VIBRATION AND THE SENSORY SYSTEM

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ABSTRACT

Whether one is trying to hold a can of soda or hit a ball with a bat, the ability to sense joint posture and movement and to dynamically control that movement is important to almost all human activities. Mechanical vibration has a number of unique effects on this ability to sense and control that can be both detrimental and beneficial. Vibration exposure in the workplace is known to increase musculoskeletal injury risk. Vibration has also been proposed for therapeutic applications such as vibrating insoles for the elderly and vibrating platforms in the gym. Understanding the underlying effects of vibration on the sensorimotor system is important for examining the potential for vibration-induced injury as well as the potential for therapeutic uses of vibration. This chapter will examine the existing research on vibration and the sensorimotor system, the potential for vibration-induced injury, and the use of vibration for therapeutic purposes.

7.1 INTRODUCTION

The sensorimotor system is integral to dynamic control and stability of human motion in movements from holding an egg without breaking it to running across a field without tripping. The human neuromotor system contains a complex integration of a variety of sensory elements and neurological circuits that allow for dynamic control in a wide variety of activities. Mechanical vibration has a number of effects on this sensorimotor system that can have both beneficial and detrimental effects on human activity and neuromotor performance. This chapter begins by introducing the sensorimotor system and components of that system such as the muscle spindle organ (Section 7.2). This is followed by a review of the experimental literature on the effects of mechanical vibration on specific elements of the sensorimotor system, including the muscle spindle organ (Section 7.3), the cutaneous sensors (Section 7.4), and the central nervous system (CNS; Section 7.5). Occupational vibration exposure and the potential for vibration-induced sensorimotor effects to play a role in occupational injury are examined (Section 7.6). Finally, possible therapeutic applications of mechanical vibration in rehabilitation and athletic performance are examined (Section 7.7).

Some terminology used in this chapter includes:

Afferent and efferent nerve fibers: Nerve fibers are defined by the direction stimulus that normally travels to (afferent) or from (efferent) the spinal cord and the central nervous system.

Agonist and antagonist muscle: In experimental studies, the agonist muscle is the muscle that generates a movement (or in the case of vibration studies, the muscle that is vibrated). An antagonist muscle is a muscle that acts in opposition to the agonist. For example, if the agonist flexes a joint, the antagonist will extend the joint.

Alpha motor neuron: The alpha motor neuron is an efferent nerve fiber that starts at its origin in the central nervous system (typically the spinal cord) and innervates a portion of a muscle (known as a motor unit).

Aperiodic stochastic resonance: Aperiodic stochastic resonance is a method by which the response of a non-linear system such as a sensory system with a threshold can be enhanced by the use of a low-level, aperiodic noise.

Central nervous system (CNS): The CNS refers to the centrally located components of the nervous system including the brain, brain stem, and spinal cord.

Electroencephalography (EEG): EEG is a method for measuring the electrical activity of the brain using electrodes placed on the scalp.

Functional magnetic resonance imaging (fMRI): fMRI is a brain imaging modality that allows visualization of the blood flow and oxygen consumption in the brain. This method works using a pulse sequence that reflects the presence of deoxyhemoglobin. Such MR images at two time points are compared in a method known as blood-oxygen-level-dependent (BOLD) contrast to examine cerebral blood flow.

Kinesthesia: Kinesthesia is the sense of joint posture and movement.

Kinesthetic illusion: A kinesthetic illusion is the sensation of joint motion induced by vibration of a muscle or its associated tendon.

Muscle spindle organ: The muscle spindle organ is a complex sensory structure. It is made up of both muscle fibers and nerve fibers and is located within muscle tissue. The muscle spindle organ responds to changes in muscle length and the velocity of muscle lengthening.

Golgi tendon organ: The Golgi tendon organ is a sensor that is located at the junction of the muscle and tendon, and responds nonlinearly to muscle force.

Magnetoenchephalography (MEG): MEG is a brain imaging modality that measures the magnetic fields created through the electrical activity of the brain.

Positron-emission tomography (PET): PET is an imaging modality that measures the emissions of gamma radiation by injected radioisotopes. This modality has been used in brain imaging to image cerebral blood flow.

Proprioception: The term proprioception is used in this chapter to refer to the physiological ability to sense joint posture and movement, and the sensory elements and neural pathways that make up this sensation.

Sensorimotor system: In this chapter, the sensorimotor system is used to refer to the neuromotor and sensory elements that integrate to allow for dynamic motion, joint stabilization, and neuromotor control. The sensorimotor system consists of the sensory elements of the nervous system, those neural pathways through the peripheral and central nervous system that integrate activity of sensory elements, and the neural pathways involved in the innervation of the musculature.

Transcranial magnetic stimulation (TMS): TMS is a method for examining excitability of motor regions of the brain by manipulating of the magnetic field in a focused brain region to create a stimulus and by measuring muscle activity with electromyography.

7.2 THE SENSORIMOTOR SYSTEM

Control of human movement requires integration of a number of elements in the sensorimotor system. These include sensory elements, afferent signal pathways to the CNS, CNS signal integration, and efferent muscle activation. The sensory elements include proprioceptive sensors, the vestibular system, vision, nocioceptors, and cutaneous sensory elements. Proprioception is a controversial term but is typically used to refer to neural input originating in the muscles, tendons, ligaments, and other deep tissues that allow sensation of joint posture and motion [1]. Sensory elements that contribute to proprioception include the muscle spindle organs, the Golgi tendon organs, and the articular and ligamentous receptors.

The muscle spindle organs are important in modulating sense of joint position. If you close your eyes and try to touch your finger to your nose, it is the muscle spindle organs within the muscles of your arm that allow you to sense the position of your arm in space. The muscle spindle organ is a complex structure composing of two types of intrafusal muscle fibers: the bag fibers and the chain fibers [2, 3]. These fibers are activated by the gamma motor neurons. Stimulation of these neurons results in contraction of the ends of these fibers. These fibers are also innervated in the central region by two types of afferent nerve endings: primary (Ia) nerve endings that are located in the bag and chain fibers and secondary (II) nerve endings that are located in the chain fibers. This structure of innervated intrafusal muscle fibers exists within the muscle body in series and parallel with the extrafusal muscle fibers of the normal muscle tissue. This specialized structure creates a sensory system that responds to both muscle length and velocity of muscle lengthening. Increases in muscle length result in an increased frequency in the pulse train of the afferent nerve fibers (Ia and II) [2, 3]. With the primary nerve endings (Ia), this pulse train frequency is also increased with increasing velocity of motion. Activation of the gamma motor neurons in the muscle spindle organs allows the muscle spindle response to change with muscle activation.

The Golgi tendon organ (GTO) is a slow-adapting, high-threshold, proprioceptive sensor that is located in the junction between muscle and tendon [3]. The GTO is considered to be a force sensor. The afferent pulse frequency of this sensor is a non-linear function of the muscle force of the muscle fibers in series with the GTO. The Golgi tendon organ is believed to link to negative (inhibitory) feedback to the same muscle preventing excessive overloading of the muscle (Fig. 7-1).

Other proprioceptive elements, including Golgi endings, Pacinian corpuscles, and free-nerve endings, exist in a number of joint tissues such as the ligaments, knee meniscus, joint capsule, and other articular structures [1, 2]. These articular and ligamentous sensors often fire more rapidly when a joint approaches anatomic limits and can contribute to the overall sense of joint posture.

The cutaneous sensory system can also act to provide postural information through the sense of pressure. This is most evident in the use of pressure in the sole of the foot to sense posture during upright standing. Like the proprioceptive sensory system, the cutaneous
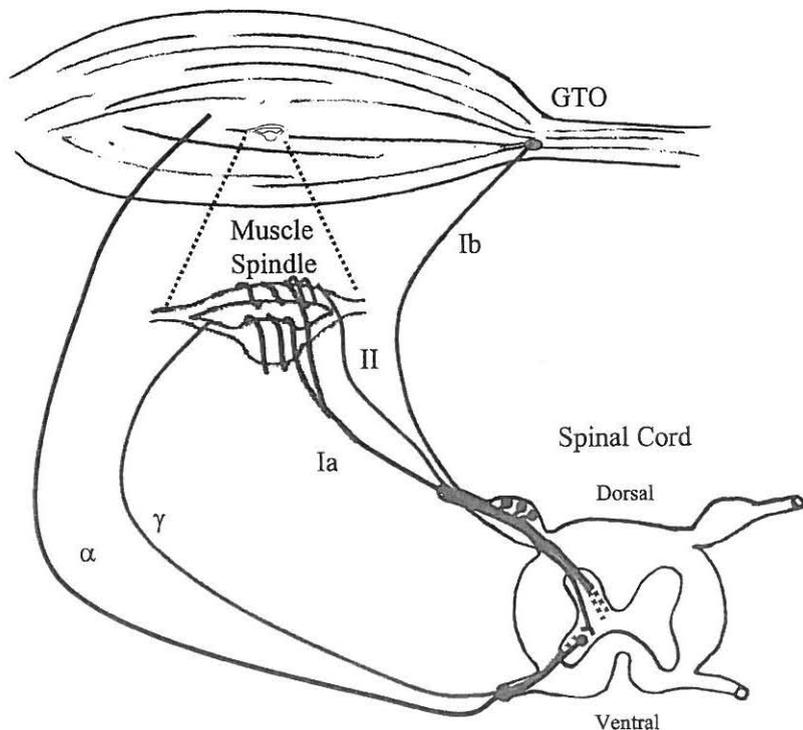
Figure 7-1. The muscle spindle organ and Golgi tendon organs are two sensory elements associated with the muscle and its tendon. The muscle spindle organ is innervated by the efferent gamma motorneuron and the afferent Ia and II nerve fibers. The afferent nerve fibers from the muscle spindle organ (Ia and II) and Golgi tendon organ (Ib) come into the spinal cord on the dorsal side and can synapse with both mono- and polysynaptic pathways. The simplest, monosynaptic pathway, the stretch reflex, is illustrated here. In that reflex, the Ia afferent synapse with the alpha motorneuron of the same muscle

sensory system is made up of a number of elements including Meissner corpuscles, Ruffini endings, Merkel disks, and Pacinian corpuscles [3]. Of these elements, Meissner corpuscles are close to the skin surface and are known to be sensitive to quick changes in pressure in small areas of the skin. Pacinian corpuscles are larger and are sensitive to quick changes in mechanical deformation over a larger area.

7.3 VIBRATION AND THE MUSCLE SPINDLE ORGAN

Vibration of muscle and/or its associated tendon has long been known to alter sense of joint position and create illusions of joint motion. In 1972, both Eklund [4] and Goodwin et al [5] demonstrated that mechanical vibration of muscle tendon creates an altered perception of joint position and an illusion of joint motion. Goodwin remarked that subjects exposed to tendon vibration made a systematic misjudgment of elbow angle and suggested that the muscle spindle organ firing as a result of vibration is interpreted by the CNS as muscle lengthening. A number of studies have since followed this by examining the effects of muscle and/or muscle tendon vibration on the muscle spindle activation and neuromotor response.

In 1982, Roll and Vedel [6] examined the role of muscle tendon vibration frequency (10-120 Hz) on illusory movement by applying vibration to the left arm and having the

subject demonstrate the perceived motion of the left arm with the right arm while blind-folded. These researchers found that when the triceps or biceps tendon in the stationary left arm was vibrated, the velocity of the muscle lengthening illusion increased with increasing frequency up to a vibration frequency of 60 Hz to 80 Hz. Above 80 Hz, the velocity of the muscle-lengthening illusion diminished. Examining the afferent signal of the primary nerve endings from the muscle spindle organ of the tibialis anterior and extensor digitorum longus muscles, the authors demonstrated a one-to-one response of the muscle spindle to vibration cycle at lower frequencies and a combination of harmonic and subharmonic activation at higher frequencies. In a following study, Roll et al [7] examined the afferent signals of the Ia (muscle spindle organ), Ib (Golgi tendon organ), and II (muscle spindle organ) nerve fibers as a result of tibialias anterior and extensor digitorum longus muscle tendon vibration. In this study, the authors demonstrated that the Ia nerve endings fire at the vibration frequency for frequencies up to 80 Hz. Above 80 Hz, the Ia nerve ending firings were often at subharmonic frequencies relative to the vibration frequency. Unlike the Ia nerve ending, the Ib and II nerve endings demonstrated little response to vibration above frequencies of 20 Hz. From these studies, it is evident that muscle tendon vibration activates the muscle spindle and that such activation can be interpreted by the CNS as lengthening of the muscle. This illusion of muscle lengthening has been called a "kines-thetic illusion."

A number of studies have examined aspects of this kinesthetic illusion. Cordo et al [8] demonstrated that, when a muscle is lengthening at a specified velocity (45° per second), the perception of that lengthening velocity can be altered, with a lower frequency (20 Hz) leading to an illusion that the muscle is lengthening slower and a higher frequency (40 Hz) leading to an illusion that the muscle is lengthening faster. One can also vibrate more than one muscle. When an agonist muscle and antagonist muscle are vibrated at the same frequencies and magnitudes, no illusions occur [9]. However, when the agonist muscle is vibrated at a frequency higher than the antagonist muscle, the illusion corresponds to the difference in the frequencies [9].

The activation of the muscle spindle organ, in addition to causing kinesthetic illusions, can also activate monosynaptic and polysynaptic reflex pathways. The simplest pathway that can be activated is the stretch (or tendon) reflex. This reflex loop is a monosynaptic connection from the afferent muscle spindle nerve fibers to the alpha motor nerve fibers of the same muscle. The classic test for this reflex is a tap with a reflex hammer on a muscle tendon (such as the patellar tendon), leading to activation of the muscle (such as the quadri-ceps muscles). At low frequencies, muscle or muscle tendon vibration might lead to a pha-sic muscle activation at the frequency of vibration [10, 11]. However, at higher frequencies, a steady increase in muscle activation [measured as integrated electromyographic (EMG) activity] and force is seen. This constant increase in muscle activity is known as the "tonic vibration reflex" [2, 7, 12, 13]. Underlying this tonic vibration reflex is the cyclic activa-tion of the monosynaptic reflex loop. Examination of the power spectrum of the raw EMG signal of the muscle has demonstrated a frequency spike at the frequency of vibration [12]. In addition to activating the vibrated muscle, muscle vibration has been shown to result in antagonist muscle vibration response [9, 14]. This antagonist vibratory response appears to be associated with the kinesthetic illusions and is, therefore, a product of a perceptual-to-motor loop rather than a simpler reflex loop [9].

Over a longer exposure to muscle or muscle tendon vibration, long-term effects can include altered reflex dynamics and altered ability to obtain maximum contraction. Force, EMG muscle activity, and motor unit firing rates during maximum voluntary contractions (MVC) have all been demonstrated to decrease during exposure to prolonged vibration of 2 minutes [12, 15]. Tonic vibration reflex magnitude has also been shown to decrease with prolonged vibration exposure of up to 7 minutes [12]. It has been speculated that prolonged vibration reduces the excitatory input of the primary (Ia) nerve afferents [16].

7.3.1 After-Effects of Exposure of the Muscle Spindle to Vibration

When a muscle has been vibrated, patterns of muscle spindle activity, reflex dynamics, and neuromotor control can·be altered post-vibration. After exposure as short as 30 seconds, decreased firing rates can be observed in most (73%) of the primary muscle spindle endings for a similar period [17]. These effects can also be observed in increased positioning error after vibration exposure [18]. Short-term vibration has been found to decrease the H-reflex (time from electrical stimulation of the afferent nerve input to monosynaptic activation of the muscle) [19]. However, while the stretch reflex has been found to decrease in some studies [17, 20], others have noted an increase in stretch reflex magnitude [21]. Wierzbicka et al demonstrated the after-effects of muscle-tendon vibration on postural control [22]. These authors found that after 30 seconds of the 80-Hz vibration of the soleus or tibilias anterior tendons, subjects exhibited increased standing sway in the anterior-posterior direction and an altered standing posture. This increase in sway was found to last from 3 minutes to 19 minutes post-exposure.

7.4 VIBRATION AND CUTANEOUS SENSORS

Like proprioception in the muscle spindle organs, cutaneous sensation of pressure by both the Pacinian corpuscles and other cutaneous pressure receptors is sensitive to applied vibration [23, 24]. Vibrotactile sensitivity is a frequently used diagnostic test for neuropathies [25-29]. These tests examine the vibration magnitude required to sense vibration (the vibration threshold) as a function of vibration frequency. As most vibration applied to muscle or tendon is applied through the skin, activation of vibration-sensitive, cutaneous sensors can have a confounding effect on measures of muscle spindle vibration effects. In human neuromotor control, input from cutaneous receptors on the plantar surface of the foot has been demonstrated to play a role in dynamic control of standing posture [30]. Vibration of 100 Hz applied at specific plantar locations in a blindfolded, standing subject resulted in an illusion of a lean toward the vibrated location.

Adaptation to long periods of cutaneous vibration exposure has also been examined. Over time, subjects can exhibit decreased tactile sensitivity, impaired afferent activation response (particularly in slow-adapting and Pacinian corpuscle mechanoreceptors), and bursting activity [31-33]. This adaptation can remain after removal of vibration exposure with afferent activation patterns recovering before psychophysical measures [34, 35]. This pattern of recovery suggests that adaptation is a function both of sensor adaptation and CNS factors.

7.5 VIBRATION AND THE CNS

While the vibration sensitivity of the muscle spindle organ and other sensory elements has already been demonstrated, it is also necessary to understand how these signals are conveyed in the CNS. There is still debate as to whether the kinesthetic sense is central or peripheral in origin [36]. Several technologies have been developed that allow researchers to explore activity within the different regions of the brain. Each of these imaging modalities offers different spatial and temporal resolutions and, coupled with an appropriate research paradigm, allows for investigation of the underlying physiological processes occurring in the brain. Magnetoenchephalography (MEG) is a technique that directly records the magnetic fields generated by the electrical activity in the neurons of the brain and is considered to have excellent temporal resolution (on the order of 1 ms). Similarly, electroenchephalography (EEG) is a method that measures regional electrical activity in the brain. Like MEG, EEG has an excellent temporal resolution but, as a surface measure, has poor

spatial resolution. Functional magnetic resonance imaging (fMRI) indirectly records brain activity through metabolic correlates of neural activity, such as blood oxygenation level, via magnetic resonance of a target molecule and is considered to have very good spatial resolution (~1 mm). Both MEG and fMRI are considered non-invasive and complimentary techniques, as their respective strengths are in different areas. Positron-emission tomography (PET), another imaging modality, detects radiation from an injected radioisotope that is introduced into the body before scanning. The need to use an injected radioisotope makes this modality invasive and more problematic. PET was the most common form of neuroimaging used before the widespread adoption of fMRI. Finally, transcranial magnetic stimulation (TMS) is a method used to manipulate magnetic fields in a localized region of the brain to evoke a motor response that might be measured with electromyography. This method is used to determine the excitability of a motor region.

The use of these imaging modalities presents some unique challenges. Other studies examining the effects of mechanical vibration on the sensorimotor system generally have utilized inertial devices consisting of a DC motor and off-center weight or electromagnetic shakers to create the vibrations used to probe the human control system. However, as the most popular imaging modalities rely on large powerful magnets to produce their images or are sensitive to electromagnetic disturbances, these devices become less practical. Several new approaches have been investigated to safely introduce vibration in the imaging environment. Solutions have included the uses of non-magnetic materials, pneumatics and magnetomechanical vibrotactile devices operated from the magnetic fields of the scanners themselves [37-40].

These imaging modalities are particularly important in the examination of the neural pathways within the sensorimotor system that may mediate any response to mechanical vibration exposure. A neural pathway is a series of neurons relaying specific information from one location to another. In the case of proprioceptive information, this pathway might be from the muscle spindle organ (sensory element) to the spinal column (tract) and ultimately to the cerebral cortex (processing element). An important observation here is that both afferent and efferent pathways convey information to the contra-lateral side of the body. The CNS is comprised of the brain and spinal cord, while other elements, including the sensory and neuromotor units, exist in the peripheral nervous system. The brain is divided into quarters by two large fissures. The lateral fissure divides the brain into anterior (toward the base of the brain) and posterior (toward the top of the brain) regions, while the central fissure separates the rostral (toward the front) from the caudal (toward the rear). Sensory pathways terminate in the somatosensory region of the cerebral cortex located posterior of the lateral fissure and caudal to the central fissure. Motor responses are generated in the motor cortex region posterior of the lateral fissure but rostral of the central fissure.

Several researchers have identified activity in the sensory regions of the brain during applied muscle vibration using fMRI [37-39, 41, 42]. A couple of these studies have found that increased vibration frequency corresponds with activity in additional locations of the brain rather than an increase in intensity in a specific brain region [41, 42]. When a net vibration frequency was applied within the range responsible for producing kinesthetic illusions, activity was found in the primary motor area on the contralateral side with both PET and MEG [43, 44]. Interestingly, a kinesthetic illusion experienced in one arm (exposed to vibration) was transferred to the non-vibrated arm when conducted with the two hands in contact [45]. fMRI images from this experiment demonstrated increased activity on both sides (contralateral and ipsilateral) of the motor cortex. This interconnection of the kinesthetic illusion suggests a complex integration of sensory input that is still not well understood. TMS has been used to demonstrate increases in the excitability of the motor cortex during muscle vibration, particularly for a muscle that is an antagonist to the vibrated muscle [46]. In addition, there is evidence to suggest that post-vibration, kinesthetic illusions are associated with a decrease excitability in the TMS of the antagonist muscle [46].

This is to say that vibration of the agonist muscle will lead to increased excitability of the antagonist muscle, which will essentially reverse once vibration is removed. The perception of both position and movement are likely dependent on much more than the simple signal received by the sensory terminus.

7.6 OCCUPATIONAL EFFECTS OF VIBRATION

A number of occupations experience vibration as part of the occupation such as hand-arm vibration with hand tool operation and whole-body vibration with vehicle operation. With hand tool operation, vibration-induced illusions, neuromotor adaptation to vibration, and muscular fatigue can alter the dynamic control of the tool [47-49]. Anyone who has ever used a hand sander in their garage shop has experienced the loss of tactile sensitivity and "numbness" that follows [49]. In the minutes that follow such exposure, the ability to perform hand tracking tasks can also be altered [48]. Long-term professional exposure to hand-arm vibration has been shown to lead to hand-arm vibration syndrome (also known as "white finger"). Beyond the neuromotor effects of hand-arm vibration, it has been suggested that hand-arm vibration syndrome may be a result of biochemical and blood flow-related changes including constriction of the artery walls and decreases in blood flow [50].

Recent studies have also suggested that whole-body vibration may have some neuromotor effects that may increase risk of low-back injury. Whole-body vibration in occupations such as truck driver and helicopter pilot is known to increase low-back injury risk by 1.2- to 39.5-fold [51]. This epidemiological evidence of vibration-induced injury risk has led to the establishment of ISO guidelines for acceptable occupational vibration exposure [52]. Several studies have demonstrated that whole-body vibration in frequencies of 3 Hz to 10 Hz elicits a neuromotor response in the paraspinal musculature that is similar to the monosynaptic reflex activation described in Section 7.3 [10, 11, 53]. It has been suggested that whole-body vibration transmitted to the paraspinal musculature activates muscle spindle organs resulting in reflex activation. The frequencies that result in kinesthetic illusions (20-120 Hz) are attenuated in whole-body vibration, so it is unlikely that kinesthetic illusions would result from this stimulation [6, 7, 52, 54]. However, such stimulation could result in neuromotor adaptation or muscular fatigue. Evidence of such adaptation includes increases in lumbar position sense errors after vibration exposure and changes in dynamic response to sudden unexpected perturbations [55, 56]. In response to a sudden perturbation, subjects exposed to whole-body vibration have been found to have delayed neuromotor response and greater joint motion excursion [55, 56]. Increases in position sense error and delays in response to unexpected perturbations have been suggested as a potential mechanism by which occupational vibration might alter spinal stability and increase risk of low-back injury [55, 56].

7.7 THERAPEUTIC USES OF MUSCULOSKELETAL VIBRATION

The neuromotor effects of vibration are not necessarily all detrimental. Several researchers have suggested using many of the same vibration-induced neuromotor effects to improve athletic training and rehabilitation. The methods suggested by these researchers have included the use of subthreshold vibration to enhance cutaneous sensation, the use of vibration-induced neuromotor activation during athletic training to improve strength and endurance, and the use of vibration-induced neuromotor activation in rehabilitation for a number of neurological conditions such as cerebral palsy and Parkinson's disease [57-74]. Whole-body vibration platforms are even appearing in a number of gyms and exercise facilities with claims of improving strength, endurance, and bone density [57, 61-69]. It is, therefore, worthwhile to examine the scientific evidence that exists for therapeutic effects.

7.7.1 Subthreshold Vibration

In 2003, J. J. Collins received the MacArthur Fellowship (often referred to as the "Genius Award") for work using vibrating shoe insoles to improve dynamic balance and control in the elderly [58]. The principle of this work was the use of subsensory, cutaneous, white-noise vibration to enhance sensation in those with high vibrotactile thresholds such as stroke patients. Subsensory vibration is vibration below the vibrotactile threshold of the cutaneous sensors and therefore below the ability of the patient to perceive. These researchers suggested that adding a low aperiodic signal to a weak signal pushes the signal above detection thresholds. This phenomena is known as aperiodic stochastic resonance (Fig. 7-2). This method requires a vibration that is large enough to enhance the sensory response but not so large that the vibration overwhelms the actual sensory signal. This research group has demonstrated that the use of such stimulation improves vibrotactile sensitivity and reduces postural sway in patients with diabetic neuropathy, patients with stroke, and elderly subjects [59, 60]. By keeping the added vibration below sensory thresholds, the authors suggest that possible neuromotor adaptation to prolonged vibration exposure is limited.

7.7.2 Vibration, Exercise, and Training

It has been suggested that vibration might also be used in combination with an exercise or training regiment to improve athletic performance or to rehabilitate patients with Parkinson's disease, stroke, or cerebral palsy. In healthy young adults, a number of long-term studies have shown an improvement in measures of muscle strength or performance (such as jump height) after whole-body vibration of 26-40 Hz during exercise [61-65]. Others have found little or mixed effects of adding vibration to exercise [66, 67]. Reviews of this literature have been critical of the control groups selected and have not provided strong recommendations for whole-body vibration exercise [68, 69]. Similarly, in patient populations, mixed results have been observed with whole-body vibration training, producing no significant differences in post-acute-stroke patients but some improvement in Parkinson's and cerebral palsy patients in neurological measures such as spasticity, tremor, and rigidity [70-73].

The proposed mechanisms for improved strength and motor performance with whole-body vibration are based on a number of the neuromotor effects described in this chapter. The tonic vibration reflex, which is observed as an increase in the level of muscle activity with high-frequency vibration, is thought to lead to a higher magnitude of muscle exertion and therefore improved training [68]. Vibration could also create kinesthetic illusions and increased error in proprioception, forcing use of other sensory pathways and development of these pathways. Another study has suggested that the low-frequency vibration used in whole-body vibration exercise increases muscle blood flow (unlike the high-frequency hand-arm vibration that decreases muscle blood flow) [74]. Such an increase in blood flow could improve endurance, allowing for additional training effort. These proposed mechanisms are generally speculative, and further research is needed to fully support these theories and to understand the possible therapeutic effects of whole-body vibration.

All of these possible mechanisms do require that the vibration is successfully transmitted to the target musculature and is not attenuated by the soft tissues between the vibration source and the muscle. In seated whole-body vibration, frequencies above 4-6 Hz can be attenuated [52]. In standing whole-body vibration, frequencies above 20-25 Hz are attenuated [75]. High frequencies would likely be attenuated between the vibration source and the musculature, reducing their potential effects. This would particularly affect mechanisms that rely on the tonic vibration reflex or kinesthetic illusion, as these occur at higher frequencies.
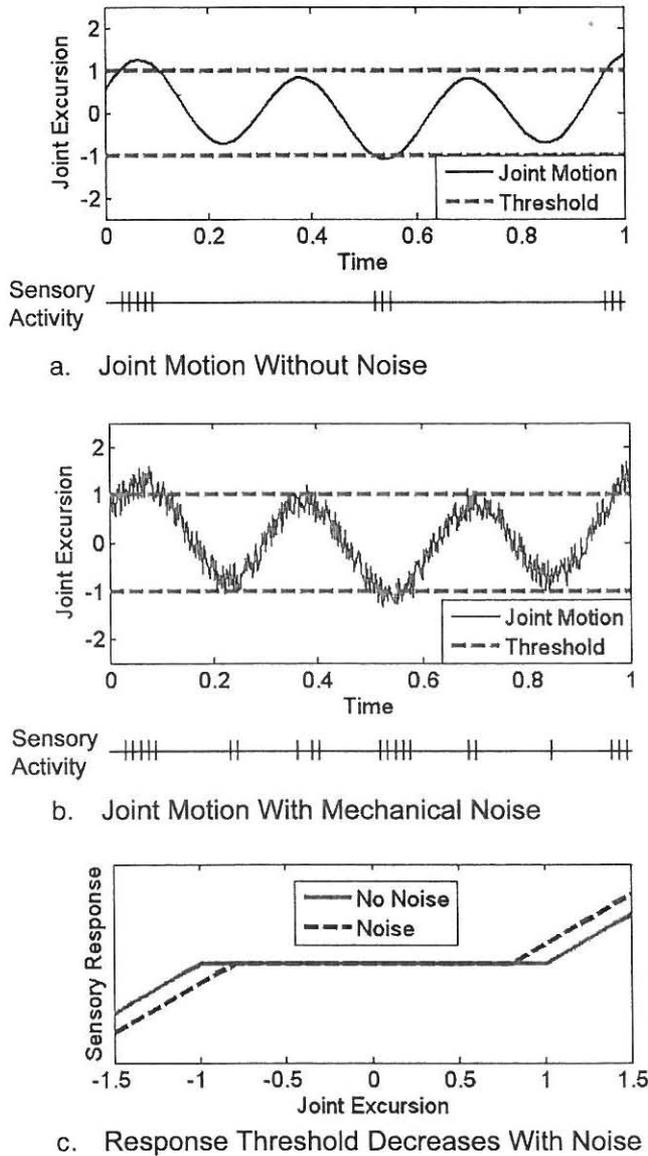
a. Joint Motion Without Noise

b. Joint Motion With Mechanical Noise

c. Response Threshold Decreases With Noise

Figure 7-2. The phenomena of aperiodic stochastic resonance involves adding a small amount of noise to a signal. If such a signal is measured by a sensor with a threshold (such as a cutaneous sensor), the noise will enhance the possibility of subthreshold signals being detected. a) Small-joint excursions (solid line) without noise may not be enough to overcome sensory thresholds (dashed line). b) Joint excursions with noise overcome sensory thresholds with smaller excursions. c) Adding subthreshold noise decreases the excursion needed to obtain a sensory response

7.7.3 Vibration and Bone Density

While not a neuromotor effect, one of the proposed effects of vibration exposure during training over a long-term has been to alter bone mineral density [76-83]. Rubin et al have proposed that low-amplitude (0.3 g), high-frequency (30 Hz) vibration applied to a standing animal or human would create enough strain in the bones of the legs to encourage bone remodeling and growth [81]. Bone mineral density in sheep exposed to such vibration for

20 minutes per day for 1 year increased significantly [81]. While successful in sheep, it has had mixed results in post-menopausal women, possibly due to issues relating to the transmissibility of vibration to the bones and compliance of subjects [80]. It has, however, been more successful in children and young women [77, 83].

7.8 FUTURE STUDIES

There is still much left to understand about the effects of vibration on the sensorimotor system. While it is known that the muscle spindles and cutaneous sensors respond to vibration and that, over time, the response of these sensors to vibration can change the behavior of the sensorimotor system, it is still unclear where in the circuitry of the CNS such responses take place. Brain imaging studies begin to give a glimpse of this circuitry but have yet to describe the neural pathways fully.

The detrimental effects of occupational vibration, particularly whole-body vibration induced low-back injuries, have been well documented in epidemiological studies. The studies described in this chapter have suggested that adaptation to vibration in the sensorimotor system may be a mechanism for altered control dynamics and increased injury risk. However, little is known about the effect of frequency, duration, and magnitude of vibration exposure on these adaptation effects or the duration these effects might persist post-vibration.

The therapeutic effects of vibration also require further study. While some studies suggest that using vibration in training and rehabilitation may enhance gains due to training, other studies do not find such enhancements, and little work has been done investigating the underlying mechanisms. The use of low, aperiodic vibratory noise to enhance sensory thresholds has been investigated with greater success, but more research is needed to prove its clinical efficacy.

7.9 CONCLUSION

Vibration has diverse effects on the sensorimotor system. It stimulates the muscle spindle organs and cutaneous sensors, resulting in afferent nerve activity, kinesthetic illusions and altered postural control. This activity interacts with the spinal cord reflexes and CNS, resulting in neuromotor activation of the musculature and vibration-induced adaptation of the sensors and the CNS. Beyond the basic physiological responses, such responses to vibration can be utilized to assess sensorimotor health and possibly in rehabilitation and improvement of athletic performance. Occupational vibration exposure may also affect the sensorimotor performance, resulting in detrimental effects that may increase risk of injury.

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BIOMEDICAL APPLICATIONS OF VIBRATION AND ACOUSTICS IN THERAPY, BIOEFFECTS AND MODELING

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