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original research

Elbow Joint Position Sense After Neuromuscular Training With Handheld Vibration

Brady L. Tripp, PhD, LAT, ATC*; Donald Faust, MS, LAT, ATC†; Patrick Jacobs, PhD‡

*University of Florida, Gainesville, FL; †Broward Health, Fort Lauderdale, FL; ‡Florida Atlantic University, Davie, FL

Context: Clinicians use neuromuscular control exercises to enhance joint position sense (JPS); however, because standardizing such exercises is difficult, validations of their use are limited.

Objective: To evaluate the acute effects of a neuromuscular training exercise with a handheld vibrating dumbbell on elbow JPS acuity.

Design: Crossover study.

Setting: University athletic training research laboratory.

Patients or Other Participants: Thirty-one healthy, college-aged volunteers (16 men, 15 women, age = 23 ± 3 years, height = 173 ± 8 cm, mass = 76 ± 14 kg).

Intervention(s): We measured and trained elbow JPS using an electromagnetic tracking device that provided auditory and visual biofeedback. For JPS testing, participants held a dumbbell and actively identified the target elbow flexion angle (90°) using the software-generated biofeedback, followed by 3 repositioning trials without feedback. Each neuromuscular training protocol included 3 exercises during which participants held a 2.55-kg dumbbell vibrating at 15, 5, or 0 Hz and used software-generated biofeedback to locate and maintain the target elbow flexion angle for 15 seconds.

Main Outcome Measure(s): We calculated absolute (accuracy) and variable (variability) errors using the differences between target and reproduced angles.

Results: Training protocols using 15-Hz vibration enhanced accuracy and decreased variability of elbow JPS ($P \leq .005$), whereas 5-Hz vibration did not affect accuracy ($F_{1,61} = 2.625$, $P = .100$) but did decrease variability ($F_{1,61} = 7.250$, $P = .009$). The control condition and 0-Hz training protocol had no effect on accuracy or variability ($P \geq .200$).

Conclusions: Our results suggest these neuromuscular control exercises, which included low-magnitude, low-frequency handheld vibration, may enhance elbow JPS. Future researchers should examine vibration of various durations and frequencies, should include injured participants and functional multijoint and multiplanar measures, and should examine long-term effects of training protocols on JPS and injury.

Key Words: sensorimotor system, proprioception, neuromuscular control, rehabilitation, conditioning

Key Points

- Neuromuscular training that included handheld vibration of 15 or 5 Hz acutely enhanced participants' acuity of active elbow joint position sense.
- Neuromuscular training that employed both auditory and visual biofeedback without vibration (0 Hz) had no effect on either measure of elbow joint position sense acuity.
- Clinicians should be cautious when incorporating handheld vibration into programs designed to facilitate neuromuscular control because the balance between the positive and negative effects of vibration is not understood.

Precise neuromuscular control and joint stability are critical to performance and injury-free activity, particularly in the upper extremity, which has an inherent lack of bony stability.[1,2] The *sensorimotor system* (SMS) is the collective term used to describe the physiologic integration of the neurosensory and neuromuscular processes responsible for providing the body with such coordination and dynamic stability.[3] The SMS encompasses the processing and integration of both afferent and efferent signals by the central nervous system at the spinal level through a reflex activation or at higher levels after transmission to the brain stem and cerebral cortex.[4,5] The constant and dynamic integration and comparison between afferent and efferent data provide neuromuscular control and facilitate dynamic joint stability through both feed-forward and feedback mechanisms.[3,6,7] However, these vital SMS functions are greatly hindered by both fatigue[1,8–10] and injury.[2,11] Such compromised neuromuscular control diminishes functional stability and may cascade into a cycle that includes further structural damage, fatigue, and dysfunction. This cycle of events is illustrated by the paradigm of pathophysiology that clinicians and researchers use to identify prospective interventions, such as surgery, rehabilitation, and prevention (Figure 1). In 2 studies, researchers[12,13] have examined the effects of shoulder surgery on the SMS. However, because of the limitations in the design and methods employed in each study, the precise effects of surgery on upper extremity SMS function are unclear. Although surgery may restore structural stability when appropriate, clinicians are often charged with addressing functional stability and neuromuscular control.

Exercises prescribed during nonoperative or postoperative rehabilitation and injury prevention programs with the goal of enhancing neuromuscular control include plyometrics, manual rhythmic stabilization, and oscillations

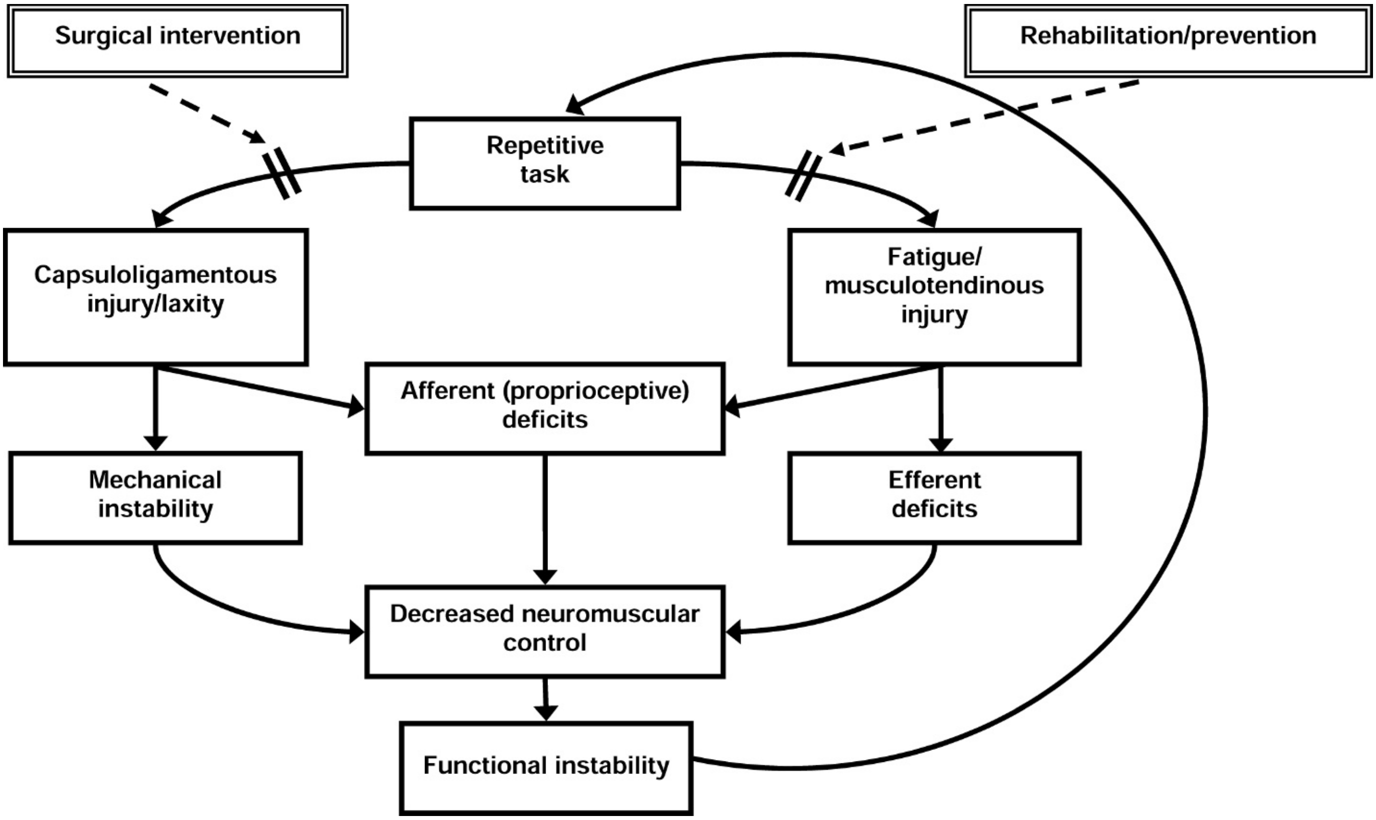

Figure 1. The paradigm of pathophysiology identifying possible mechanisms to prevent or interrupt the cycle.

using oscillatory devices.[14,15] These exercises tax multiple components of the SMS, requiring both conscious and reflexive reactions to short bursts of resistance to restore or maintain joint position and stability. However, little empirical evidence describing the effects of such exercises on upper extremity SMS function exists. Swanik et al[14] suggested that 6 weeks of upper extremity plyometric training may enhance specific aspects of SMS function, but Padua et al[16] indicated that a similar exercise program provided no benefit. To optimally prevent upper extremity injuries and treat and rehabilitate injured patients, we must evaluate the capacity of such interventions to restore or enhance SMS function.

When seeking to validate therapeutic interventions for low back pain, Fontana et al[17] reported that adding whole-body vibration to a simple weight-bearing exercise enhances lumbosacral position sense after a single 5-minute session. Researchers[17,18] have postulated that vibration provides the SMS with additional afferent input that may facilitate position sense. Melnyk et al[19] measured the response to anterior tibial translation before and after two 60-second bouts of whole-body vibration. Their results indicated that whole-body vibration increases stiffness and subsequent functional stability of the knee.[19] Although these investigators have suggested that vibration may enhance SMS function in the lower extremity, most research employing whole-body vibration has been focused on its growing use in strength training and conditioning programs.[20–26] Our understanding of the effects vibration has on upper extremity SMS function are limited to reports employing direct muscle or tendon vibration[8,27] or high-frequency vibration,[28] which have shown no effect[28] or deleterious effects[8,27] on SMS function. Any possible SMS benefits of incorporating vibration similar to that used in the lower extremity[17,19] into upper extremity therapeutic exercises remains unknown.

The exercises clinicians traditionally have used to restore or enhance SMS function are difficult to standardize appropriately for research, leaving little empirical evidence validating their efficacy. Specifically, the inability to control the magnitude and frequency of resistance applied through manual stabilization or an oscillatory device has limited such scientific investigations. However, the recent popularity of whole-body vibration platforms in strength training and conditioning programs[28] has fostered the development of handheld vibrating dumbbells. These handheld vibration (HV) devices enable standardization and precise control of the magnitude and frequency of the resistance and facilitate investigation into the effect of such exercises on upper extremity SMS function. Therefore, our purpose was to examine the acute effects of neuromuscular training with HV on upper extremity SMS function assessed with active joint position sense (JPS) measure of elbow flexion-extension. We hypothesized that neuromuscular training exercises including vibration of 15, 5, and 0 Hz would enhance elbow JPS.

METHODS

Study Design

To assess the effects of neuromuscular training using HV on elbow JPS, we used a 4 (condition) × 2 (time) crossover,

Table 1. Order of Procedures for Testing Elbow Joint Position Sense (Pretest, Posttest) and Control and Experimental Conditions[a]

Arm 1	Arm 2	Time, min
Biofeedback familiarization		2–3
Pretest		1
Control condition		5[b]
Posttest		1
	Pretest	1
	Control condition	5[b]
	Posttest	1
Pretest		1
Experimental condition 1		5[c]
Posttest		1
	Pretest	1
	Experimental condition 1	5[c]
	Posttest	1
Break		45
Biofeedback familiarization		2–3
Pretest		1
Experimental condition 2		5[c]
Posttest		1
	Pretest	1
	Experimental condition 2	5[c]
	Posttest	1
Pretest		1
Experimental condition 3		5[c]
Posttest		1
	Pretest	1
	Experimental condition 3	5[c]
	Posttest	1

[a] The order of arm (left or right) and experimental conditions was randomized and counterbalanced.

[b] Participants rested.

[c] The time included the time during which participants used biofeedback to find the desired elbow position, as well as the three 15-second bouts of neuromuscular training with vibration at 1 of 3 frequencies (15, 5, or 0 Hz) and the three 1-minute relaxation periods.

counterbalanced, repeated-measures design for each elbow. Dependent measures were accuracy and variability of elbow JPS. We tested both arms of each participant separately and randomly assigned the order of arm testing (left or right). To assess any learning effect, the first condition for each arm served as a control. We counterbalanced the 3 experimental conditions using a Latin square 3 × 3 matrix.

Participants

Thirty-one healthy, recreationally active, college-aged individuals (16 men, 15 women; age = 23 ± 3 years, height = 173 ± 8 cm, mass 76 ± 14 kg; 29 right-hand dominant, 2 left-hand dominant) volunteered to participate in the study. We defined *recreationally active* as engaging in aerobic or anaerobic exercise (or both) for a minimum of 30 minutes, 3 times per week. Exclusion criteria included history of upper extremity injury within the year before the study, major upper extremity surgery, or central nervous system disorder. We instructed participants to abstain from strenuous upper extremity activity during the 24 hours before testing to reduce the likelihood of muscle fatigue or soreness. All participants read and signed an informed consent form, and the university's institutional review board approved the study.

Instrumentation

We recorded bilateral humeral and forearm position using 4 wired sensors from the Flock-of-Birds electromagnetic tracking device (Ascension Technology Corp, Burlington, VT), which has an accuracy of 0.5° at 0.91 m.[29] We attached the sensors bilaterally to each participant's radius (distal dorsal aspect) and lateral humerus with elastic straps and a mild spray adhesive. We palpated, marked, and digitized bony landmarks on each arm, including medial and lateral humeral epicondyles and radial and ulnar styloid processes. We digitized participants according to the International Society of Biomechanics' standardized protocol to create local and anatomic coordinate systems.[30] These procedures have yielded reliable measures of elbow position.[29] Motion Monitor software (Innovative Sports Training Inc, Chicago, IL) calculated and recorded elbow flexion angle and provided real-time biofeedback.

Procedures

An overview of the order of data collection procedures is illustrated in Table 1. Each arm of each participant experienced 4 conditions (1 control, 3 experimental) and had pretest and posttest JPS measures with each condition. The first condition was used as a control, during which participants rested for 5 minutes between pretest and posttest JPS measures.

The intervention for each experimental condition included short bouts of neuromuscular training employing HV. The frequency of vibration used constituted the 3 experimental conditions (15, 5, and 0 Hz). The 0-Hz condition served to isolate the effects that the neuromuscular training (biofeedback) imposed from those that the vibration imposed.

JPS Testing. During elbow JPS testing, participants stood and rested the test elbow on a padded armrest, the height of which we adjusted to maintain a humerothoracic angle of 60° ± 5°. To retain consistency with our neuromuscular training protocol, participants held a dumbbell during JPS testing. Because the metal vibrating dumbbell used during neuromuscular training exercises would distort the electromagnetic field, participants held a sand-filled polyvinyl chloride dumbbell of identical physical dimensions and mass.

To identify the elbow flexion angle that participants would be instructed to reproduce (90°), an investigator (D.F.) first familiarized each participant with the software's real-time visual and auditory biofeedback for 2 to 3 minutes. A monitor facing participants presented 2 oscilloscopes indicating angular orientation of the test elbow in relation to the desired angle. The Motion Monitor software also generated a pitch-scaled tone during familiarization and training when the elbow deviated more than 1° from the target angle. We chose a test angle in midrange of elbow flexion-extension to amplify the contribution of afferent information via muscular receptors relative to capsuloligamentous sources.[31]

Participants began JPS testing by using the visual and auditory biofeedback to identify and maintain the target angle of 90° for 5 seconds, while investigators instructed participants to "remember the position of your elbow." Participants then briefly relaxed the arm, resting the

Figure 2. A blindfolded participant holds a dumbbell and attempts to reproduce the elbow flexion angle during joint position sense testing.

dumbbell on the table. Before participants attempted 3 angle-reproduction trials, the investigator blindfolded them, muted the auditory biofeedback, and instructed them to reproduce the elbow position. During each trial, participants pressed a trigger held in the contralateral hand to indicate when they believed they had reproduced the target angle (Figure 2). Participants then returned the arm to the resting position for 3 seconds before beginning the next angle-reproduction trial.

Neuromuscular Training. Each participant removed his or her blindfold and remained standing, facing the biofeedback monitor for neuromuscular training. Because providing biofeedback may enhance JPS,[32] participants used both real-time auditory and visual biofeedback during neuromuscular training. For standardization of the applied resistance, participants held a 2.55-kg dumbbell capable of vibrating at 5 to 30 Hz with 2-mm amplitude (Mini-VibraFlex; Orthometrix Inc, Naples, FL). Each experimental condition included three 15-second bouts of neuromuscular training employing vibration at 1 of 3 frequencies: 15, 5, or 0 Hz. To enable participants to maintain the humerothoracic angle of 60° ± 5° during neuromuscular training, we lowered the padded armrest by 1.9 cm and instructed participants to refrain from resting the elbow on the padded bar during the training. This eliminated dampening of vibrations by the armrest that would have reduced the work imparted to the elbow. To further encourage transmission of vibration to the extremity, the investigator instructed participants to maintain a ‘‘very firm’’ grip on the dumbbell.

Participants began each bout of neuromuscular training by using the biofeedback to find the desired elbow position of 90° of flexion. The investigator initiated the dumbbell vibration at the predetermined frequency while participants used the biofeedback to help actively maintain the position of their elbows for 15 seconds, after which the vibration ceased. After each bout, participants lowered their arms to the armrest and relaxed for 1 minute. Participants completed 2 more bouts of neuromuscular training under the same conditions before the JPS posttesting measure.

Data Reduction

We used a fourth-order, zero–phase-shift Butterworth filter with a cutoff frequency of 20 Hz to smooth the data before exporting it into Excel software (Office 2000; Microsoft Corp, Redmond, WA) to calculate error scores. We included separate measures for each arm of each participant in all analyses. We calculated absolute and variable errors using the differences between the target and repositioned angles for each trial. *Absolute error* describes the magnitude of repositioned error and represents JPS accuracy.[33] We calculated absolute error using the following equation:

$$\text{Absolute error} = \sum \left| X_{\text{trial}_i} - X_{\text{target}} \right| \Big/ n,$$

where X_{trial_i} and X_{target} are the angle of trial i and the target angle, respectively, and n is the number of trials (3). *Variable error* represents participants' variability or consistency among repositioning trials.[33] We calculated variable error using the following equation:

$$\text{Variable error} = \sqrt{\sum \left(X_{\text{trial}_i} - X_{\text{mean}} \right)^2 \Big/ n},$$

where X_{trial_i} and X_{mean} are the angle of trial i and mean of the trials, respectively, and n is the number of trials (3). Researchers have suggested that these 2 measures constitute a thorough investigation of JPS acuity.[33]

Statistical Analysis

We performed statistical analyses using SPSS (version 14.0 for Windows; SPSS Inc, Chicago, IL) with the α level set a priori at .05. For each dependent variable (accuracy, variability) and each condition (control, 15 Hz, 5 Hz, 0 Hz), we used separate, repeated-measures analyses of variance to compare pretest and posttest values. To evaluate any learning effect involved in our measure of SMS function, we compared JPS acuity before and after 5 minutes of rest (control condition). When appropriate, we calculated effect sizes using the standard mean difference equation to determine the clinical meaningfulness of changes.[34]

RESULTS

Our participants displayed elbow JPS accuracy ranging from 5.5° to 7.0° and variability ranging from 2.8° to 3.1° for pretest scores. We found no differences between control condition accuracy pretest (5.5° ± 2.8°) and posttest (5.1° ± 3.0°) scores ($F_{1,61} = 1.724$, $P = .200$) or between control variability pretest (3.1° ± 1.3°) and posttest (3.0° ± 1.4°) scores ($F_{1,61} = 1.689$, $P = .200$). Tables 2 and 3 present the effects of the 3 different frequencies of HV used in

Table 2. Effects of the Frequency of Dumbbell Vibration Used During Neuromuscular Training Exercises on Absolute Error (ie, Accuracy) of Active Reproduction of Elbow Flexion Angle (Mean ± SD)

Vibration, Hz	Pretest, °	Posttest, °	$F_{1,61}$	*P* Value[a]	Effect Size[b]
0	7.0 ± 4.9	6.3 ± 4.3	1.310	.2	Not applicable
5	5.4 ± 3.5	4.7 ± 2.8	2.625	.1	Not applicable
15	6.5 ± 4.9	5.0 ± 3.5	8.681	.005	0.33

[a] Results of repeated-measures analysis of variance.

[b] Calculated using standard mean difference equation.[34]

Table 3. Effects of the Frequency of Dumbbell Vibration Used During Neuromuscular Training Exercises on Variable Error (ie, Variability) of Active Reproduction of Elbow Flexion Angle (Mean ± SD)

Vibration, Hz	Pretest, °	Posttest, °	$F_{1,61}$	*P* Value[a]	Effect Size[b]
0	3.0 ± 2.1	2.9 ± 1.8	0.007	.900	Not applicable
5	3.0 ± 1.8	2.3 ± 1.3	7.250	.009	0.42
15	2.8 ± 1.8	1.8 ± 1.2	24.027	<.001	0.62

[a] Results of repeated-measures analysis of variance.

[b] Calculated using standard mean difference equation.[34]

neuromuscular training on JPS accuracy and variability, respectively. Exercises that included 0-Hz vibration had no effect on accuracy or variability ($P \geq .200$). Neuromuscular training that employed 5-Hz vibration did not affect accuracy ($F_{1,61} = 2.625$, $P = .1$); however, it reduced variability ($F_{1,61} = 7.250$, $P = .009$). Exercises that included 15-Hz vibration enhanced accuracy and decreased variability ($P \leq .005$).

DISCUSSION

We examined the acute effects of neuromuscular training with a handheld vibrating dumbbell on acuity of elbow JPS. Our results indicated that neuromuscular training that included vibration enhanced participants' acuity of elbow JPS (Tables 2 and 3). The pretest accuracy and variability with which our participants actively recreated the elbow flexion angle were similar to findings noted in other reports.[35,36] Our observation that vibration may have positive acute effects on upper extremity SMS function is unique. Our results are supported by a recent report of lumbopelvic position sense in which Fontana et al[17] described acute improvements in JPS after a short bout of exercise that included low-frequency, whole-body vibration. Whereas some researchers have postulated that JPS acuity may benefit from low-volume vibration (low magnitude and short duration of exposure),[18] our results and those of Fontana et al[17] provide the only empirical evidence supporting the theory. Researchers have suggested that vibration provides additional afferent stimulation to the SMS, which facilitates the development of a clearer image of limb position in relation to the remembered framework of the central nervous system.[18] Enhancing SMS function by employing such exercises clinically would benefit any intervention designed to avoid or disrupt the paradigm of pathophysiology illustrated in Figure 1.

To better understand the mechanisms by which vibration may enhance JPS acuity, we explored research describing both the positive and negative effects of vibration. In occupational research, investigators[8,27,37] have consistently reported the deleterious effects of vibration. However, these investigators[8,27,37] employed direct muscle or tendon vibration and observed JPS during exposure to the vibration. In addition, the SMS deficits resulting from large-amplitude or high-frequency vibration employed for long durations[38] and after muscular fatigue[8,9] are well established. The nature of HV and the various settings (eg, duration, frequency, intensity) of the vibration we employed may help explain our unique observations. Relative to the aforementioned reports, we used low-amplitude, low-frequency vibrations for short durations and incorporated only light resistance. This combination may have limited the negative effects of vibration commonly reported.[8,27,37]

We may gain insight into our results by examining the strength and conditioning research in which the acute effects of short bouts of vibration are described. Researchers have indicated acute enhancements in average movement velocity, force, and power after high-frequency, whole-body vibration, with exposure ranging from 1 to 10 minutes.[20–26] The precise mechanisms behind such acute adaptations remain largely unknown; however, researchers have postulated they are similar to the enhanced neuromuscular efficiency observed over the initial 10 weeks of power training.[23,39] Although our JPS measure assessed function of the neuromuscular components proposed to act more efficiently, it is not clear if the enhanced position sense we observed was a result of a similar mechanism. Further investigation is needed to identify whether vibration may enhance SMS function by improving efficiency of the transmission, processing, or integration of afferent or efferent signals.

Our results hold implications for clinicians designing rehabilitation and conditioning programs. Our data suggest that adding low-volume vibration into upper extremity neuromuscular control exercises may enhance JPS. Although additional research is warranted to understand the balance between the positive and negative effects of vibration, our results provide a framework on which to build. However, the effects of adding biofeedback alone to exercises designed to facilitate JPS remain unclear. Neuromuscular training that employed both auditory and visual biofeedback without vibration (0 Hz) had no effect on either measure of elbow JPS acuity ($P \geq .200$), which did not support our hypothesis. Integrating our results into previous reports would suggest that biofeedback may enhance neuromuscular control only when available to participants during the actual position-reproduction measure.[32] We provided biofeedback during training exercises only. Although our results apply only to acute effects of such exercises, the advantages of this feedback alone remain largely unclear.

Limitations and Recommendations for Future Research

As in all research, our study had limitations and identified areas that warrant additional investigation. We used a standard dumbbell and chose not to normalize the resistance to each participant's body mass. However, we used a lightweight dumbbell and short duration of vibration exposure, after which participants did not report fatigue, regardless of body mass. Our results apply only to the neuromuscular training we employed. In future studies, investigators should isolate the effects of different vibration durations and frequencies and forms of biofeedback, as well as the chronic effects of extended training regimens. Although the acute and chronic effects of vibration are complex and identifying their precise mechanisms is beyond the scope of this study, they certainly warrant further evaluation. In future studies, researchers also should include additional healthy and injured populations and consider assessing increasingly functional multijoint and multiplanar measures.

CONCLUSIONS

We observed acute improvements in active elbow JPS acuity in healthy individuals after neuromuscular training exercises that included HV of 15 or 5 Hz. Our data indicated that the enhanced JPS was not a byproduct of the biofeedback we provided to participants or of any learning effect but could be attributed to the vibration alone. Although these results support the use of low-volume HV in programs designed to facilitate neuromuscular control, incorporating vibration into such exercises should be done with caution, as the balance between the positive and negative effects of vibration is not understood. Researchers should manipulate the duration and frequency of vibration treatments, should include injured participants and functional multijoint and multiplanar measures, and should examine long-term effects of similar training protocols on JPS and injury.

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Brady L. Tripp, PhD, LAT, ATC, and Donald Faust, MS, LAT, ATC, contributed to conception and design; acquisition and analysis and interpretation of the data; and drafting, critical revision, and final approval of the article. Patrick Jacobs, PhD, contributed to conception and design; analysis and interpretation of the data; and drafting, critical revision, and final approval of the article.

Address correspondence to Brady L. Tripp, PhD, LAT, ATC, Clinical Assistant Professor and Director of Graduate Athletic Training Education Program, Department of Applied Physiology & Kinesiology, College of Health and Human Performance, FLG 148, University of Florida, PO Box 118205, Gainesville, FL 32611-8205. Address e-mail to trippb@hhp.ufl.edu.