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The effects of muscle vibration on gait control: a review

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ABSTRACT

Background: The purpose of the review is to summarize the literature surrounding the use of muscle vibration as it relates to modifying human gait.

Methods: After a brief introduction concerning historical uses and early research identifying the effect of vibration on muscle activation, we reviewed 32 articles that used muscle vibration during walking. The review is structured to address the literature within four broad categories: the effect of vibration to ‘trigger’ gait-like lower limb motions, the effect of vibration on gait control of healthy individuals and individuals with clinical conditions in which gait disorders are a prominent feature, and the effect of vibration training protocols on gait.

Results: The acute effects of vibration during gait involving healthy participants is varied. Some authors reported differences in segmental kinematic and spatiotemporal measures while other authors reported no differences in these outcome measures. The literature involving participants with clinical conditions revealed that vibration consistently had a significant impact on gait, suggesting vibration may be an effective rehabilitation tool. All of the studies that used vibration therapy over time reported significant improvement in gait performance.

Conclusions: This review highlights the difficulties in drawing definitive conclusions as to the impact of vibration on gait control, partly because of differences in walking protocols, site of vibration application, and outcome measures used across different investigative teams. It is suggested that the development of common investigative methodologies and outcome measures would accelerate the identification of techniques that may provide optimal rehabilitation protocols for individuals experiencing disordered gait control.

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Introduction

For well over a century, various forms of muscle vibration have been employed to promote healthy functioning of the human body. There were several advocates of shaking muscles as a component of traditional massage techniques in the late 19th century. In his Guide to Healthy Living published in 1885 (Taylor 1885), Taylor recommends muscle vibration, as well as explicitly suggesting that vibration is linked to spinal and sympathetic nerve fibres. Zander was another early practitioner of muscle vibration; he designed and built a variety of machines which ‘shook’ different body segments to relieve muscle and joint ailments (Levertin 1892). Focussing more narrowly on medical applications, Charcot (1892) and Goetz (2009) developed a vibrating chair for use with his patients with Parkinson’s Disease (PD) while his student, Tourette, built a helmet that incorporated a vibrator (Walusinski 2019).

In the mid-twentieth century, Hagbarth and Eklund (1966) reported the effect of muscle vibration on patients with spasticity resulting from a variety of conditions including tumours, stroke, and spinal cord injuries (SCIs). Of significant interest is the fact that these authors reported that vibration increased muscle power output during voluntary contractions of the muscle being vibrated, but also decreased power production when the antagonist was vibrated. Additionally, these effects were often seen in nearby functional agonists and persisted beyond the period of vibration. This paper was followed up by a classic paper concerning the tonic reflex contraction on human skeletal muscle, including protocols that examined a range of vibration frequencies, initial muscle lengths, and initial contraction levels (Eklund and Hagbarth 1966). That same year, Matthews (1966a, 1966b) reported that vibration of the primary afferents in decerebrate cats produced a ‘stretch reflex’.

Subsequent research identified that vibration results in small changes in muscle length (Goodwin et al. 1972) that activate both the primary and secondary muscle spindle afferents, resulting in an illusionary stretching of the vibrated muscle. Primary afferents are more sensitive than secondary afferents, which tend to respond at sub-harmonic frequencies of the vibration, and are able to respond one-to-one to a large range of vibration frequencies more effectively (Burke et al. 1976; Roll and Vedel 1982). Vibration-induced afferent activation results in homonymous muscle reflex activation as well as increased and protracted motor unit activation,

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extending well after vibration has ended. The previous research regarding vibration and muscle functioning paved the way for scientists and clinicians to begin to more actively explore the possibility that vibration may play a prominent role in rehabilitation therapies for a variety of clinical conditions as well as for maintaining healthy functioning in aging individuals. Within the past decade, there have been a number of reports detailing the use of vibration for clinical applications. Recently, a commercial product sector using vibration to restore or enhance gait performance has emerged. For example, TechnoConcepts has developed the Vibramoov™, which provides patterned vibration stimulation for the neurorehabilitation of gait.

Despite these advances, there is no definitive information on the effects of vibration on gait performance for healthy individuals or patient populations, let alone an identified protocol designed for optimal results. This review will summarize the current state of the use of vibration to modify gait performance in healthy individuals, young and old, as well as the effects of vibration during walking for those with diseases and clinical conditions. Several papers that we reviewed contained information that would be appropriately included in several different sections of this review. Therefore, we included the relevant information from a given paper in the appropriate section. This approach results in many of the reviewed papers being mentioned in multiple sections throughout this review. For instance, Mullie and Duclos (2014) included information about the effects of vibration on gait of healthy individuals, and this information is included in the section titled 'Lower limb vibration applied to healthy individuals'. These same authors also applied vibration to individuals with hemiparesis due to stroke, and this information is reported in the section titled 'Effects of vibration applied to individuals with clinical conditions.'

There are two explanations as to why the application of vibration during walking may modify gait. The first explanation has been alluded to previously; that is, vibration generates a reflex activation in the homonymous muscle which increases power output while simultaneously reducing antagonist muscle activation (Eklund and Hagbarth 1966). It is therefore reasonable to speculate that repeated vibration-induced reflex activation could impact muscle function to the extent that segmental kinematics could be modified while walking. A second explanation may be that the afferent input to the spinal cord from vibration activates central structures responsible for the basic alternating flexion-extension pattern of segmental motion during walking. It has long been known that afferent input can trigger locomotion in animal preparations (Grillner and Zangger 1979), and there is evidence that vibration in humans can lead to activation of muscles several spinal segments distant from the vibrated muscle. This indicates that vibration effects extend beyond mono-synaptic reflex activation of the homonymous muscle and therefore are mediated by additional spinal mechanisms (Lin et al. 2012). It is reasonable to speculate that these mechanisms are influenced by supraspinal input which is also used to shape segmental walking motion. It is probable that both local reflex and broader central mechanisms cooperate to mediate the effects of vibration on walking.

The majority of studies investigating the impact of vibration on gait have employed vibration in the range of 70–100 Hz because the Ia spindle response can follow vibration frequencies in a one-to-one manner and this range seems to provide the greatest effect. Unless stated otherwise, papers included in this review have used vibration frequencies in the range of 70–100 Hz. However, as will become evident, beyond a relatively narrow range of vibration frequencies, there is not a commonly accepted methodological protocol that a majority of investigators adopt when conducting studies of vibration's effects on gait control. At what frequency and to what muscles vibration is applied, the walking tasks employed, and the measures used to determine if vibration impacts gait control vary widely across laboratories and clinics. Thus, generalization of the effects of vibration are somewhat challenging.

As with any investigation of gait, independent of the effect of vibration, there is a range of measures used by investigators to characterize gait performance. Gait motion describes characteristics that define how a person walks and includes spatiotemporal characteristics, kinematics, kinetics, and weight distribution. Spatiotemporal characteristics are measures which assess distance and time. This includes measures such as gait speed (distance travelled per unit time), cadence (steps per unit time), stride time (time to complete a full gait cycle), stride length (distance travelled by one complete gait cycle), and double support time (time spent with both feet touching the ground in a cycle and often represented as a percent). Kinematic data describe how the body is moving and responding during the gait cycle and are often depicted via measures of joint angles, angle-angle diagrams, and phase portraits. Typically, kinematic data are obtained via a camera system that detects the motion of the body's segments. Inertial measurement units (IMUs) have also been used to obtain segmental kinematic data. Kinetic data include measures of segmental accelerations, forces, and moments. Weight distribution is often analyzed to assess stability and balance during walking, using force plates to quantify centre of mass (COM) and centre of pressure (COP). Measures can also be evaluated in terms of their variance or consistency. As a final note, this review does not include the research devoted to the application of vibration to the soles of the feet, often at subthreshold levels, during walking. This review also does not include works regarding the effects of whole-body vibration on walking. Instead, we focus on research involving vibration being applied directly to muscles, most often in the form of a vibrator being secured with a strap or band over the muscle(s) to be vibrated.

The following section will review papers whose authors used protocols designed to determine if vibration can 'trigger' central mechanisms to initiate gait-like behaviours.

Can vibration 'trigger' segmental walking motion?

Gurfinkel et al. (1998) were the first to investigate the use of vibration to trigger gait-like movements in humans. Healthy individuals were placed in a double leg suspension system while lying on their side. Vibration was applied to the quadriceps (Q), biceps femoris (BF), flexor digitorum brevis, tibialis anterior (TA), tensor fascia latae (TFL), and triceps surae (TS).[1] Some conditions involved vibrating a single muscle while other conditions involved pairing vibration of two muscles. Gurfinkel et al. found that vibration of a single muscle could elicit air-stepping with kinematics and electromyogram (EMG) bursts similar to that of voluntary air-stepping patterns independent of the location of the stimulated muscle. Additionally, simultaneously stimulating antagonistic muscles produced a more efficient air-stepping motion than stimulating one muscle. Field-Fote et al. (2012) also investigated the effects of vibration on air-stepping, comparing the effects in healthy individuals to those with varying levels of SCIs. Participants underwent two sessions of side-lying trials with vibration continuously applied to either the Q, H, or TFL. Consistent with Gurfinkel et al. (1998), these authors also reported that thigh muscle vibration triggered air-stepping. This was true for both healthy individuals and patients with SCIs. Kinematics were recorded to assess consistency and robustness of the lower limb motion via hip versus knee angle-angle diagrams, Robustness was defined as the area that represented the excursion of the hip-knee movement with a larger area indicating greater robustness. The researchers found that vibration of a variety of muscles resulted in air-stepping, but vibration of the TFL had significantly higher robustness when compared with other vibration sites. The authors used the results from the TFL vibration condition to compare the results of individuals with SCI to those of healthy participants. The severity of the SCI injury did not influence the effects of vibration, so the results of the SCI individuals were pooled into one group and compared to the healthy individuals. As expected, SCI patients had significantly lower consistency and robustness than healthy individuals.

Duclos et al. (2014) also investigated the efficacy of vibration to trigger stepping in place in an individual with an incomplete SCI compared to that of a healthy individual. Vibration was applied bilaterally to the Q, H, TA, and TS in a phasic pattern that mimicked the typical gait cycle. The period of this vibration cycle was varied between one and two seconds, depending upon a given trial. Duclos et al. reported that for both individuals, vibration induced stepping in place but with limited ranges of joint motion. The healthy participant followed a typical order of joint motion in a gait cycle: hip flexion, knee flexion, ankle dorsiflexion, hip extension, knee extension, ankle plantarflexion. However, the individual with the SCI was found to have hip flexion associated with knee extension and ankle plantarflexion. This pattern was followed by hip extension associated with knee flexion and ankle dorsiflexion. It was also noted that the performance was slightly improved in both participants when using a two-second period for the gait cycle when compared with the one-second vibration cycle.

De Nunzio et al. (2010) provided phasic vibratory stimulation to a group of healthy individuals and a group of individuals with PD during a bipedal standing task. Alternating left side-right side trains of erector spinae (ES) vibration were provided every 600, 800, or 1100 ms to test frequencies of stimulation that were below, similar to, or above the frequency associated with spontaneous gait. Centre of pressure data were obtained and fast Fourier transfer (FFT) power spectrum peaks were assessed to determine if COP sway was coupled to vibration activation patterns. The authors reported significant coupling between FFT peaks and mediolateral COP displacement that were consistent with the oscillations observed in the frontal plane during walking. This suggested that patterned vibration can generate functional body shifts between the legs in both healthy individuals and individuals with PD. Although the De Nunzio et al. (2010) methodology was not designed to trigger walking *per se*, the pattern of body sway generated by their phasic vibration resembled walking. This suggests appropriately timed afferent stimulation can influence both local and central mechanisms associated with gait control.

Although limited in the number of studies and methodological scope, the existing evidence suggests that muscle vibration, including even the vibration of a single lower limb muscle, can be used to trigger the basic locomotor pattern. It is suggested that this pattern of motion is the result of afferent input activating central structures, presumably primarily located in the spinal cord, that subsequently lead to muscle activation and the associated segmental movement.

Lower limb vibration applied to healthy individuals

As mentioned previously, in addition to vibration potentially serving to 'trigger' central mechanisms associated with gait, vibration may also modify gait through reflex activation of vibrated muscles. However, there is currently no clear consensus on the anatomical location at which the optimal effects of vibration on gait can be produced. Most investigators interested in determining the effects of vibration on gait parameters have applied vibration to muscles of the lower limb. The literature reveals that there are two basic approaches to the application of vibration. One approach is to activate the vibrator continuously throughout the gait cycle, and the other is to provide vibration during specific phases of the gait cycle (e.g., during mid-stance). The literature on the effects of continuous vibration on gait significantly outnumbers the literature on the effects of phasic vibration on gait in healthy individuals. It is still unclear as to which method has a greater effect on gait parameters in healthy individuals. This section will initially review papers focussed on lower limb continuous vibration applied to healthy individuals.

Continuous vibration

Several investigators evaluated the effects of continuous vibration on gait during overground walking tasks. Courtine et al. in 2001 investigated the effects of vibration applied bilaterally to the TS on lower limb kinematics in young, healthy individuals (Courtine, Pozzo, Schieppiti 2001; Courtine, Pozzo, Lucas et al. 2001). The participants were tasked with walking overground with eyes closed in order to remove visual input and magnify the effect of the vibrational sensory input (Schmid et al. 2005; Layne et al. 2015). The researchers found that there was a weak but systematic reduction in foot and leg angle amplitude and step length with vibration (Courtine, Pozzo, Lucas et al. 2001). It was also reported that TS vibration led to a significant increase in step frequency and a significant decrease in the duration of stance phase. It is worth noting that most of the effects demonstrated during walking with vibration tended to be retained after testing while duration of stance phase tended to move back toward baseline values (Courtine, Pozzo, Schieppiti 2001; Courtine, Pozzo, Lucas et al. 2001). Ivanenko et al. (2000a) found that vibration to the H also elicited a significant increase in walking velocity and stepping frequency with a trend toward an increase in stride length during treadmill walking.

Verschueren et al. (2002) also found significant results when vibration on young, healthy individuals was applied to lower limbs during overground walking without vision. These authors used continuous unilateral vibration applied to individual muscles: TA, TS, H, Q, and the rectus femoris (RF) at the hip. Kinematics and spatiotemporal variables were used to assess the impact of vibration. The researchers found that vibration to the ankle musculature (TA and TS) resulted in significant local effects with TA vibration significantly decreasing plantarflexion at toe-off and TS vibration significantly decreasing dorsiflexion during the swing phase. Vibration to the Q led to a significantly increased relative phase of the vibrated limb, suggesting that its effects were present in both the knee and ankle. Furthermore, vibration of the RF at the hip led to a decrease in knee flexion during swing phase and a decrease in dorsiflexion during stance phase. Finally, vibration had an overall effect of decreasing walking velocity independent of the location of vibration (Verschueren et al. 2002).

Mullie and Duclos (2014) investigated the effect of continuous vibration during treadmill walking on healthy individuals and hemiparetic patients with vibration applied to the TS of the nondominant side. Whole body kinematics and force plates were used to monitor gait. The maximum stabilizing force (theoretical force needed to stop motion of the body's COM and COP) and minimum destabilizing force (minimum force needed to move the body into an unstable position) were major measures of balance during gait. The researchers found that vibration to the TS led to an increase in destabilizing force and a decrease in stabilizing force, meaning that the difficulty in maintaining balance was significantly reduced. Additionally, vibration led to a significant shift backward in body position while walking.

Kwak et al. (2017) also found that continuous vibration to the TA tendon led to significant modifications in lower limb kinematics in healthy elderly individuals. Kwak et al.'s participants walked overground with eyes open, with and without vibration. Their data was compared to a group of healthy, young individuals who walked without vibration. Frequencies were varied in the range of 180–200 Hz. Kinematic and kinetic measures revealed improvement in the healthy elderly individuals during the stance phase of the gait cycle. TA vibration led to a reduction in ankle dorsiflexion in early stance and an increase in dorsiflexion during late stance. The authors reported an overall reduction in plantar flexor moment and positive and negative power during early stance and an increase in plantar flexor moment and negative power during late stance. Vibration led to reduced knee flexion during early stance phase and increased flexion during late stance as well as increased flexor and extensor moments. These findings were accompanied by a reduction in positive and negative power. In the hip, flexion tended to decrease, accompanied by a reduction in extensor moment in early stance and a reduction in flexor moment in late stance. The researchers found that the kinematic and kinetic differences between young and elderly individuals decreased when vibration was applied. Furthermore, differences in effects were observed when frequencies were varied, but generally, improvements were present at all frequencies.

While there have been results supporting that vibration applied continuously during gait has significant effects in healthy individuals (Ivanenko et al. 2000a; Courtine, Pozzo, Schieppiti 2001; Courtine, Pozzo, Lucas, et al. 2001; Verschueren et al. 2002; Mullie and Duclos 2014; Kwak et al. 2017), there has also been evidence of vibration not having an effect or not having a consistent effect on healthy individuals. Layne et al. (2015) investigated the effect of vibration applied unilaterally to the H or Q during split-belt treadmill walking in healthy individuals. The researchers evaluated the ability of individuals to adapt to split-belt walking with and without vibration. Ultimately, vibration led to changes in kinematics, but these changes varied between participants. Beyond a significant reduction of percent stance time associated with Q vibration, no consistent findings were reported (Layne et al. 2015). Pereira et al. (2015) conducted a study on the ability of young, healthy individuals to perform a sit-to-walk test with vibration applied bilaterally to the following muscles: TA, Q, or upper trapezius. First step time, length, and velocity were recorded and ultimately, vibration of any of the tested muscles did not have any significant effects. Ivanenko et al. (2000a) also found that vibration to the Q, TA, and TS produced weak effects on spatiotemporal measures of gait during treadmill walking. Similarly, Mullie and Duclos (2014) found no effect on spatiotemporal gait characteristics in response to vibration to the TS during treadmill walking. In a 2007 study, Courtine et al. (2007) investigated the effect of muscle vibration in healthy individuals on walking trajectory and found that vibration to multiple muscles of the lower limb had no effect on angle of deviation. Ultimately, this result is supportive of using lower limb vibration, if proven to be effective for improving gait, as it does not alter a person's ability to walk in a straight line.

Phasic vibration

Phasic vibration has also been shown to induce gait-like motions in healthy individuals (Duclos et al. 2014; Barthélémy et al. 2016) and thus has exciting applications for improving gait. The motive for phasic vibration is that carefully timed vibration to muscles can stimulate sensory afferents during the step cycle to excite and enhance muscle activation (Ivanenko et al. 2000a). In the Ivanenko et al. study, mechanical sensors were positioned on the heel to identify heel strike and set the phasic cycle for vibration during treadmill walking of healthy participants. Phasic vibration to the H was found to increase walking velocity and stepping frequency (with a trend toward increasing stride length), while phasic vibration to the Q, TS, and TA produced weak, if any, effects. These results are consistent with the findings obtained during continuous vibration. Mullie and Duclos (2014) investigated phasic vibration to the TS during stance phase during treadmill walking in healthy individuals and found no change in spatiotemporal gait characteristics (consistent with their results for continuous vibration). However, the researchers did find the minimum destabilizing force was decreased and stabilizing force was increased, ultimately suggesting reduced difficulty in maintaining balance while walking.

Roden-Reynolds et al. (2015) and De Nunzio et al. (2010) also investigated the effects of phasic vibration in a slightly different manner. Roden-Reynolds et al. applied phasic vibration to the glutaeus medius during right leg stance or swing phase. However, vibratory perturbations were not induced during every step to remove the participant's ability to anticipate the onset of vibration. Healthy individuals conducted trials of treadmill walking with control of mediolateral motion as the primary outcome measure. The researchers found that vibration to the hip abductor during stance phase led to a narrower step while vibration during swing phase led to a wider step. Roden-Reynolds et al. suggested lateral COM velocity is an indicator of the likelihood of falling. De Nunzio et al. applied phasic vibration bilaterally to the TA and TS, alternating the side at a frequency that was 10% above the preferred step cadence of each participant. Spatiotemporal gait characteristics and COM measurements were recorded. De Nunzio et al. found that TS vibration led to decreased stance time and that vibration to the both the TA and TS led to a significant increase in the width of the base of support.

Continuous versus phasic vibration

The number of investigations on the effects of continuous vibration on the gait of healthy individuals significantly outnumbers those on the effects of phasic vibration. It remains unclear as to which method has a greater effect on gait parameters in healthy individuals. Ivanenko et al. (2000a) and Mullie and Duclos (2014) compared continuous and phasic vibration in their studies. Ivanenko et al. found that continuous vibration elicited greater changes in overall velocity than did phasic vibration (Ivanenko et al. 2000a), while Mullie and Duclos (2014) did not find any significant differences between phasic and continuous vibration.

Vibration initiated by abnormal gait or obstacles

Sorensen et al. (2002) and Yu et al. (2010) designed investigations where vibration was not initiated until an abnormal gait event occurred in healthy individuals. Sorensen et al. created an abnormal gait event by instructing participants to step over an obstacle during overground walking. Force sensors were used to identify the step immediately prior to stepping over the obstacle and this information was used to initiate one second of vibration to either the TS or TA. These authors found that vibration of the TS reduced mediolateral COM acceleration while vibration of the TA increased mediolateral COM acceleration and mediolateral COM displacement. Additionally, vibration to both muscles led to a decrease in the difference between COM and COP. Yu et al. (2010) monitored gait using an ankle accelerometer, which identified abnormal acceleration peaks during overground walking of young, healthy individuals. When the abnormal peaks were detected, one second of vibration was initiated simultaneously to both the TA and TS. Kinematics and reaction forces were obtained. In agreement with Sorensen et al., Yu et al. reported that vibration led to a decrease in both mediolateral acceleration and the difference between COM and COP. Additionally, they reported that vibration decreased trunk tilt and concluded that vibration had a stabilizing effect when triggered by abnormal gait motion.

As is evident, it is difficult to draw definitive conclusions regarding the effects of lower limb vibration on gait parameters when applied to healthy individuals other than in general, they tend to be minimal. This conclusion seems to be particularly true in reference to kinematic measures. Several authors did report some impact of lower limb vibration on spatiotemporal gait parameters during both overground and treadmill walking. The lack of a large effect of vibration when applied to healthy individuals during walking is not particularly surprising as the vibration is being applied to participants with intact sensory-motor systems, which generally negate the potential to 'improve' gait control through the use of vibratory sensory input. Conversely, it can be argued that it is surprising that lower limb vibration has such a limited effect on gait control as the sensory input associated with vibration serves to distort the natural afferent inflow associated with walking and can therefore be considered potentially disruptive. However, vibration may result in positive outcomes when applied to individuals with disordered sensory-motor systems. This possibility will be explored in the next section of this review.

Effects of vibration applied to individuals with clinical conditions

Although limited effects of lower limb vibration were observed when applied to healthy individuals during gait, the literature reflects a greater effect when vibration is applied to those with clinical conditions that involve disordered gait control.

Parkinson's disease (PD) is a chronic and progressive disease which exhibits characteristic changes in motor activity. Patients often suffer from disorders of posture, balance and gait, which can lead to falls. The characteristic Parkinsonian movement includes small shuffling steps and a slowness of movement (Kimmeskamp and Hennig 2001). De Nunzio et al.

(2010) investigated the effect of phasic vibration to the TS and TA with a group of individuals with PD during overground walking. They reported that TS vibration led to an increased stride length while TA vibration led to a decreased stride length. Both TS and TA vibration led to an increase in width of support base. Han et al. (2014) conducted a study on individuals with PD where vibration was applied bilaterally to the TA, TS, H, and Q simultaneously. These researchers found that stride length and walking speed were significantly increased while other spatiotemporal parameters were improved but failed to reach statistical significance.

Freezing of gait (FOG) is a symptom experienced by many patients with PD. Pereira et al. (2016) explored the use of vibration as method to prevent or minimize FOG. Vibration was applied unilaterally to the TS during the first instance of FOG and remained on for the duration of the trial. The effects of vibration were investigated on both the more affected limb (MAL) and less affected limb (LAL). Pereira et al. found that vibration to the LAL significantly decreased the duration of only the first instance of FOG, while vibration to the MAL slightly lengthened the duration of the first FOG. Subsequent FOG durations were unaffected as was the time between FOG episodes. The authors suggested their findings support the idea that vibration has an alleviative, though not preventative, effect on the duration of FOG. The researchers also found that participants reinitiated walking using the vibrated limb significantly more often after FOG, providing further validation that vibration has only an alleviative effect.

In addition to the effects of vibration on PD, Mullie and Duclos (2014) investigated the effects of lower limb vibration during treadmill walking in patients with hemiparesis due to stroke during treadmill walking. In one condition, vibration was continuously applied to the paretic TS and in another condition applied to the paretic TS only during the stance phase. Whole-body kinematics and force plates were used to monitor gait. The researchers found that vibration had no effect on gait-related segmental motions or associated forces.

Vibrational effects on muscle activity

In addition to monitoring the effects of vibration on spatiotemporal parameters, kinematics, and kinetics of gait, vibration's effect on neuromuscular activation has also been investigated. Ivanenko et al. (2000a) reported no significant effects of vibration on EMG signals of several lower limb muscles in healthy individuals during treadmill walking. Conversely, Courtine, Pozzo, Lucas, et al. (2001), reported decreases in TA activity when vibration was applied to the TS of healthy individuals during overground walking. Hubbuch et al. (2015) found a reduction in TS activity during midstance, but an increase during late-stance while performing a graded treadmill walking task. Additionally, they reported that vibration increased the time required to adapt to increases in treadmill incline as well as metabolic rates. Hubbuch et al. concluded that vibration served as a proprioceptive disrupter, at least for their healthy participants. Verschueren et al. (2003) investigated the effects of vibration on the neuromuscular activation of the major muscle groups of the lower limbs (Q at hip and knee, H at hip and knee, TA, and TS) during blindfolded, overground walking in healthy individuals. EMG data was recorded during stance and swing phase for lower limb muscles and activation onset time for TA was recorded to assess the timing of phase transfer. The researchers found that only vibration to the Q and H at the knee led to significant increases in activity during stance phase. Vibration of H at the hip led to a significant decrease in activity. Interestingly, in several vibration conditions, the EMG of the vibrated muscle did not demonstrate significant changes, but remote muscles of the vibrated limb did. For instance, TA vibration affected Q activity during stance phase and TS vibration affected TA activity during swing phase. Furthermore, the only vibrated muscle to have an effect on TA onset time was the Q.

The effects of vibration on muscle activity were also investigated in patients with chronic SCI by Cotey et al. (2009). The researchers compared the effects of continuous and phasic vibration in SCI patients and healthy individuals during robotic-assisted treadmill walking with partially or completely supported weight bearing, depending on the severity of the injury. Vibration was applied either to the Q continuously or at different phases of the gait cycle: swing phase, stance phase, transition to stance, transition to swing. Muscle activity and activation onset timings of the TA, TS, Q, and H were recorded. The researchers found that continuous vibration led to a significant increase in EMG activity in the Q and H of the vibrated leg in both SCI patients and healthy individuals when compared to no vibration, while the TA and TS activity remained unchanged. Additionally, during continuous vibration, the activation timing of the Q and H during the stance phase of SCI patients was significantly modified to more closely resemble that observed in healthy individuals without vibration. Continuous vibration also improved the activation timing of the Q in SCI patients during the transition to stance phase. Although not definitive, these studies tend to reinforce the suggestion that muscle vibration has an effect beyond the vibrated muscle, possibly modulated through more central mechanisms, at least during gait.

Neck and trunk vibration

Effect on healthy individuals

The effects of vibration applied to muscles in the neck and trunk in healthy individuals have also been investigated by several research teams. However, unlike the lower limb studies, these tended to focus more on the effect of vibration on directional steering during overground walking, although some did report spatiotemporal gait parameters. Two papers, one by Schmid et al. (2005) and the other by Courtine et al. (2007), focussed specifically on the angle of deviation during overground walking. Participants were tasked with walking in a straight line while vibration was applied. Schmid et al. applied continuous vibration to the left (ES) muscles with the conditions of whole-time vibration (WTV) or half time vibration (HTV), with and without vision. The researchers found that WTV with vision had no deviations compared to the control condition without vibration, while HTV resulted in a slight deviation to the right. Walking without vision, WTV had a slight deviation compared to the control, while HTV had significantly greater deviation than both the control and WTV (Schmid et al. 2005). Courtine et al. (2007), applied continuous vibration to a number of upper and lower body muscles but found that only splenius, sternocleidomastoid, trapezius, and trunk vibration led to significant angles of deviation. In fact, of the upper body muscles tested, only the triceps did not result in veering. Similarly, Bove et al. (2002) found that vibration applied continuously and unilaterally to the sternocleidomastoid during blindfolded stepping in place led to a rotation. More specifically, vibration applied *during* stepping caused rotation away from the source of vibration. Vibration applied *before* stepping caused an initial rotation away from the source of vibration, but switched to be towards the source of vibration before stopping rotation altogether. Additionally, both vibration conditions led to an increase in step length.

Ivanenko et al. (2000b), investigated the effect of symmetrical vibration applied to the trapezius and splenius tendons during treadmill walking in healthy individuals. Ivanenko et al. found a shift forward in stepping motion and, in agreement with Bove et al. (2002), an increase in step length which was accompanied by an increase in step frequency. Additionally, walking backwards elicited the opposite results with a decrease in speed. De Nunzio et al. (2010) applied phasic vibration bilaterally to the ES and found that cadence was significantly increased and both stance and swing time were decreased. Stride length and velocity were not affected by ES vibration. Pereira et al. (2015) and Mullie and Duclos (2014) found that vibration to the posterior neck muscles also had no effect during a sit-to-walk test or during overground walking, respectively, in healthy individuals. Contrarily, Wannaprom et al. (2018) found that vibration to the posterior neck muscles caused a decrease in overground walking speed. These data indicate that vibration of some trunk and neck muscles affect directional steering during overground walking, but it is less clear as to the effect on gait parameters. Differences in protocols may well account for the differences in outcome measures with the application of trunk and neck vibration during walking.

Effect on individuals with clinical conditions

Similar to lower limb vibration, the effects of neck and trunk vibration on patients with neck pain, PD, and stroke on spatiotemporal gait parameters have been investigated. Wannaprom et al. (2018) investigated the gait speed of individuals with chronic neck pain when vibration was applied to the posterior neck muscles during overground walking. The researchers found an increase in walking speed such that there was no significant difference in those with chronic neck pain from healthy individuals. De Nunzio et al. (2010) and Ghoseiri et al. (2009) investigated the effect of vibration to the trunk during overground walking in patients with PD. De Nunzio et al. found that ES phasic vibration led to significant increases in stride length, cadence, and walking velocity. Cadence was improved to the extent that it was not significantly different from that of healthy individuals without vibration (De Nunzio et al. 2010). Similarly, Ghoseiri et al. (2009) found that phasic vibration led to an increase in walking velocity when applied bilaterally to the lumbar region. Conversely, Mullie and Duclos (2014), found no spatiotemporal effect on gait when vibrating the posterior neck muscles in stroke patients during a sit-to-walk test.

Vibrational therapy programme

For patients with diseases that negatively impact gait, vibration training has been investigated as a potential therapy to help induce rehabilitation. As with the previously reviewed research, specifics of the training protocols, outcome measures, vibration location, and duration of training varies between studies. Several therapy programmes applied subthreshold vibration that allowed for blinded studies where participants were not aware of their group placement. Vibrational therapy has been investigated in patient populations composed of individuals with post-stroke, cerebellar ataxia, multiple sclerosis (MS), and SCI.

Of those who survive a stroke, between 20 and 30% are unable to walk and many others have severe walking disabilities (van de Port et al. 2006). Paoloni et al. (2010) and Lee et al. (2013) have investigated if vibrational therapy programmes are beneficial for improving the rehabilitation process for stroke survivors. Participants in Paoloni et al.'s study had foot drop resulting from chronic stroke. These participants underwent a general physical therapy session three times a week for four weeks with the experimental group receiving vibration at the end of each session while lying in a supine position. The control group received no vibration. Vibration was applied to the TA and peroneus longus. An overground walking test prior to and after completion of the training programme was conducted to evaluate spatiotemporal, kinematic, and EMG data associated with walking. Paoloni et al. (2010) found that the experimental group demonstrated significant improvements in gait speed, healthy side swing velocity, stride length on both the healthy and paretic side, and healthy side toe-off time percentage. Additionally, the experimental group experienced an increase in ankle ROM on both sides as well as a significant increase in TA activity during swing phase. The control group experienced no significant improvements with training. In the Lee et al. (2013) investigation, individuals with chronic stroke were split into an experimental group, which received subthreshold vibration, and a control group, which received sham vibration. Both groups participated in a six-week rehabilitation programme. Vibration was applied to the heel, TS, and TA for 30 minutes during the training programme, which included balance exercises and squats. Participants performed overground walking tests prior to and at the end of the training programme and spatiotemporal gait parameters were recorded. The authors found that the experimental group significantly improved their gait speed, cadence, step length, and single limb support time, while the control group only improved in gait speed and step length. When comparing the two groups, the experimental group had a significantly greater improvement in gait speed, cadence, and single limb support time.

Cerebellar ataxia is a degenerative disease of the cerebellum which has major debilitative effects on gait (Jayadev and Bird 2013). Leonardi et al. (2017) investigated the effects of a three-week training programme with vibration for the rehabilitation of patients with cerebellar ataxia. A wearable proprioceptive stabilizer provided continuous vibratory stimulation to the seventh cervical vertebra and bilaterally to the TS for three hours per day while participants continued their current treatment and training plans. Participants performed a 6-minute walking test (6MWT) prior to programme initiation, at the conclusion of the programme, and three weeks after the programme was completed during which spatiotemporal gait measures were obtained. The researchers reported significant improvements at the end of the training programme in cadence, cycle length, double support time, and single support time. When comparing measures at the end of the training programme to those obtained three weeks later, only cycle length returned to baseline values while the other variables remained significantly improved.

Multiple Sclerosis is a chronic inflammatory disease which targets the central nervous system causing demyelination and axonal loss (Kamm et al. 2014). In Larocca 2011 study, gait impairment from MS was reported by 85% of patients and was considered the most challenging aspect of living with MS by the majority of patients. Similar to the Paoloni et al. (2010) investigation with stroke patients, Camerota et al. (2017) did not apply vibration during physical training but as a separate aspect of the therapy programme for individuals with secondary progressive MS with lower limb spasticity and low or no response to antispastic drugs. For three days, vibration was applied bilaterally to the Q and the lumbar paraspinal muscles for ten minutes each. An overground walking task was completed by each participant at baseline, one week after treatment ended, and one month after treatment ended. Gait spatiotemporal parameters, kinematics, and kinetics were used to evaluate improvement and asymmetry of gait was specifically investigated. The researchers found that at one-month post-treatment, there was a significant increase in step length and stride length while there was a significant reduction in double support base time in the MAL. The LAL displayed a significant increase in swing phase, step length, and stride length as well as a significant reduction in stance and double support time. Additionally, cadence and walking speed were significantly increased, and gait symmetry improved. Moreover, hip ROM was significantly increased in both limbs, and maximum moment at the hip and ankle of the MAL, maximum hip power in both limbs, and maximum ankle power of the MAL all remained significantly increased compared to baseline.

Spina et al. (2016) investigated the effect of subthreshold vibration applied in patients with MS for one hour per day for three weeks. The experimental group received vibration at the C7 vertebra and TS if there was no impairment to the pyramidal system; otherwise, vibration was applied to the TS, patellar tendon, Q, and glutaeus medius. The control group received sham vibration. The participants were therefore blinded to whether they were in the treatment group. An overground walking test was conducted at baseline, at the end of treatment, and three weeks after the treatment period ended. Spatiotemporal parameters were recorded during each test. In agreement with Camerota et al. (2017), the authors reported that average stride length, first right step length, and double support time for both legs were significantly improved in the experimental group but not in the control (Spina et al. 2016).

SCIs disrupt the pathways for communication between the supraspinal and spinal centres and can result in major impairments in gait (Field-Fote et al. 2012). Barthélémy et al. (2016), investigated the use of a two-week training programme which used phasic vibration to induce stepping in place in a 62-year-old chronic incomplete SCI patient. Vibration was applied bilaterally to the flexors and extensors of the hip, knee, and ankle, and stimulation timing was based on a typical gait cycle. A 6MWT was conducted at baseline and following the training programme. The authors found that there was an increase in self-selected gait speed and total distance travelled after training. Furthermore, there were significant changes in hip angle, (shifting more toward extension in both hips) and a significant increase in ROM in the left hip. However, the ankle and knee kinematics appeared to be unaffected. The researchers also noted that angle-angle diagrams provided qualitative evidence of greater variability during the post-test, suggesting that the participant had more ability to modify his gait.

The literature suggests that, like the acute application of vibration, vibration therapy programmes generally result in improved gait performance across a range of individuals with clinical conditions affecting their gait. However, the important question of whether the improvements reported following vibration therapy programmes are sustainable remains to be addressed in a more systematic manner.

Summary

Since the early work of the mid to late 19th century, there has been interest in the potential health benefits of muscle vibration. The seminal work of Eklund and Hagbarth, Matthews, Goodwin, and others in the mid-20th century led to a greater understanding of the relationship between afferent input, particularly from Ia receptors, and its associated muscle activation. This work paved the way for the concept that muscle vibration might be an effective countermeasure and rehabilitative tool to assist individuals with disordered gait. A limited number of investigators have used lower limb and trunk vibration to determine if gait-like lower limb movements could be initiated by vibration. The results of these studies indicate that either continuous or phasic muscle vibration can initiate 'air-stepping' in participants suspended in harnesses. This result has been explained by suggesting that the vibration is able to trigger central mechanisms in order to generate the lower limb flexion-extension motion that was observed during these investigations.

Gait research with healthy individuals as participants presents a range of results. Some investigators reported effects of vibration on multiple lower limb muscles, including modifications in both kinematic and spatiotemporal gait measures, during both overground and treadmill walking. In contrast to the above, several authors have reported little to no effect of lower limb vibration during gait when healthy individuals are study participants. Thus, it remains an open question as to the extent that lower limb muscle vibration affects healthy individuals. Furthermore, the limited amount of evidence available suggests that the effects of continuous and phasic vibration during the gait cycle are similar, but further investigation is required. In contrast to the assortment of findings on healthy individuals, there is more agreement in the literature when vibration is used with a variety of clinical populations. Most studies that included individuals with clinical gait disorders displayed improvement in a variety of measures such that these measures often approached those obtained from healthy individuals. These improvements were suggested to result from interactions between central and local neuronal mechanisms used to support gait and offer promise that effective rehabilitation protocols employing muscle vibration can be developed in the near future.

The literature, although limited, provides mixed support for the contention that any changes in behavioural gait measures are likely to be accompanied by alterations in neuromuscular activity. Several papers indicated that lower limb muscle EMG was either increased or decreased in a manner that would be expected based upon the observed change in joint motion. For example, Verschueren et al. (2003) reported increases in TA activity associated with significantly decreased plantarflexion at toe-off. Conversely, other investigators reported no changes in EMG activity when vibration was applied during gait. Investigators have also assessed the effect of both trunk and lower limb vibration on steering during overground walking. While lower limb muscle vibration does not impact steering, trunk and neck muscle vibration has a strong impact by causing veering in almost all circumstances.

Finally, several groups have explored the effects of vibrational training protocols for those with clinical conditions that negatively impact gait. In all cases, regular exposure to vibration over a period of time, days to weeks, had a positive impact on a variety of reported gait variables. Of most importance, perhaps, is that these positive effects are reported to be maintained up to one month after vibration training has been completed. This may suggest that relatively permanent alterations in neuronal activity can result from vibration therapy.

This last finding, while encouraging, is much like many of the findings that have been reported in this review. That is, there have been a limited number of investigations, with few utilizing similar protocols or outcome measures; therefore, drawing definitive conclusions about the effect of vibration on gait control remains elusive. In the final section, we offer several recommendations we believe would strengthen the scientific community's ability to determine the potential for muscle vibration to serve as a component of gait rehabilitation protocols.

Recommendations

Each of the papers reviewed tested hypotheses with methodologies and outcome measures that were appropriate to answer the investigators' questions. However, the wide range of methodologies and outcome measures used makes it difficult to accurately and consistently discern the impact of vibration on gait. Thus, while the literature suggests that the potential for vibration to positively impact gait is promising, it remains unclear regarding the optimal protocol and measures to be used. Standardizing the methods used in vibration studies examining gait control, especially in populations in which disordered gait is a feature of their clinical condition, would be a positive step toward reaching a consensus as to the effectiveness of vibration. Standardizing walking protocols and outcome measures across laboratories and clinics would enable the community to answer several foundational questions that would ultimately help to identify effective rehabilitation techniques and produce maximal positive outcomes for a variety of clinical populations.

To develop consensus concerning optimal rehabilitation protocols and gait measures that most accurately represent the positive outcomes of vibration therapy, we encourage our colleagues to write methodology papers that could be utilized by other investigative teams. Additionally, further understanding of the range of benefits of vibration therapy could be accelerated through a gathering of interested scientists and clinicians, perhaps at a satellite symposium or through a special issue of an appropriate journal.

Note

1. To assist in summarizing results across various studies, this review will label vibration applied to the anterior aspect of the thigh as Quadriceps (Q) vibration, vibration delivered to the posterior thigh as Hamstring (H), anterior shank as Tibialis Anterior (TA) and to the posterior shank as Triceps Surae (TS) vibration. If muscles other than those encompassed by the anatomical areas listed above were vibrated, those muscle will be identified individually. We believe this naming convention is appropriate given that the vibratory stimulus effects spread extend beyond individual muscles, there is no compelling evidence that vibration of an individual muscle in a given anatomical area produces differential effects than its neighbouring agonist, and this naming convention simplifies the description of the predominate effects of muscle vibration during walking.

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