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Review

Effects of Whole-Body Vibration on Flexibility and Stiffness: A Literature Review

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ABSTRACT

International Journal of Exercise Science 12(3): 735-747, 2019. The effects of whole-body vibration (WBV) on flexibility and muscle stiffness are focused areas of research. Many studies have been performed over a large range of vibratory conditions and have reported varied results on effectiveness. When reviewing the published literature, it is difficult to track the vibration parameters that have positive effects and which have negative or no effects. In writing this paper, over 80 articles were evaluated, 24 of which met the inclusion requirements. The data gathered in the articles were used to develop charts that illustrate the vibration conditions that elicit helpful, harmful, and no effects on flexibility and muscle stiffness. A combination of published data shows that acceleration is the best metric to predict the effectiveness of WBV for improving flexibility and muscle stiffness. This review shows that acceleration in the range of 5g to 10g was most effective in increasing flexibility. Published data on muscle and tendon stiffness are limited, but shows that although WBV is generally significantly less effective in increasing stiffness than increasing flexibility, accelerations below 6.4g were the most effective.

KEY WORDS: Vibration, muscle flexibility, stiffness

INTRODUCTION

As early as the 1890s, studies on the use of whole-body vibration (WBV) to improve various conditions of the human body have been performed (1). Because WBV can be applied using many different vibration parameters such as frequency, amplitude, duration, body position, and vibration type either vertical or oscillating, the studies which have been performed have reported a wide variety of results. Since the late 1990's, many studies have focused on improved muscle power and strength, for which WBV has been shown to be generally effective (24, 27). WBV effects on flexibility and muscle stiffness also have been investigated. Although there are significantly fewer studies compared to power and strength, there are sufficient to merit a review summarizing the findings and potentially guiding future research efforts.

This literature review summarizes the results of 24 studies on the effectiveness of WBV on flexibility and stiffness. In general, these studies indicate that vibration frequency and amplitude are the most commonly used parameters to describe an induced vibration. As a result, this literature review compares the frequencies and amplitudes of vibration that demonstrated effective and ineffective results associated with flexibility and stiffness. Strengths, weaknesses, and other general information about many of these studies are also presented. This review paper identifies; (1) conditions of effective WBV on flexibility and muscle stiffness, (2) areas of study where data are limited and where future studies are needed, and (3) the existence of conflicting data.

METHODS

Systematic Review: A review of the existing literature was performed to identify studies that used WBV with different frequencies and amplitudes to affect flexibility and muscle stiffness. The review was conducted between June and December, 2018 using the PubMed database. Terms that were used to search the database were "whole-body vibration," "muscle flexibility," "muscle stiffness," "tendon stiffness," or a combination of these terms.

Inclusion and Exclusion Criteria: Inclusion criteria for the systematic review were: 1) a human study was performed; 2) both frequency and amplitude were reported in the article as WBV parameters; 3) the experimental group received WBV and was compared with a control group; 4) training protocol utilized was consistent throughout the time of each intervention.

Exclusion criteria for the systematic review were: 1) the inclusion criteria were not met; 2) the conclusions made in the articles were uncertain; 3) the study measured muscle or tendon stiffness using the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) scale. Articles that used the WOMAC scale were excluded due to the fact that the assessment is made through a series of questions directed toward patients with osteoarthritis. While there are many studies that have been conducted on local vibration, which is applied to certain parts of the body, this literature review focuses only on WBV, and local vibration articles were excluded from the review.

Selection of Studies: The search terms outlined above were used to find 87 articles. The inclusion/exclusion criteria were then applied and 63 articles were excluded, which resulted in 24 studies that were included in the literature review.

Data Extraction: Participant characteristics (age, gender, height, and weight), WBV parameters (frequency and amplitude), program length, testing methods, and outcomes were extracted from each article. To best compare the articles to each other, the outcome extracted was generally a percentage of improvement. For example, if the test group was reported to have an increase in flexibility of 2%, that number was used as the outcome. Due to the fact that three articles did not list a percentage and only categorized the outcome as "increased," the outcome extracted from those articles was listed as it was described.

Due to the fact that many articles used different methods to obtain results, it is therefore necessary to compare the methods and define the terms used in each study.

A wide variety of tests were used to measure flexibility. In one study, improvement in flexibility was measured using a trunk flexion test (23). Another study used a stand and reach test and also found an increase in flexibility (22). In the stand and reach test, subjects hold one hand over the other one and flex their trunk slowly. Measurements are taken based on the maximum distance held for two seconds. An anterior Y balance test, (YBT) was used in another study to measure balance, where an increase in anterior YBT reach distances due to an improvement in flexibility was reported (3). Two articles used a passive knee extension test, which determined the flexibility of the hamstring muscle by measuring its degrees of motion (15, 31). All other results were measured using the sit and reach test, which was the most common way to measure flexibility in the articles that were reviewed. In this test, the subject generally sits on the floor with the hips and back against the wall, then reaches forward as far as possible (30). A device or measuring stick is placed at the feet of the subject to measure how far they are able to reach.

Muscle stiffness is defined as the ratio between changes in force and muscle deformation (25). As a muscle increases in stiffness, it requires more force to deform than it did before, which in turn affects muscle performance. Like flexibility, muscle stiffness was also measured using a variety of different methods. The major differences were where and how the stiffness was measured. Two of the studies measured stiffness in the patellar tendon (25, 26), one measured stiffness in the Achilles tendon (19), two studies measured stiffness in the lower limbs (6, 28), one study measured stiffness in the quadriceps and hamstring muscles (29), and one study calculated the stiffness in the plantar flexor muscle (8). One of the methods used to calculate stiffness was to use ultrasound to measure the elongation of the tendon due to an applied force, and calculating the stiffness from the ratio between tendon deformation and changes in force (19, 25, 26). Another method used the force developed and the length of time it was applied during a hopping test, using the mass, contact time, and time the limbs were in the air into one equation (6). Another study used ultrasound to measure the Young's modulus of elasticity as a stiffness index (29), and one study calculated the stiffness from the damped oscillation of the lower limbs (8).

RESULTS

Effects of Whole-Body Vibration on Flexibility: All but one of the reviewed articles (30), showed an increase in flexibility due to WBV. One commonality between the articles is that most studies used frequencies between 15 and 40 Hz, and amplitudes between 2- and 6-8-mm peak-to-peak. Peak-to-peak values are shown for all amplitudes in this paper.

Figure 1 summarizes the data from 24 trials. The vertical axis represents the peak-to-peak amplitude of vibration and the horizontal axis identifies the excitation frequency. The number inside the box indicates the acceleration in g. The values of acceleration for the plotted data range from 0.9g to 50g. The solid colored boxes imply that all studies conducted at those settings produced the same results. For example, the solid green box at 35 Hz and 2mm means that all trials indicated an improvement of 16% or greater. The mixed colored boxes show that multiple studies showed varying results. For example, the yellow to light green box at 30 Hz and 4 mm means that studies showed a range from 1% to 15% improvement. Due to the fact that three articles only reported an increase in flexibility without a percentage, those boxes were categorized as having 1-5% improvement.

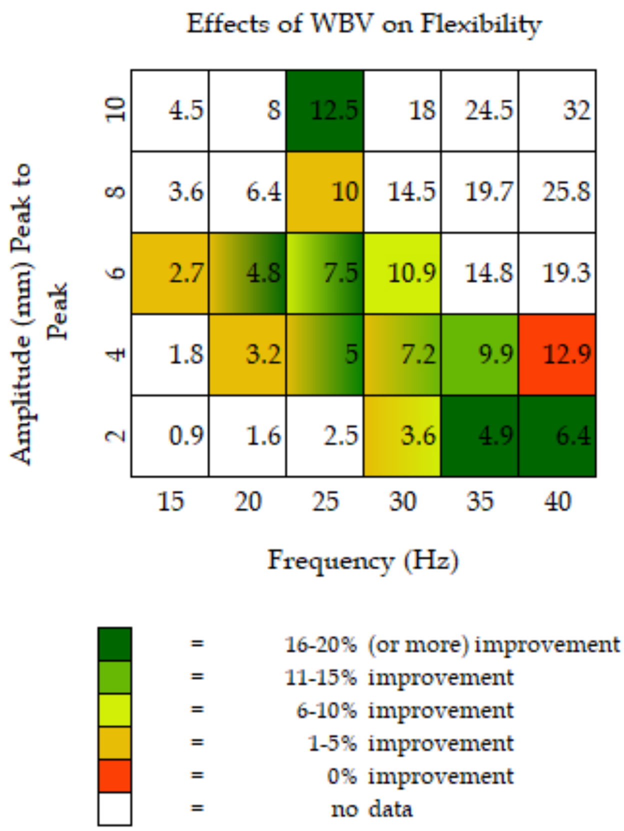

Figure 1. Chart of effects of 25 separate trials of WBV on flexibility. The number inside each box represents the acceleration experienced as a multiple of gravity.

It is important to note that the 58% improvement using the frequency of 30 Hz, amplitude of 4 mm, resulting in a 7.2g acceleration was measured in fibromyalgia patients whose training also included physical exercise with WBV (13). The 70.4% improvement using a frequency between 35-40 Hz, with amplitude of 2 mm, for a 4.9g-6.4g acceleration was measured in elderly patients (1).

Several articles that used the same parameters had similar results. This is best demonstrated by the fact that four different studies found that the parameters of 30 Hz, 2 mm, 7.2g were effective, increasing flexibility by 2.81% (9), 3.64% (12), 3.86% (11), and 6.35% (10). Table 1 provides more detail about each trial and the associated findings that were used to populate the graph in Figure 1.

Table 1. A comparison of vibration parameters and flexibility test results.

Study	Group size (n) (Sex: M/F)	Participant Characteristics: Age (yr)	Height (cm)	Mass (kg)	Training Program Parameters and Results: Frequency (Hz)	Amplitude (mm)	Program Length (weeks)	Test	Results	Notes
Karatrantou et al. (21)	26 (0/26)	20.4 ± 0.4	167.2 ± 2.3	59.9 ± 3.5	25	6	3	Sit and reach	13% increase	Side-to-side, alternating WBV
de Hoyo et al. (13)	46 (0/46)	58.23 ± 8.5	156.9 ± 6.1	72.05 ± 9.6	30	4	8	Sit and reach	58% increase	Subjects had fibromyalgia
Tseng et al. (30)	30 (13/17)	69.6 ± 3.9	160.9 ± 7.9	60.8 ± 9.8	20	4	24	Sit and reach	Increase	-
(same study)	30 (13/17)	69.6 ± 3.9	160.9 ± 7.9	60.8 ± 9.8	40	4	24	Sit and reach	No increase	-
Dallas & Kirialanis (9)	12 (12/0)	21.9 ± 1.1	170.5 ± 6.8	65.76 ± 7.3	30	2	After 1 min.	Sit and reach	2.81% increase	Gymnasts, 4.5% after 15 min.
Despina et al. (12)	11 (11/0)	17.54 ± 0.52	170.54 ± 3.48	51.27 ± 2.24	30	2	After 15 min.	Sit and reach	3.64% increase	Olympic gymnasts
Dallas et al. (10)	34 (15/19)	9.22 ± 1.34	132.9 ± 5.33	30.25 ± 4.35	30	2	After 15 min.	Sit and reach	6.35% increase	Gymnasts
Kurt (22)	24 (24/0)	21.8 ± 5.9	166 ± 6.0	63.7 ± 7.6	30	4	After 5 min.	Stand and reach	Increase	-
Kurt & Pekünlü (23)	20 (8/12)	22.8 ± 3.1	168.8 ± 8.8	65.4 ± 10.7	26	4	1	Trunk flexion	5.30% increase	-
Cochrane & Stannard (4)	18 (0/18)	21.8 ± 5.9	166 ± 6.0	63.7 ± 7.6	26	6	After 5 min.	Sit and reach	8.20% increase	Elite hockey players

Gerodimos et al. (18)	18 (0/18)	20.2 ± 2.0	166 ± 5.0	59.7 ± 7.4	15	6	After 15 min.	Sit and reach	3.0% increase	Recreationally active
(same study)	18 (0/18)	20.2 ± 2.0	166 ± 5.0	59.7 ± 7.4	20	6	After 15 min.	Sit and reach	4.80% increase	Recreationally active
(same study)	18 (0/18)	20.2 ± 2.0	166 ± 5.0	59.7 ± 7.4	30	6	After 15 min.	Sit and reach	5.30% increase	Recreationally active
(same study)	18 (0/18)	20.2 ± 2.0	166 ± 5.0	59.7 ± 7.4	25	4	After 15 min.	Sit and reach	6.0% increase	Recreationally active
(same study)	18 (0/18)	20.2 ± 2.0	166 ± 5.0	59.7 ± 7.4	25	6	After 15 min.	Sit and reach	6.0% increase	Recreationally active
(same study)	18 (0/18)	20.2 ± 2.0	166 ± 5.0	59.7 ± 7.4	25	8	After 15 min.	Sit and reach	5.0% increase	Recreationally active
Cloak, Nevill, & Wyon (3)	44 (44/0)	22.1 ± 2.1	175.3 ± 6.9	77.1 ± 8.2	40	4	After 4 min.	Anterior YBT reach	Increase	Soccer players
Colson et al. (7)	14 (14/0)	23.1 ± 0.9	178.0 ± 1.7	72.1 ± 2.0	30	4	After 5 min.	Sit and reach	13.56% increase	-
Bissonnette et al. (1)	19 (5/14)	71.4 ± 7.2	Not listed	Not listed	35 to 40	2	8	Sit and reach	70.40% increase	-
Fagnani et al. (14)	13 (0/13)	24 ± 1.82	168.3 ± 5.1	59.8 ± 3.4	35	4	8	Sit and reach	13.00% increase	Athletes
Felund et al. (15)	34 (22/12)	23.4 ± 1.7	175.6 ± 6.4	74.9 ± 11.8	26	4	4	Passive knee extension	22.00% increase	-
van den Tillaar (31)	19 (7/12)	21.5 ± 2.0	Not listed	Not listed	28	10	4	Passive knee extension	30.00% increase	-
Dallas et al. (11)	18 (10/8)	17.9 ± 2.4	163.8 ± 9.1	52.8 ± 10.4	30	2	After 15 min.	Sit and reach	3.86% increase	Divers

(same study)	18 (10/8)	17.9 ± 2.4	163.8 ± 9.1	52.8 ± 10.4	50	4	After 15 min.	Sit and reach	3.77% increase	Divers
Gerodimos et al. (17)	24 (0/24)	43.2 ± 3.0	164.0 ± 5.0	68.3 ± 7.6	20 to 25	6	8	Sit and reach	30.00% increase	Side-to-side, alternating WBV

Effects of Whole-Body Vibration on Stiffness: Research into the effects of WBV on muscle stiffness is a relatively new area of study. The earliest article found was published in 2004, which was followed much later by an article in 2010. With a thorough literature search, seven articles focusing on the effects of WBV on muscle and tendon stiffness were found.

Figure 2 shows a plot of the frequencies and displacement amplitudes where WBV was shown to increase or have no effect on muscle stiffness. The acceleration in g, caused by the frequency and displacement amplitude, is again shown inside each box. There were only three articles that showed an increase in stiffness over the frequency range of 25-50 Hz. There are conflicting findings from no improvement to 16% or more improvement at the frequency of 30 Hz and displacement of 2 mm. From the available data, the lower frequency and displacement vibration settings giving accelerations of 7.5g or less showed an improvement in stiffness with substantial improvement being obtained at accelerations of 6.4g or less. This is significantly different than what was found for the effective acceleration levels for improving flexibility. Figure 2 also indicates several WBV parameter settings which remain to be tested. Table 2 provides more detail about each trial and the associated findings that were used to populate the graph in Figure 2.

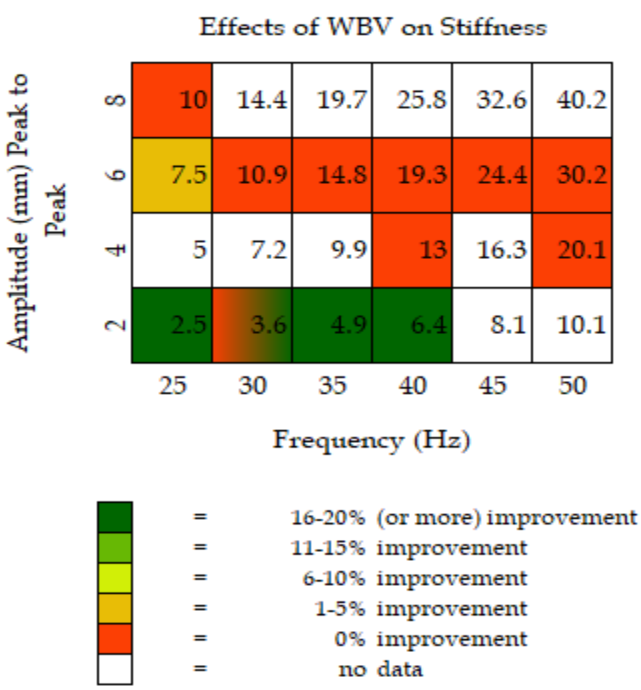

Figure 2. Chart of effects of 9 separate trials of WBV on stiffness. The number inside each box represents the acceleration experienced as a multiple of gravity.

Table 2. A comparison of vibration parameters and stiffness test results.

Study	Group size (n) (Sex; M/F)	Participant Characteristics: Age (yr)	Height (cm)	Mass (kg)	Training Program Parameters and Results: Frequency (Hz)	Amplitude (mm)	Program Length (weeks)	Test	Results	Notes
Rieder et al. (25)	28 (28/8)	31.0 ± 5.0	173.0 ± 9.0	69.0 ± 13.0	30	2	1 day	Force to deformation ratio	No effect	Patellar tendon
Han et al. (19)	40 (0/40)	58.23 ± 8.5	156.9 ± 6.1	72.05 ± 9.6	25 to 40	1.1 to 2.5	8	Force to deformation ratio	20% increase	Achilles tendon
Colson & Petit (6)	148 (86/62)	21.8 ± 5.9	166 ± 6.0	63.7 ± 7.6	50	4	30 min.	Hopping test	No effect	Lower limb stiffness
(same study)	148 (86/62)	21.8 ± 5.9	166 ± 6.0	63.7 ± 7.6	30	2	30 min.	Hopping test	No effect	Lower limb stiffness
Roschel et al. (28)	16 (12/0)	35.0 ± 8.0	172.6 ± 5.6	71.3 ± 9.1	30 to 50	6	6	Force to deformation ratio	No effect	Lower limb stiffness
Siu et al. (29)	10 (10/0)	21.9 ± 2.5	174.0 ± 5.3	64.0 ± 7.1	26	8	5 min.	Young's Modulus	No effect	Quadriceps and hamstring
(same study)	10 (10/0)	21.9 ± 2.5	174.0 ± 5.3	64.0 ± 7.1	40	3.4	5 min.	Young's Modulus	No effect	Quadriceps and hamstring
Cronin et al. (8)	11 (7/4)	24.6 ± 3.6	176.0 ± 9.9	69.3 ± 13	26	6	10 min.	Response of lower limb	1% increase	Plantar flexor muscle
Rieder et al. (26)	55 (17/38)	32.3 ± 9.2	172.0 ± 9.0	71.5 ± 12.3	30	2	8	Force to deformation ratio	8.1% increase	Patellar tendon

DISCUSSION

In this paper, studies were included that focused on several different groups—including gymnasts, physically active adults, seniors, both amateur and elite soccer players, field hockey players, and others. The results, as shown in Figure 1, are that all groups can use WBV to improve their flexibility. The data show a trend of darker green indicating a 16% or greater increase in flexibility on a downward diagonal from 20 Hz (6 mm) to 40 Hz (2 mm). The platform acceleration in this diagonal ranges from 4.8g (5g) to 9.9g (10g). Platform accelerations greater than 10g and less than 5g are shown to provide only a modest improvement. It was further noted that WBV did not cause a decrease in flexibility in any of the studies.

The only study where WBV was shown to be completely ineffective in improving flexibility was with 30 elderly subjects (30). In this study, two vibration groups and one control group were compared against each other. The first vibration group was subjected to WBV at a frequency of 20 Hz with an amplitude of 4 mm for an acceleration of 3.2g and the results proved to be effective in eliciting an increase in sit-and-reach flexibility. However, at a platform frequency, amplitude, and acceleration of 40 Hz, 4 mm, and 12.9g, there was no improvement compared with the control group. The author of this particular study surmises that the higher frequency vibration could have affected muscle strength and caused muscle adjustment changes.

One article reported that trunk flexion in male and female athletes improved by 5.3% when subjected to a vibration at a frequency of 26 Hz with an amplitude of 4 mm for a 5.4g acceleration. However, the article also reported that there was no statistical difference. Although it is still an increase in flexibility, the lack of statistical significance could be a result of the high variability in participant flexibility (23). As pointed out by the authors of this article, a possible reason WBV may not have been very effective in this study is that the participants' highly trained muscles may already have been close to their genetic potentials (23).

The use of WBV training to increase flexibility is effective due to circulatory, thermoregulatory, and neural factors (16, 20). One of the effects vibration has on the body is that it increases blood circulation and generates more heat, which in turn helps facilitate flexibility (20). Vibration also causes muscle to contract and relax, which raises the pain threshold one experiences when stretching. This increase in pain threshold allows one to stretch further by experiencing less pain.

It is shown in this paper that an increase in flexibility does not necessarily change a person's stiffness. The primary reason for this might be that the improvement of flexibility through vibration is due to the increase in stretch tolerance and not due to stiffness properties changing in the muscle tissue (2). This is supported by the fact that in the majority of the reviewed studies, WBV has little to no effect on muscle and tendon stiffness. Additionally, its effects do not compare well with resistance training, which does affect the muscle tissue directly and can increase the stiffness by 15-84% (20, 26).

Most of the studies that have been conducted on the effects of WBV on muscle stiffness have used frequencies ranging from 25-50 Hz and amplitudes of 2 mm and 6 mm. There have been studies that have been conducted that use different parameters, but they were performed on people with osteoarthritis.

In general, it is shown in Figure 2 that WBV is significantly less effective at increasing muscle and tendon stiffness than it was for improving flexibility. Only three of the seven studies showed that WBV was effective in increasing stiffness (8, 19, 26), and two of these studies stated that their results were not statistically significant (8, 26). In the study conducted by Han et al., forty elderly women underwent an 8-week WBV therapy program designed to examine whether muscle force and tendon stiffness changed synchronously as a result of WBV treatment (19). The vibratory parameters for this study were (25 – 40) Hz and (1.1-2.5) mm. The results of the treatment showed that tendon stiffness and muscle force changed asynchronously. It was shown that tendon stiffness increased by 20%, meaning that the Achilles tendon was more efficient in converting muscle energy into mechanical work (19). The authors report that younger populations experience distinctly different responses to WBV. The other articles both stated that while WBV increased stiffness, there was no statistical difference between the vibration and test groups (8, 26). It was speculated that the reason for this was the methodological limitations of testing human tendons *in vivo* (26).

The four remaining articles on stiffness document studies with WBV protocols which were unable to elicit any response in muscle or tendon stiffness. Colson and Petit (6) begin by noting the lack of research on the effect of WBV on muscle and tendon stiffness. In order to better understand its effects, they conducted a study where a group of 223 participants was assembled randomly into three groups—high frequency/high amplitude (HH), low frequency/low amplitude (LL), and SHAM (followed the same training protocol as for the other groups, but the platform did not vibrate). The HH group's vibration parameters were 50 Hz (4 mm) and the LL group's parameters were 30 Hz (2 mm). Each group performed the same resistance training protocol with their vibration parameters (6).

This study concluded that there were no observable differences in muscle or tendon stiffness response to the WBV training protocol. It is difficult to determine the exact cause of these results; finding proper vibratory parameters is the key to understanding and controlling the biological effects of WBV. One possible reason for the lack of response in this study could be that all participants wore socks and stood on a closed-cell rubber mat in order to avoid bruising. This could have allowed for damping which likely would have inhibited the vibration amplitude, thereby decreasing the biological response (6).

Note that the 20% improvement using the vibration parameters 25-40 Hz and 2 mm all came from one study. Similarly, the data from 30-50 Hz and 6 mm were also from one study. The vibration parameters of 30 Hz and 2 mm were shown to be ineffective in two separate studies, but yielded an 8.1% increase in stiffness in another study. See Table 2 for more details.

In another study, WBV was used in an attempt to improve vertical stiffness in runners. Two groups were assembled—one received resistance training and the other received the same training supplemented with WBV using the vibration parameters of 30-50 Hz and 6 mm (28). The data showed that neither group experienced any improvement in vertical stiffness. The author reports that these results could be due to an insufficient training regimen. The expectation is that WBV training alone has the potential to elicit beneficial biological responses.

Therefore, the vibration parameters of WBV in this study could have been insufficient to cause the desired changes (28).

Siu et al. analyzed the effects of two different parameters settings (26 Hz, 8 mm and 40 Hz 3.4 mm), which both yield an acceleration of 10.9g (29). The study was performed on 10 recreationally active males, and measured the modulus of rigidity using an ultrasound machine in the affected muscle to characterize deformability and estimate stiffness. The authors found that there was no statistically significant difference in muscle stiffness in either group after WBV, concluding that vibration most likely does not affect muscle tissue stiffness properties. One possible reason why there is less improvement in stiffness is that stiffness has a larger variance in general and so slight improvement is more difficult to determine.

While there is a wealth of research in the area of WBV therapy, it can be difficult to determine the parameters that have shown to improve or not improve certain body conditions. The focus of this paper was to assemble the findings that have been published on how WBV has been shown to effect flexibility and stiffness. In conclusion, the analysis of other studies shows that effective frequencies and amplitudes to increase flexibility through WBV include a range that will provide a platform acceleration of 5g to 10g. Since frequencies above 40 Hz have not been sufficiently studied in relation to WBV and flexibility, more research in that area is suggested. Another conclusion that the analysis draws is that stiffness is generally not affected by WBV; while three studies showed minimal increase in stiffness, the others showed no increase. However, platform accelerations of less than 6.4g might provide the best results. This review has also brought to light the need for more research on the effects WBV has on stiffness.

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