is achieved with the new design and adaptive software.

To start with, the user performs an isometric leg press exercise with maximum push effort, against the steady foot plate. The value of this effort is recorded as the Maximum Voluntary Contraction (MVC); the individual is capable of producing, see Figure 6 . Then, within the software, a threshold (force) level for receiving vibrations is set; where the threshold is a percentage value of the MVC. For example, assuming the MVC value is recorded and threshold is set at 50% of the MVC; then, if the user applies a force which is equal to greater than 50% of the MVC; he/she will start receiving vibrations. Also, the user has to keep applying at least the threshold level force to continue receiving vibrations. As soon as his/her applied force level drops below the threshold, vibration delivery stops. The threshold level is easy to set within software and can be varied from 0 to 100% of individual's recorded MVC value.

In summary, reception of vibration in this device, depends on (1) the MVC, which measures the user's maximum capacity and (2) the duration of the force application, i.e. how long the user 'wants to' or 'can keep' applying the minimum level of force.

V. Results

Two healthy male volunteers aged 30 and 50 were subjected to vibrations of 4.28g at 30 Hz and 19g peak to peak at 50 Hz. sEMG data was collected under three conditions (1) no activity (baseline), (2) 100% MVC with no vibration (control) and (3) 100% MVC with vibration (both at 30 Hz and 50 Hz). Data was collected for duration of 40 sec each and five minutes rest was allowed between each exercise condition. WBV with the device led to an increase of EMG root-mean-square (EMGrms) activity of level of all four muscles analyzed, namely the Vastus Lateralis, Vastus Medialis, Rectus Femoris and Hamstring, see Figures 7 and 8. The highest increase in EMGrms activity, at 50 Hz, in both volunteers, was observed in Vastus Lateralis followed by the Rectus Femoris. The Vastus Medialis also showed an increase in EMGrms signal but the hamstring muscles displayed little increment in EMGrms. Irrespective of muscle group, there was a clear increase in EMGrms signal when exposed to vibration as compared to the control condition. Also, an increment in EMGrms from baseline condition to control condition is clearly represented in the values above. Vibration delivery at 30 Hz displayed similar results, with increase in EMGrms of all four muscles particularly of the Vastus lateralis and the Rectus Femoris. Again the Hamstring showed only a small increment in EMGrms.

VI. Discussion

This paper has introduced a novel vibration device for neuromuscular stimulation for sports and rehabilitation application. The apparatus and methodology of this device were tested with two subjects and showed that it was possible to superimpose vibration stimulation even while the subjects were exerting a force equal to 100% of their MVC. This is quite encouraging, as it would offer many uses ranging from training elite athlete to patients in hospitals. One current limitation of the device is its bulkiness and therefore it is not portable or mobile, however further research projects will be directed towards developing portable tools with similar functionalities to be able to apply this technique in various settings. Preliminary results of vibration treatment with this device show an increase in the EMG activity of

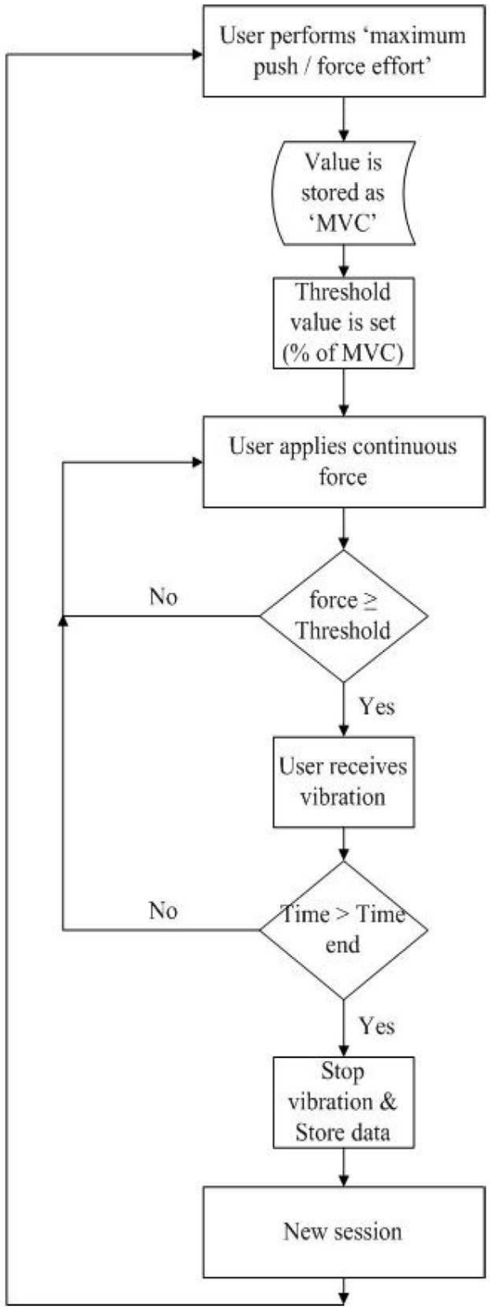

Fig. 6. Device vibration delivery flowchart

the principle muscles involved in the exercise as compared to nonvibrating condition. As the EMG amplitude increases in parallel with the levels of force produced by muscles, this increase in EMGrms is representative of an increase in force level. Muscle tuning response to sinusoidal force modulated signals has previously been shown not only to be affected by the frequency and amplitude of such signals [20] but also by muscle stiffness [21], [22]. An increase in neuromuscular activity as identified by a rise in EMGrms in target muscles would suggest muscle tuning response and added benefit of vibration as a training stimulus if such

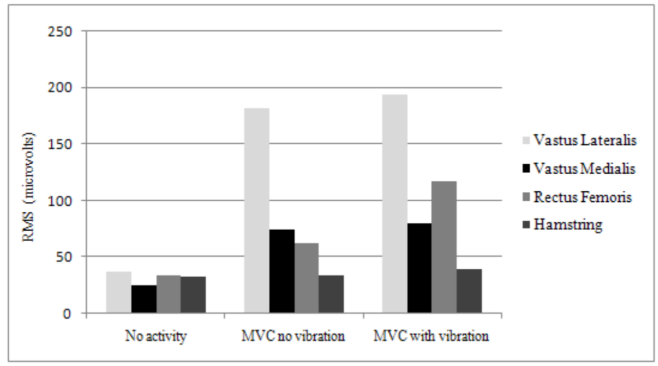

Fig. 7. activity bar chart of the first participant, y- axis (rms) levels in micro volts.

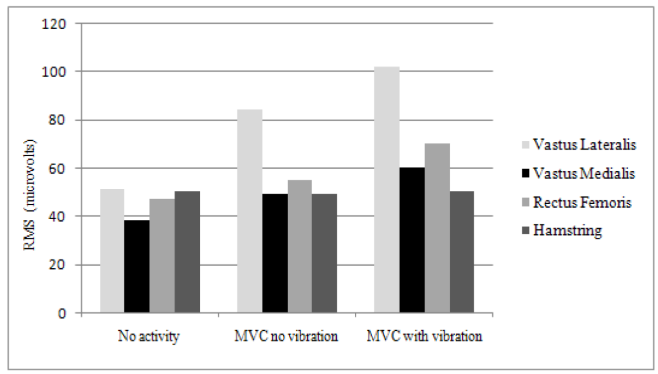

Fig. 8. RMS activity bar chart of the second participant, y- axis (rms) levels in micro volts.

activity is higher than conventional resistance exercise. Our preliminary data suggest in both subjects an increase in the leg extensors but not in the hamstrings muscles when vibration is superimposed at an MVC.

Clearly, EMG signal could be used to measure and analyze the muscle activation and to optimize the vibration treatment so as to tailor it to individual's needs and capacity. However caution should be applied when interpreting results related to vibration stimulation as appropriate filtering techniques need to be applied in order to exclude noise. The next step will be to study the chronic effects of WBV on large number of individuals with this device. The factors to analyze will be muscle recruitment, synchronization, inter and intramuscular coordination and proprioceptor's responses, as these are the principal factors in enhancement of neuromuscular performance [20].

Also, the results of different vibration frequencies and amplitudes will be analyzed to identify the vibration load individual can sustain and to probe its effectiveness. These studies should help to indentify more effective vibration protocols suitable to an individual's requirement and capacity.

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