Vibrations and their applications in sport

A review

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In sport, mechanical vibration is used as a massage tool and/or for training purposes. Two varieties of vibration training (VT) can be distinguished: strength exercises with superimposed vibratory stimulation (VS exercises) and motor tasks performed under whole-body vibration (the WBV training). Vibratory massage has been used extensively since the beginning of the 20th century while VT is a relatively new technique. In the research literature, the main subjects addressed have been acute and cumulative effects of VS on flexibility and strength. Marked enhancement effects were obtained in medium-duration stretching and short-duration dynamic strength exercises while prolonged efforts did not show positive impact. The observed effects of vibration depend on various neural facilitatory and inhibitory mechanisms. In comparison to VS exercises, WBV tasks generate more global neuromuscular, metabolic and hormonal responses. WBV training resulted in significant changes in several motor variables, with stretch-shortening cycle tests (such as countermovement jumps, serial high jumps, etc.) being the most sensitive to WBV treatment. Based on available knowledge about proprioceptive spinal reflexes that feedback from the primary endings of motor spindles produces a stimulatory effect via increased discharge of α-motoneurons, and activation of Golgi tendon organs (GTO) evokes inhibition of muscle action—a hypothesis has been proposed that VT enhances excitatory inflow from muscle spindles to the motoneuron pools and depresses inhibitory impact of GTO due to the accommodation to vibration stimuli. The intensity and duration of vibration used in VT dramatically exceed the standards for occupational vibration established by the International Organization for Standardization.

KEY WORDS: Vibration – Exercise – Training, effects.

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Vibrations, i.e. periodic mechanical oscillations applied to an athlete’s body, are of special interest from both the scientific and practical viewpoints. While the use of vibration is not new—vibration as a medical technique was mentioned in ancient Greco-Roman sources (cited in Snow) and vibratory massage (VM) was popular among physicians in the 19th century—the use of mechanical vibration for training purposes began attracting interest less than 2 decades ago. Since then much information has been accumulated enough, in fact, to discern a new branch of applied sport science and exercising practice-vibration training (VT).

The application of vibrations in sport embraces 2 major areas: VM and VT. The latter contains 2 varieties: 1) physical exercises with local vibration, and, 2) motor tasks performed under vibration of the whole body (whole body vibration, WBV). The sport industry produces various devices for vibration treatment that attract many potential users, which is why it is important to analyze, summarize and discuss the most relevant aspects of vibration application in contemporary sport. This is the purpose of the present review.

Vibratory massage

Retrospective analysis reveals 2 chronological periods when VM was extensively studied. The first one
was the beginning of the 20th century when the basics of vibratory treatment were founded. At that time a number of pioneer investigations was conducted by world renowned experts and at least 2 books devoted to vibratory massage were published.\textsuperscript{1, 2} The latter publications were focused on 2 principal aims of the VM: restoration and stimulation/mobilization. The main characteristics determining the effect of VM are vibration frequency and procedure duration. Low-intensity VM with a 15-50 Hz frequency band increases oxygen uptake, blood and muscle oxidation, local and general blood circulation, local temperature in massaged tissues, and muscle enzymes activation.\textsuperscript{8} Other effects include marked general relaxation, relaxation of myofascial tissues, decrease of emotional tension and general sedative effect.\textsuperscript{9, 10} High-frequency VM (100-170 Hz) of high intensity increases excitability of the central nervous system and raises blood pressure.\textsuperscript{8} Professional reports provide evidence that this VM mode increases muscles tone and impart them the quick heating effect.\textsuperscript{10-12}

Sport-related studies of VM were initiated in the 1960s with 2 major goals:

1) to activate restorative processes and thereby enhance athletes’ adaptability to higher training workloads, and

2) to increase athletes’ working potential and their readiness for forthcoming competitive or training efforts.

It was found that positive effects could be induced by both low-frequency \textsuperscript{11, 13} and high-frequency VM.\textsuperscript{12} The procedure duration in these studies (as well as in regularly accepted practice) differed depending on VM mode: low-frequency VM usually lasted about 20-30 min while high-frequency VM was much shorter, lasting about 3-5 min.\textsuperscript{11}

It has been reported that VM incorporated into warm-up procedures had a stimulating effect on sport-specific performances of kayakers, speed skaters, weightlifters and boxers.\textsuperscript{11} However, the placebo effect cannot be discounted in this study. Moreover, the reported outcomes were inconsistent with the study of the VM impact on maximal leg force,\textsuperscript{14} which did not find any positive effect. Unfortunately, it is not clear what vibration frequency was used in the latter study. Another study revealed enhancement of force differentiation in fresh muscles after vibration treatment of 130-160 Hz while the fatigued muscles did not show this effect.\textsuperscript{15}

Many researchers reported the analgesic effect of VM.\textsuperscript{8, 16, 17} It was emphasized that a powerful local anesthetic action is the main benefit of VM, which can be exploited in various situations.\textsuperscript{16} In particular, VM is useful for treating musculoskeletal pain.\textsuperscript{18} VM of 10-15 Hz effectively reduced muscle soreness caused by strength and endurance workouts.\textsuperscript{11}

The physiological mechanisms of VM that decrease muscle soreness and speed restoration processes are mainly unknown. Several studies pinpointed the mechanoreceptors that are particularly sensitive to vibration; they are the Pacinian corpuscles and the primary endings of the muscle spindles.\textsuperscript{19} More effective restoration and pain alleviation was obtained by using moderate pressure and cushioning when a large surface area and a larger volume of the underlying tissues were affected. Such manipulations can activate the Pacinian corpuscles in connective tissues, ligament and joints, and primary endings of motor spindles. Other receptors located in skin, subcutaneous tissues and bones may also contribute to this effect.\textsuperscript{19}

The restorative effect of the VM is frequently attributed to the improvement of circulation. Rhythmic low-frequency mechanical oscillations of subcutaneous and deep tissues produced by VM consistently increase blood flow, enhance capillary permeability and the transport of metabolites accumulated during previous work.\textsuperscript{12, 16, 17}

\textbf{Vibration training}

Mechanical vibration may induce non-voluntary muscular contraction. Vibration can evoke contraction even in muscles that are unable to react to electrical stimu li.\textsuperscript{1} The effect was initially attributed to the possible “increase in the activity of a nerve cell or of the part to which it is applied”.\textsuperscript{7} The phenomenon of vibratory induced non-voluntary contraction was thoroughly studied later and Eklund and Hagbarth\textsuperscript{20} coined the term tonic vibration reflex (TVR). Extensive attempts were made in a number of physiotherapeutic techniques to exploit TVR to facilitate contraction of paretic or damaged muscles.\textsuperscript{21, 22}

In physiotherapeutic and clinical settings vibratory stimuli are applied to the targeted muscle or tendon. This stimulation mode is not suitable for training athletes. A more appropriate approach for the sport practice is based on the application of vibration to the entire limb or even to the entire body. This approach
can be implemented, for instance, via vibrating plates which transmit vibratory wave from distal-to-proximal body links while the muscles are either contracted or stretched.\(^3\)\(^4\) Such equipment makes it possible to combine static stretching and/or contraction with locally transmitted superimposed vibration. The intensity of vibrating load is characterized by vibration acceleration that depends on frequency and amplitude of oscillation.

To perform dynamic exercises with full range of motion; the original vibratory stimulation (VS) modulus was modified so that mechanical oscillations were transmitted via the cable to a specific ending element—such as a handle, strap or cushioned ring—and then on the athlete's extremity.\(^5\)\(^23\) Both techniques—static and dynamic—were employed for flexibility and strength training. The oscillation frequency in these exercises—from 4 Hz to 70 Hz—was much lower than the frequencies used in clinics, which were usually in the 50-300 Hz range.\(^21\)\(^24\) The differences are determined by the mechanics of vibratory wave propagation: high-frequency vibration is absorbed by soft body tissues whereas the low-frequency component propagates well through the contracted or stretched muscles.\(^25\)

In comparison to local vibration, whole body vibration is a relatively new technique.\(^26\)\(^-\)\(^28\) It was suggested for use although the adverse effect of the WBV exposure was well known and widely discussed.\(^29\)\(^-\)\(^30\) This innovation may have been based in part on previously conducted studies on local vibration. In any case, both VS and WBV exercises are worthy of serious consideration, and both the acute and the cumulative effect on motor output and physiological responses deserve to be addressed.

**Using vibration for flexibility training**

Enhancement of athletes' flexibility as a result of vibration training has been shown in both short-term and long-term studies. Nazarov and Zilinsky\(^3\) found significant acute effect of shoulder joint stretching performed on vibrating gymnastic rings. The net duration of vibration stimuli was 4 min per session. Fourteen gymnasts increased their range of motion, which remained on the improved level for 30 min. A similar training over 4 days induced more pronounced and statistically significant gains (n=39, p<0.05).

Issurin* et al.\(^23\) studied the effect of lower body flex-

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Table I.—Summary of the acute effect of superimposed VS on the force and power output.

<table>
<thead>
<tr>
<th>Source</th>
<th>Effect</th>
<th>Subjects</th>
<th>Exercise and vs conditions*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Armstrong et al., 1987</td>
<td>Vibration causes the grip force increase by 55%</td>
<td>14 healthy men</td>
<td>Holding a cylinder during 60 s with vibration 0, 40 and 160 Hz; 49 m/s²</td>
</tr>
<tr>
<td>Samuelson et al., 1989</td>
<td>Vibration reduces the time of sustained contraction by 29.8%</td>
<td>8 healthy 20-year-old men</td>
<td>Isometric knee extension until the force decrease (15-23 s); 20 Hz; 20 m/s²</td>
</tr>
<tr>
<td>Samuelson et al., 1989</td>
<td>Vibration reduces the exercise time by 21.7%; no difference in HR and blood pressure</td>
<td>8 healthy 20-year-old men</td>
<td>The long lasting ergometry cycling with and without vibration applied to pedal; 20 Hz; 20 m/s²</td>
</tr>
<tr>
<td>Bongiovanni and Hugharth, 1990</td>
<td>VS enhances the force contraction in moderate efforts and when the muscles are fatigued</td>
<td>5 healthy subjects aged 33-63 years</td>
<td>Ankle dorsiflexion in series of brief contractions with and without VS applied over the muscles' tendon; 150 Hz</td>
</tr>
<tr>
<td>Bongiovanni et al., 1990</td>
<td>Prolonged VS caused decline of contraction force about 8% in intermittent efforts and about 25% in sustained contraction</td>
<td>25 healthy subjects aged 9-70 years (mean 40)</td>
<td>Maximal isometric ankle dorsiflexion: 1) intermittent brief contractions; 2) sustained 1 min contractions; VS of 150 Hz applied over the muscles' tendon; 150 Hz</td>
</tr>
<tr>
<td>Issurin et al., 1990</td>
<td>Maximal isometric force increased by 5.8%; isometric endurance by 5.9-17.8%; isotonic force by 26-41%</td>
<td>6 trained and 8 former high-class kayakers</td>
<td>Kayak stroke simulation: isometric maximal effort, isometric sustained effort, maximal isotonic effort; VS of 17-38 Hz; 12-41 m/s²</td>
</tr>
<tr>
<td>Liebermann and Issurin, 1997</td>
<td>The maximal isometric force increased by 4.9-8.3% depending on athletic level</td>
<td>41 trained male athletes</td>
<td>Sitting bench pull to achieve the maximal lifted weight; 44 Hz; 30 m/s²</td>
</tr>
<tr>
<td>Issurin and Tenenbaum, 1999</td>
<td>Maximal power increases by 10.4% in elite and 7.9% in amateur group</td>
<td>14 amateur and 14 elite athletes</td>
<td>Dynamic bilateral biceps curl with maximal speed; vibration 44 Hz; 30 m/s²</td>
</tr>
<tr>
<td>Griffin et al., 2001</td>
<td>The endure time did not differ for tasks with and without vs (5.4 vs 5.2 min)</td>
<td>3 females and 4 males 24-45 years</td>
<td>Isometric elbow extension sustained 20% of maximum; the VS was applied for 2 s every 10 s; 110 Hz, 3 mm</td>
</tr>
<tr>
<td>Warman et al., 2002</td>
<td>Torque improvement of 14.7±2.9%</td>
<td>28 recreational athletes</td>
<td>Isometric knee extension from 90 till 180°; vibration 50 Hz; 13-24 m/s²</td>
</tr>
<tr>
<td>Humphries et al., 2003</td>
<td>No difference in peak isometric force and rate of force development</td>
<td>17 males aged 22±4.4</td>
<td>Isometric knee extension; vibration 50 Hz; 13-24 m/s²</td>
</tr>
</tbody>
</table>

*) The presented data: frequency, amplitude and vibration acceleration transmitted to the muscles

The motor effects produced by the VS treatment indicates certain tendencies (Figure 11):5, 37, 38, 40, 41, 42, 43, 46

1) positive effects were achieved mainly in short-term but not in long lasting efforts;
2) higher effects were observed in dynamic rather than in isometric contractions;
3) maximal gains were obtained in high-speed movements;5, 42, 46
4) VS treatment during prolonged muscle activity usually caused a suppressive effect.37, 38, 40

The summary information on acute postvibration effects (Table II)44-49 shows that prolonged VS lasting 6-30 min usually led to a significant decrease of maximal force 47, 49 and take-off power.44 A high-frequency VS lasting totally about 60 s during a 5-min session did not induce any effect on maximal torque.48 The latter finding is in contrast to the study of Bosko et al.45 where a 10-min VS resulted in a significant increase in forearm flexion power. Short-term VS (about 6-7 s) combined with explosive exercise caused stimulatory effect, although insignificant, on the power output of the subsequent effort.46

Therefore, 2 opposite acute effects of the VS treatment can be highlighted and discussed:

— short-duration VS stimulates and facilitates force and power output;4, 6, 41, 42, 46

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TABLE II.—Summary of the acute postvibration effect.

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<thead>
<tr>
<th>Source</th>
<th>Effect</th>
<th>Subjects</th>
<th>VS treatment and test trial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kunnenmeyer and Schmidtblecher, 1997</td>
<td>Significant decrease of the jump height by 7.3% after VS stretching</td>
<td>12 skilled in jump sport students</td>
<td>The leg muscles stretching, 3 times 2 min; drop-jump from bench 24 cm on the force plate; 23 Hz</td>
</tr>
<tr>
<td>Bosko et al., 1999</td>
<td>Significant increase of the average power of forearm flexion by 4.8%</td>
<td>14 boxers of international level</td>
<td>Isometrically contracted arm muscles exposed to VS, 5 times 2 min, forearm flexion with the load - 5% of body mass; 30 Hz, 34 m/s²</td>
</tr>
<tr>
<td>Issurin and Tenenbaum, 1999</td>
<td>The non-significant increase of the power by 2.4-5.2% after the set with VS</td>
<td>14 amateur and 14 elite athletes</td>
<td>Three sets of biceps curl with maximal speed; the 2nd one with VS, the 3rd set without VS indicates postvibration effect; 44 Hz; 30 m/s²</td>
</tr>
<tr>
<td>Kozak et al., 2000</td>
<td>Maximal force decreased significantly after prolonged VS</td>
<td>8 untrained subjects aged 25.5 y</td>
<td>Maximal isometric knee extension; vibration applied to muscle rectus femoris during 30 min; 30 Hz; 3 mm</td>
</tr>
<tr>
<td>Griffin et al., 2001</td>
<td>The maximal force declined similarly after the tasks with and without VS</td>
<td>3 females and 4 males 24-45 y</td>
<td>Isometric elbow extension sustained 20% of maximum during 5 min; the VS acted 2 s every 10 s; 110 Hz, 3 mm</td>
</tr>
<tr>
<td>Jackson and Turner, 2003</td>
<td>Significant decrease of the maximal force and rate of force generation after VS in right and left leg</td>
<td>10 healthy males aged 26±2 y</td>
<td>Maximal isometric knee extension of both legs; VS was applied to muscle rectus femoris of right leg during 30 min; 30 and 120 Hz</td>
</tr>
</tbody>
</table>

— prolonged superimposed vibration has a suppressive impact on sustained efforts and muscular force exertion. It is well known that primary afferent endings of motor spindles are particularly sensitive to vibration. It can be suggested that vibration stimuli cause excitation of these afferents and recruit more receptors which, in turn, activate a larger fraction of α-motoneurons whose discharges recruit previously inactive muscle fibers into contraction. Unlike vibration that is locally applied to a tendon or specific muscle, the vibratory wave transmitted to a distal link propagates through proximally located muscle groups and activates an enormous number of vibratory sensitive muscle receptors. As a result a large number of additional motor units can be involved in a motor response.

Yet another explanation relates to the proprioceptive feedback of Ia afferents and stretch sensitivity of the muscles. When the muscle is pre-stretched and active prior to concentric contraction the stretch reflex greatly contributes to the force development. It is known that force enhancement in stretch-shortening cycle (SSC) exercises is strongly affected by reflexive facilitation of the afferents caused by Ia afferents. Similarly, dynamic VS exercises are performed when the muscles are preliminary activated by vibratory waves causing Ia afferent inflow which produce excitatory effect on the α-motoneurons. It is likely that vibration stimuli facilitate stretch reflex, which can have decisive impact on force and power generation in dynamic VS exercises. This partly explains why the potential of motor output improvement is higher in VS dynamic exercises than in isometric ones (Figure 1).

An important factor that has to be taken into consideration is VS frequency. Muscle tension linearly increases with the frequency of vibration. It was proposed that a vibratory stimulus selectively excites the primary endings of muscle spindles causing them to fire in synchrony with the vibration cycle. The primary afferents of muscle spindles are stimulated with a one-to-one discharge rate up to 100 Hz. It was suggested that optimal frequency can lead to synchronization of the firing of primary afferents of muscle spindles with vibration frequency while a higher-than-optimal frequency of vibration decreases motor unit synchronization with mechanical vibration. As the discharge rate of motor units during maximal effort reaches 30-50 impulses per second a VS frequency of 30-50 Hz eliciting a pronounced stimulatory effect generates a muscle spindles firing rate that corresponds to the required rate of neural input to the maximally contracted muscles. Furthermore, it has been already mentioned that only low-frequency waves propagate through the stretched or contracted muscles while high-frequency vibrations are absorbed by the soft tissues.
Another factor contributing to the VS effect is the initial length of the muscles. Preliminary stretched muscles are more sensitive to VS and contract more strongly,\(^{21,57}\) in motor tasks where movements were started from a stretched position VS induced apparent facilitatory effects.\(^6,41,46\)

The effects of the superimposed vibration depend on its duration. Vibration of 10-20 s duration caused enhancement of EMG activity, increased firing rate of motor units and a rise in maximal force in fatigued muscles.\(^{53}\) Similarly, Griffin et al.\(^{48}\) demonstrated an increase of motor units firing rate and force in isometrically fatigued muscles when short (2 s) superimposed vibration was applied. In contrast, prolonged vibration (1 min and more) reduced the firing rate of motor units and motor output.\(^{40}\) Long
TABLE III.—Summary of the cumulative effect of VS training.

<table>
<thead>
<tr>
<th>Source</th>
<th>Effect</th>
<th>Subjects</th>
<th>Training program and vibration parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nazarov and Spivak, 1987</td>
<td>Mean gains of isometric strength were equal to 49-79% in experimental</td>
<td>40 trained athletes aged 18-22 y; 4 groups</td>
<td>Intermittent VS training: 4 isometric arm exercises for 30 s 3 times a week during 4 weeks; 20-25 Hz, 4 mm</td>
</tr>
<tr>
<td>Kuksa, 1990</td>
<td>Significant benefit of VS group in power of single stroke simulation</td>
<td>12 trained kayakers aged 14-15 y, 2 groups</td>
<td>Dynamic stroke simulation with VS 3 times/week, 10-12 min VS net time during 21 days; 40 Hz, 8-12 mm</td>
</tr>
<tr>
<td>Issurin et al., 1994</td>
<td>Average gains in VS, conventional and placebo groups were 49% vs 16%</td>
<td>3 groups: 28 male athletes aged 19-25 y</td>
<td>Sitting bench pull, 6 sets with the load near to 1RM, VS net time = 2 min, 3 times/week during 3 weeks; 44 Hz, 3 mm, 22 m/s²</td>
</tr>
<tr>
<td>Issurin, 1996</td>
<td>Evident gains of arm and legstroke force and power combined with</td>
<td>1 female outstanding swimmer</td>
<td>Simulation of arm and legstroke, series for 20-60 s, the load 50-100% of 1RM, 3 times/week during 3 weeks; 44 Hz, 3 mm, 22 m/s²</td>
</tr>
<tr>
<td>Weber, 1996</td>
<td>Increase of the maximal dynamic strength (1RM) by 34%; the flexibility</td>
<td>1 recreational gymnast</td>
<td>Rowing pull of the weight 80% of 1RM; 6 series till failure, 3 times/week during 3 weeks; 25 Hz, 3 mm</td>
</tr>
<tr>
<td>Becerra Motta and Becker, 2000</td>
<td>The VS program x30 s is superior as compared with x2 min and control</td>
<td>23 trained swimmers aged 17-21 y, 4 groups</td>
<td>Arm stroke simulation of 2 modes: 1) x2 min; 2) x30 s, 3 times/week, 2 weeks; 20-24 Hz, 4 mm, 30-39 m/s²</td>
</tr>
</tbody>
</table>

periods of vibration (30 min) caused a significant decrease of muscle force and integrated EMG. This vibration induced suppression may be based on central and peripheral neural mechanisms. Bongiovanni and Hagbarth noted that muscular fatigue induced by prolonged vibration during sustained effort leads to a reduction of the voluntary drive conveyed to the α-motoneurons. This is consistent with evidence that prolonged local muscle vibration decreases cortical excitability. It is noteworthy that subjects’ motivation level can contribute to the ability to maintain a voluntary drive during sustained effort with local vibration. On the other hand it can be suggested that decreased maximum performance following prolonged vibration is caused by reduction of central drive during its peripheral transduction to the muscles. It was also proposed that vibration induced suppression of motor output is determined by reduced accessibility of the α-motoneurons to the voluntary command. Thus, the mechanism involving a tonic excitatory stimulation of α-motoneurons provides the motor output facilitation in brief efforts and its suppression during prolonged activity.

Vibratory stimulation during strength exercises: cumulative effects

Unlike the studies of acute VS effect, the longitudinal investigations of VS training revealed apparent and significant improvement of appropriate fitness estimates (Table III). The training programs and VS characteristics in different studies were very similar, namely:
- training duration ranged from 2-4 weeks;
- frequency of workouts with VS was 3 times/week in all studies;
- VS frequency ranged from 20-45 Hz;
- work interval was usually not longer than 30 s; the load value or power level was near maximum;
- subjects were usually well-trained skilled athletes (the only exception was study).

It worth mentioning that the VS and training protocols that did not induce substantial positive acute effects—i.e. the protocols with high-frequency vibration, long-duration efforts and low external load—were not used in the training programs in the mentioned studies. All the researchers used short-duration efforts and highly intensive workloads.

As the cumulative training effect is a consequence
of acute effects of several workouts, the physiological mechanisms behind the immediate reaction of the organism to VS are also relevant for understanding for long-term effects of VS training. There is reason to believe that the major factors explaining strength improvement as a result of VS training are the neural regulation of the voluntary muscular contraction and neuro-muscular adaptation. Namely, the motor learning effect, which is partly based on potentiation of proprioceptive feedback from α-afferents, seems to be the most apparent candidate for explaining the marked benefits of VS training. It is known that improvement of neuro-muscular coordination is the dominant source of strength increase during initial periods of training; however such mechanisms as motor pool activation, motoneuron recruitment, rate coding, synchronization of muscle units, and agonist/antagonist coordination contain reserves which can be exploited even in top-level athletes.

Another contributing factor to the cumulative training effect is muscle metabolism. Hoffmann et al. studied muscle energy metabolism during isometric contraction and found that superimposed vibration causes much faster decrease of phosphocreatine as compared with no vibration conditions. It can be speculated that repeated VS workouts can lead to more pronounced metabolic responses and, consequently, to increased lactic and glycolytic ability. Mechanical vibration applied to muscle directly affects contractile protein and protein synthesis. Furthermore, mechanical vibration effectively stimulates bone formation and even affects the transcriptional regulation of genes involved in this process. Thus, the positive shift in muscle metabolism and deep structural changes in the
musculoskeletal system can affect cumulative VS training effect.

**Acute effect of WBV workout**

Studies of WBV concerned selected fitness variables as well as neuromuscular, metabolic and hormonal responses (Table IV). The findings from various studies are inconsistent. Three studies showed a decrease of motor fitness variables, such as vertical jumps, leg press and knee extension force. Two studies did not find any significant changes and 2 investigations found a significant enhancement in leg power tests as a result of WBV treatment.

From a review of publications, a dose-effect analysis reveals conditions affecting positive or negative changes induced by VT. The enhancement effects were obtained in studies performed on well-trained athletes with an intermittent training protocol of work intervals of about 1 min and total duration of exposure to the vibration was 10 min. Vibration exposure of medium duration (4 min) did not induce any effect. Continuous prolonged VS (7 min and more) led to significant decrease of fitness estimates; however this decrease was not larger than after conventional exhaustive exercise. All of the above suggests that (1) well trained athletes tend to respond positively to WBV training and (2) prolonged continuous exercises cause a remarkable decrease of relevant fitness variables. The latter conclusion agrees well with the data on the prolonged local VS (Figure 1).

The neuromuscular aspects of whole body vibration in sport were first studied in Alpine skiing. Researchers particularly focused on how athletes succeed in reducing vibration transmitted from lower links to upper body and head. Later Mester et al. found in lab conditions that decrease of vibration transmission can be achieved by adequate muscle activity which considerably increases with the increase of vibration frequency. EEG during skiing simulation performed in found activation of the motor cortex region responsible for the integration of afferents' input from the sensory zones. This is consistent with a study where bursts of muscular activity were registered before the onset of WBV; this muscle pre-activation was qualified as an anticipatory response, which can be regulated on the cortical and sub-cortical level. Surface EMG investigation during continuous WVB exposure found substantial frequency decrease indicating muscle fatigue. However, other researchers observed an insignificant increase of EMG frequency after exhaustive WBV exercise; the increase was still markedly higher than EMG frequency changes during and after an exhaustive squating exercise. The frequency increase was attributed by authors to predominant recruitment of large motor units. After exposure to vibration the stretch reflex amplitude decreases. Hence, despite the fact that the majority of studies reported a decrease of the total EMG activity caused by WBV workouts, one can suggest that a proper combination of vibration parameters can enhance neuromuscular excitability in athletes.

The metabolic responses to WBV were estimated in a number of studies. A strenuous WBV—18 points on the Borg scale, i.e. very hard subjectively—applied during bicycle ergometry was accompanied by increased oxygen uptake that reached 48.8% of VO$_{2max}$. This workload caused blood lactate accumulation of 3.5 mM that, of course, cannot be considered substantial. Apparently, high rate of perceived exertion in this study was associated not with the metabolic but with the neuromuscular response. Nevertheless vibration exposure significantly increases energy expenditure in squatting (by 41%) and in squatting with additional load (by 16.7%) as compared with no vibration conditions. It was established that variations of frequency, amplitude of vibration and additional load significantly affect the metabolic cost of exercises. An additional load equal to 0.4 of lean body mass placed on the shoulders of athletes increased oxygen uptake by about 10% and 23% at vibration frequencies 18 and 34 Hz, respectively. Thus it appears that WBV applied during another motor activity causes remarkable increase of energy expenditure due to vibratory induced co-activation of the antagonists and the muscle activity elevation necessary for damping vibratory waves in soft tissues.

Bosco et al. studied hormonal responses to intermittent WBV protocols and found a significant increase in the concentration of testosterone and growth hormone level, whereas cortisol level decreased. This hormonal effect can be associated with the pronounced activation of the pituitary-adrenocortical and sympatho-adrenal systems. Another study aimed to examine the hormonal response of well-trained athletes to a continuous 7-min WBV workout. The levels of both serum testosterone and serum cortisol decreased significantly; the decrease was considered a sign of
impaired activity of pituitary-adrenocortical and pituitary-testicular axes. Hence, WBV elicits pronounced hormonal responses that depend on the treatment protocol.

**Cumulative effect of WBV training**

A number of studies were devoted to evaluating the cumulative effect of WBV training (Table V). 26, 27, 75, 79-82

In these studies, vibration exposure per workout varied from 4 min to 20 min, workout frequency was usually 3 times/week and training duration varied between 10 days and 24 weeks. Exercise selection was limited to various modifications of standing, squatting and jumping. Vibration frequency did not differ too much and varied between 25-40 Hz while the intensity of the vibration stimuli was high enough and reached 50-54 m/s². Only one study 75 revealed no effect of WBV training; perhaps the workout content was standing in semi-squat position did not provide sufficient stimulus for fitness improvement. All other research projects demonstrated significant changes of one or more motor variables. Jump performance was improved in most studies, 26, 27, 79, 81 This test seems to be the most sensitive to WBV treatment while isometric or dynamic leg strength did not reveal the benefit of WBV program as compared with resistance training. 79-82

The effects of WBV training programs are determined by neural adaptation and possible hormonal and biochemical changes. Since the stretch-shortening cycle tests (serial high jumps, countermovement jump, etc.) were the most sensitive to WBV treatment, the neural factors of training adaptation are of special interest. WBV exercises cause excitation of the primary endings of muscle spindles (whose afferent feedback stimulates increased discharge of α-motoneurons) as well as activation of Golgi tendon organs (GTO) that are sensitive to force development and

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**Table V. Summary of the cumulative effect of WBV training.**

<table>
<thead>
<tr>
<th>Source</th>
<th>Effect</th>
<th>Subjects</th>
<th>Training program and vibration parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bosco et al., 1998 26</td>
<td>Significant improvement of jumping performance in WBV group (p&lt;0.01); no training effect in control group</td>
<td>2 groups: 14 physically active males aged 20.4±1.1</td>
<td>Intermittent WBV training (standing and squatting); 5 series for 90 s with 40 s rest during 10 days; 26 Hz, 10 mm, 54 m/s²</td>
</tr>
<tr>
<td>Mester et al., 1999 27</td>
<td>Increase of the isometric strength in leg press by 43%; gain of the squat-jump height by 22.9%</td>
<td>1 well trained alpine skier</td>
<td>WBV training (squatting, jumping) combined with traditional training during 21 days; 24 Hz, 2.5 mm</td>
</tr>
<tr>
<td>Tarvinen et al., 2002 79</td>
<td>Significant benefit of WBV program vs control group in vertical jump (p&lt;0.001); no treatment effect with regard to legs' strength, shuttle run, etc.</td>
<td>2 groups: 56 nonathletic males and females aged 19-38 y</td>
<td>WBV training 4 min per day (squatting, standing, light jumping, standing on the hills) 3-5 times a week during 4 months; stepwise increase from 25 till 40 Hz, 2 mm, 25-40 m/s²</td>
</tr>
<tr>
<td>De Ruiter et al., 2003 75</td>
<td>No treatment effect on maximal isometric knee extension and electrically induced maximal rate of force rise</td>
<td>10 young male students</td>
<td>Standing on the platform with the knee angle of 110° 5 times for 1 min with 2 min rest in between 3 times a week during 2 weeks; 30 Hz, 8 mm</td>
</tr>
<tr>
<td>Delecluse et al., 2003 80</td>
<td>Significant gain of jump performance in WBV group (7.6%, p&lt;0.001), no gains in other groups; no benefits of WBV group in isometric and dynamic strength</td>
<td>67 untrained females aged 21.4±1.8 y; 4 groups: WBV, resistance, placebo and no training</td>
<td>Intermittent WBV training (various squatting exercises) progressively changed from 3 till 20 min per session 3 times/week during 12 weeks; 35-40 Hz, 2.5-5 mm, 22-50 m/s²</td>
</tr>
<tr>
<td>Berschin et al., 2003 81</td>
<td>Benefit of WBV program in countermovement jump (p&lt;0.01), shuttle run and 30-m sprint (p&lt;0.05); no difference in maximal legs' strength</td>
<td>2 groups: 24 well trained rugby-players</td>
<td>Intermittent WBV training: squatting and jumping with weighing 25-70% of 1RM, 5 series for 3 min, 3 times a week during 12 weeks; 20 Hz</td>
</tr>
<tr>
<td>Roelants et al., 2004 82</td>
<td>Significant gains of legs' isometric force in WBV and fitness groups (24.4% and 16.5%, respectively). There were no significant changes in body weight and percentage body fat</td>
<td>48 untrained female students aged 21.3 y; 3 groups: WBV training, fitness and control groups</td>
<td>WBV training (unloaded static and dynamic leg and arm exercises) increased from 3 to 20 min/session performed 3 times/week during 24 weeks; 35-40 Hz, 2.5-5 mm, 22-50 m/s²</td>
</tr>
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whose activation results in inhibition of muscle action. It can be hypothesized that the cumulative effect of regular systematic WBV training includes (a) enhancement of mono-synaptic stretch-reflexes that are initiated by afferent signals from the muscle spindles to the motoneuron pool, and (b) depression of inhibitory impact of GTO due to their accommodation to vibratory-induced excitation. A similar mechanism of neural adaptation was proposed by Zatsiorsky \(^6\) with regard to stretch-shortening cycle exercises. This similarity of biological mechanisms of vibration training and explosive exercises in jumping and bouncing was also noted by Bosco et al.\(^{26}\) Thus, it is likely that WBV training-induced adaptation includes neural potentiation that produces a target-specific effect on stretch-shortening cycle contraction.

Another possible outcome of superimposed WBV training is recruitment of high-threshold motor units.\(^{37}\) Consequently, WBV exercises affect predominantly fast-twitch fibers \(^70\) which are responsible for motor output in the SSC exercises. If this hypothesis is correct, WBV training should lead to performance enhancement in movements performed at a maximal level. Indeed, such improvement in 30-m sprint and shuttle run time was actually obtained in well-trained athletes who combined vibration exercises with a conditioning training program.\(^{31}\) In contrast, WBV training of sedentary young subjects did not affect their performance in shuttle run.\(^{79}\) The latter result can be also explained by an insufficiency of training stimuli, 4-min workouts 3 times/week.

It is well known that long-lasting vibration exposure presents a certain health risk.\(^{30, 83}\) Despite the vibration exposure of about 7.5-20 min/session \(^{26, 80-82}\) and high vibration intensity (40-54 m/s\(^2\) and even 18 g),\(^{71}\) none of the researchers reported any adverse effects of WBV treatment. Moreover, several authors reported that most subjects experienced the vibrating loading as an enjoyable.\(^{80, 82}\) However, based on evidence from extensive studies on occupational vibration,\(^{29, 30, 83}\) the possible harmful effect of the vibration exposure is far from negligible. The International Standards Organization (ISO) has established limits for vibration exposure \(^{84}\) and ISO standards for WBV strictly regulate exposure time, frequency and acceleration interactions. A general rule is that the higher intensity (acceleration) of vibration the shorter the exposure duration should be. For instance, the exposure duration of 1 min is allowed when frequency equal to 30 Hz with acceleration of about 20 m/s\(^2\); if the frequency is 45 Hz the coupled acceleration reaches 35 m/s\(^2\) (more frequent oscillations are more quickly attenuated during their transmission to head). The duration of WBV training (10-20 min/session) and its intensity (40-54 m/s\(^2\), Table V) dramatically exceed the limits established by the ISO. Of course, the standards of occupational vibration were created to decrease risk and improve the workers' comfort during regular working hours, usually 8 hours a day. The standards did not consider the use of vibration in conditioning training. In training, WBV exposures of 10-20 min per session are not applied continuously but interspersed with rest intervals. Nevertheless, even the hypothetical health risk caused by excessive vibration loading cannot be ignored. Such a risk was found in a study where low-frequency WBV training of non-athletic subjects caused significant increase of total cholesterol and its LDL fraction, which trend is associated with increased incidence of myocardial ischemia.\(^{85}\) Unfortunately, the studies on the occurrence of adverse effects of prolonged vibration were never replicated on athletes.

**Conclusions**

The application of vibration in sport has a long history. However, this training modality did not attract the attention of scientists till recently, in the late 1980s. Two varieties of vibration training can be distinguished: (1) local vibration applied during strength and flexibility exercises (vibratory stimulation, VS) and (2) whole body vibration (WBV) which also can be performed during muscle activity, e.g. during bicycle ergometry. The basic paradigms for VS exercises and WBV training are different. The first one exploits intensive muscular efforts accompanied by superimposed local vibration that stimulates motor output;\(^{4-6, 60-63}\) the latter employs an opposite approach where very intensive and prolonged vibrating loads are combined with unloaded exposure.\(^{75, 79, 80, 85}\) or with moderate physical efforts.\(^{69, 71, 82}\)

The available knowledge on vibration-induced effects is still far from complete. This is especially valid for WBV training where impact on the human organism is general and multi-faceted. Further investigations of vibration training are desirable and should focus on at least 2 major questions: what are the most efficient training protocols? and how can health risks
associated with excessive vibration loading be eliminated?

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