Directional Sensitivity of Velocity Sense in the Lumbar Spine

Joseph S. Soltys, M.S.

Sara E. Wilson, Ph.D.

Department of Mechanical Engineering, University of Kansas, Lawrence, KS

Please address all correspondence to:

Sara Wilson, Ph.D.
Human Motion Control Lab
Department of Mechanical Eng., Univ. of Kansas
1530 W. 15th St., Room 3138, Lawrence, KS 66045
Phone: 785-864-2103
Fax: 785-864-5254
Email: sewilson@ku.edu

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Abstract

Regulating spinal motion requires proprioceptive feedback. While studies have investigated the sensing of static lumbar postures, few have investigated sensing lumbar movement speed. In this study, proprioceptive contributions to lateral trunk motion were examined during paraspinal muscle vibration. Seventeen healthy subjects performed lateral trunk flexion movements while lying prone with pelvis fixed. A 44.5 Hz vibratory stimulus was applied to the paraspinal muscles at the L3 level. Subjects attempted to match target paces of 9.5, 13.5, and 17.5°/s with and without paraspinal muscle vibration. Vibration of the paraspinal musculature was found to result in slower overall lateral flexion. This effect was found to have a greater influence in the difference of directional velocities with vibration applied to the left musculature. These changes reflect the sensitivity of lumbar velocity sense to applied vibration leading to the perception of faster muscle lengthening and ultimately resulting in slower movement velocities. This suggests that muscle spindle organs modulate the ability to sense velocity of motion and are important in the control of dynamic motion of the spine.

Introduction

Highly prevalent and recurrent by nature, low back disorders present considerable social and economic burdens for industrialized societies, including the United States, where direct costs alone are estimated at over $28 billion annually (Baldwin, 2004; Deyo & Weinstein, 2001). A lack of stability in the spinal column may be related to the mechanisms of low back disorders (Panjabi, 1992b). Because stability is achieved through the interactions of the passive tissues of the spinal column (ligaments, discs, vertebrae, etc.), the active spinal musculature, and the feedback of the neural control unit (force and motion transducers) of the spine; a dysfunction in any of these elements may lead to abnormal loading (Panjabi, 1992a, 1992b). This instability can be clinically manifested as the loss of ability to maintain a normal pattern of spinal motion or perform posture related tasks (Panjabi, 1992b, 2003). Recent studies have emphasized the importance of the neuromuscular (reflex) component in the maintenance of postural stability (Li & Wilson, 2005; Moorhouse & Granata, 2007). This neuromotor component consists of sensory elements to detect joint movement, connective elements, and muscles actuating the response. Several sensory mechanisms contribute to the sense of joint movement including the muscle spindle organs located within the musculature (McMahon, 1984).

The proprioceptive system also plays a role in the appropriate coordination of movement. Variability in the coordination of repetitive lifting movements has been observed by a number of researchers (Dunk et al., 2005; Granata et al., 1999; Marras & Granata, 1997). It has been suggested that such variability may increase the number of lifts outside safe movement and loading tolerances (Granata et al., 1999; Mirka & Marras, 1993). Loss in sensory ability would impact coordination of movement by increasing dynamic variability. It can therefore be surmised that the proprioceptive system plays an important role in both the stability and appropriate control of the lumbar spine and is an important arena for future research in the low back.

Muscle spindle organs provide information on changes in muscle length relating to both joint position and velocity and additionally are sensitive to vibration (Cordo et al., 1995; Kerr & Worringham, 2002; Roll & Vedel, 1982). Sensory illusions from localized muscle vibration have been reported in several studies investigating proprioceptive ability (Brumagne et al., 1999; Cordo et al., 1995; Inglis et al., 1991; Ribot-Ciscar et al., 1998; Verschueren & Swinnen, 2001). When subjected to vibrations, increased targeting errors have been observed (Brumagne et al., 1999; Cordo et al., 1995). Vibration of the muscle and muscle spindle organs has also been shown to alter response to unexpected sudden loading in the trunk (Arashanapalli, 2005). These sensory effects have been observed for vibrations up to 120 Hz with frequencies up to approximately 50 Hz resulting in a one-to-one interaction between the vibration and Ia afferent activity from the muscle spindle (Roll & Vedel, 1982). In addition to changing the ability to sense joint position, vibration of the distal tendon of the biceps muscle in the arm has been shown to alter a subject's perception of joint movement velocity (Cordo et al., 1995). Cordo *et al.* (1995) documented that low frequency vibration (20 Hz) led to a perception of slower elbow motion and higher frequency vibration (40 Hz) led to a perception of faster elbow motion when moving between 44 and 69 degrees per second (Cordo et al., 1995). At movement speeds slower than 25 degrees per second both 20 and 40 Hz vibrations were found to lead to a perception of faster elbow movement. The authors suggested that such vibration stimulates some of the muscle spindle organs entraining their afferent output to the frequency of the vibration and overriding the normal output associated with a specific velocity. These studies have demonstrated the use of muscle vibration as a tool to alter muscle spindle organ activity and to assess the role of muscle spindle organs in neuromotor control. They have also demonstrated that these muscle spindle organs provide not only position but also velocity information to the neuromotor system.

So far, measures of the role of the muscle spindle in the control of the trunk have focused on changes observed during static position sensing. However, dynamic motion is common in the workplace and velocity of motion is a factor in low back disorders (Fathallah et al., 1998; Marras et al., 1995; Masset et al., 1998; Norman et al., 1998). Furthermore, trunk rotational velocities have been shown to distinguish injury risk groups better than trunk posture (Fathallah et al., 1998). Trunk lateral and rotational velocities during lifting are two of five workplace factors that predict risk of low back disorders in a logistic regression model (Marras et al., 1995). Additionally a prospective study found that workers who performed a lateral flexion task on a trunk dynamometer at higher velocities were more likely to develop low back pain in the workplace during the following year (Masset et al., 1998). Once injured, however, individuals with low back pain consistently move at speeds significantly slower than non-injured controls (Marras & Wongsam, 1986). These articles suggest that trunk velocity may be a key discriminator for low back pain and injury. Unfortunately, there has been relatively little examination of proprioceptive sensing of trunk velocity. One study did examine the threshold until lumbar movement was detected when rotating at a constant speed and found that individuals experiencing low back pain required higher speeds to detect motion (Taimela et al., 1999). While this article suggests that altered velocity sensing may indeed occur with low back injury, there is a need to further investigate velocity sensing in the trunk and to understand the role of proprioceptive elements including the muscle spindle organs in that sensing.

Examination of the specific contributions of the proprioceptive system to sensing of the velocity of dynamic trunk motion can serve to further elucidate the mechanisms of variability and control of trunk motion and serve as a springboard to understanding the potential etiology of injury. The muscle spindle organs have the capacity to sense velocity of motion in addition to position and have been documented to display an altered response when subject to vibration (Cordo et al., 1995). The intent of this study was to investigate the effects of muscle vibration on a trunk velocity replication task to better understand the role of the muscle spindle organs in the sensing and control of lateral trunk motion. It was hypothesized that a difference in movement velocity would be observed with the application of vibration. Additionally, it was thought that a directional difference in speed would be observed dependent upon the side of vibration. This is to say that an interaction would occur during which vibration of a single side would affect speed in one movement direction more than the other.

Methods

Seventeen healthy, male (5) and female (12) subjects (age 22.5 ± 3.4 years, weight 68.9 ± 11.8 kg, and height 172 ± 8 cm) participated in this study after providing informed written consent as approved by the University of Kansas Human Subjects Committee. All subjects identified themselves as right handed. Subjects recruited were from the university student body and personnel and were screened with a survey for musculoskeletal disorders and/or injuries. Subjects were asked to wear comfortable, non-restricting clothing and to not have eaten a large meal in the hour previous to participation.

A platform was created for this experiment to limit the subject's movement to lateral bending only (Figure 1). The platform consisted of a padded stationary base and rotating beam arm. The rotation of the beam occurred at a polished steel pin and bearing at the bottom of one end of the beam arm. The platform was supported by two omni-directional caster bearings (Spherical Wheel, Italy) each rated to support an 85 pound load. To provide a smooth surface for the casters, an 8' x 4' x 1/8" thick acrylic sheet was positioned under the entire path of the wheels. An optical encoder (US Digital, Vancouver, Washington) was attached to the pin and used to provide feedback at 1,000 counts per revolution for a resolution of .36° per count. Additionally, the platform was equipped with a clamp to restrain pelvis movement.

Vibration was applied using an inertial vibratory device operating at 44.5 Hz measured with an accelerometer (PCB, Depew, NY). This frequency was within the range of 10-70 Hz in which changes in velocity perception were observed in the upper extremity (Roll & Vedel, 1982). The vibratory device was comprised of an elastic belt with two small DC motors, each with a 1.3 gram weight offset 2 mm from the spindle axis, attached. The belt was placed at the L3 level and adjusted to apply the vibratory stimulus to the underlying paraspinal muscles on either side of the spine independently. The three levels of stimulus were Vibration OFF (VOFF) during which neither side of the back musculature was vibrated, Vibration LEFT (VL) during which only the left side musculature was vibrated, and Vibration RIGHT (VR) during which only the right musculature was vibrated.

Lateral flexion was measured using the encoder attached to the beam arm. The signal from the encoder was sampled at 1,000 Hz. A computer interface, created in Labview (National Instruments, Austin, Texas), was used to provide audible feedback to the subject. The performance-based feedback consisted of a single audible cue for every 21 encoder steps (7.56 degrees).

For the protocol, subjects were blindfolded and asked to lay prone on the platform to allow for the vibration device on the back. Subjects were aligned by placing the midpoint between the anterior iliac crest and the navel over the pin connector of the beam. After the subjects were aligned, the pelvis was restrained by locking the position of an adjustable brace connected to the stationary portion of the platform. A digital metronome was used to provide a target audio cue corresponding to three target velocities of 9.5, 13.5, and 17.5 deg/sec respectively. The trials were randomized by target speed.

The three different stimulus conditions (VOFF, VL, VR), were randomly ordered within each target speed block. During each trial, subjects were asked to flex laterally from as far left to as far right as comfortably possible at the targeted speed. They were asked to pause at the extreme and then flex laterally from the right to the left at the targeted speed. This was repeated until two consecutive left-right-left motions were performed for each trial.

The protocol consisted of alternate training and assessment trials. During the training trials all audio cues were available. Subjects were asked to match the encoder cue to a metronome generated pacing beat to achieve the target speed. During assessment trials all audio cues were removed and subjects were asked to replicate movement speeds from memory. The training and assessment trials were repeated until two assessment trials were successfully collected for each condition. A practice session was performed at the beginning of the experiment to allow the subject to become comfortable with the task of matching the encoder audio cue to the metronome beat.

The raw encoder step data was converted into velocity values by dividing step angle by time interval. The average velocity for the middle 30% of motion for each movement direction was then calculated. Data were examined with analysis of variance using a general linear model in SPSS (v14) using the Type III sum-of-squares method. There were no missing values. All tests of significance were performed at $\alpha = 0.05$. To provide a more conservative analysis, degrees of freedom were corrected using a Huynh-Feldt, repeated measures ANOVA to correct for any possible violations of the sphericity assumption. An initial ANOVA was performed to examine the main effects of the independent variables: vibration, movement direction, and target speed on the dependent variable: movement speed. If a significant main effect was found then a simple contrast was performed between levels. An additional Huynh-Feldt repeated measures ANOVA was then used for *post hoc* analysis. All tests were determined to be significant for a $p \leq 0.05$.

Results

For this study, variation in lumbar lateral flexion variables were assessed during a replication task with targeted velocities at 9.5, 13.5, and 17.5°/sec. The mean velocities and standard error of the means at each target speed were 9.39 (±.45), 13.88 (±1.00), and 17.48 (±.92) °/sec respectively for assessment trials and 9.12 (±0.41), 13.30 (±.67), and 16.88 (±.82) °/sec for the training trials. These values represent the average of left and right movement velocities across all stimulus conditions with the average assement trial values per condition represented in Figure 2.

Changes in speed due to movement direction were evaluated for all stimulus levels (VOFF, VL, and VR) and target velocity conditions during assessment trials (Figure 2). During these trials, movement speed was found to be significantly affected by vibration condition ($p < 0.05$), target speed ($p < 0.05$) (indicating the subjects did move at three distinct target speeds), but not movement direction ($p = 0.628$). The only interaction of these variables that proved significant was vibration condition*movement direction ($p < 0.05$) (Table 1). The within-subjects contrast revealed that the mean movement speed value during both the VL and VR conditions were different than the VOFF condition

($p<.05$). Contrast of the vibration_condition*movement_direction revealed that while the VL condition was significantly different from the VOFF condition ($p < 0.05$), the VR condition was not ($p = 0.71$).

To further investigate this interaction the Directional Difference Speed (DDS) was analyzed. The DDS was specifically defined as the difference in magnitude of right and left movement velocity so that a positive number would indicate a faster movement speed to the right and a negative would indicate a faster movement to the left. This measure would then allow us to explain for the expected interaction of movement direction and vibration, essentially comparing a muscle spindle group experiencing vibration with one that wasn't. The DDS was calculated for each right-left paired movement. A separate, repeated measures ANOVA was performed indicating a significant main effect of vibration ($p<0.05$) in agreement with the interaction observed with vibration condition and movement direction. A trend towards greater DDS magnitude was observed at the faster movement velocities (13.5 and 17.5 degrees per second) with vibration even though the interaction between vibration condition and target speed in the original ANOVA was not significant ($p = 0.447$), (Figure 3). The *post hoc* within-subjects ANOVA comparing DDS for the VL and VR conditions revealed a significant ($p < 0.05$) difference between the means of the VL and VR conditions (Figure 4, Table 1).

Discussion

It was the aim of this study to examine velocity sense in the lumbar spine during a lateral flexion task and, in particular, to examine the role of muscle spindle organs in velocity sensing through the use of locally applied vibration. Our main hypothesis was that a difference in lateral velocity would be observed during lumbar vibration. To investigate the significance of directional differences, a symmetrical task was chosen. Movement of the multi-segmented anatomy of the lumbar spine was limited to a single plane of lateral rotation utilizing a platform strategy. A calculated DDS was used to describe the observed differences in lateral flexion velocity due to the side of applied vibration.

The primary finding of this study was slower average movement velocity during application of lumbar vibration (Figure 4). This change in velocity due to vibration was not observed to be dependent upon movement speed as might have been expected. We had anticipated that entraining the muscle spindle afferents to a specific vibration signal would alter the subjects' perceived velocity and result in a change of their movement speeds toward the velocity corresponding to the entrained signal. That is to say that movements normally faster than that induced by the vibration would be slower and vice versa. However, this was not evident by our data.

Additionally, our data suggested that the lateral lumbar DDS was significantly altered with applied muscle vibration (Figure 3). This would suggest that subjects peceived themselves as moving faster when vibration was applied to the lengthening muscle group resulting in a slower movement. We had originally expected to observe a significant difference that was mirrored in both the VL and VR conditions reflecting a similar sensitivity for each lengthening muscle group experiencing vibration. While a significant difference in DDS was witnessed during the VL condition, the effect during the VR condition was very slight and not significant.

Overall this directional difference appears to agree with research on the elbow which found vibration of the biceps brachii at 40 hz resulted in subjects preceiving faster motion and undershooting a target (Cordo et al., 1995). However, while Cordo et al. found that this effect decreased with increased movement velocity, in the current study the largest DDS was observed at the highest target velocity. In the study by Cordo et al. the velocity range was 16_to_69 degrees per second. This was much greater than the current study with a velocity range of 8 degrees per second. A greater range of velocities may be necessary to observe a similar pattern in the DDS.

The DDS was found to be significantly larger when vibration was applied to the left (VL) than when compared to the VOFF and/or right (VR) conditions (Figure 4). When vibration was applied to the right, the effect was smaller and not statistically different from the no stimulus condition. Though not specifically investigated in this study, these directional effects may indicate side-dominance of the musculature, the muscle spindle organ density, and/or proprioceptive coordination of the low back (Hides et al., 1994; Sung et al., 2004). The increased senstivity of the DDS to vibration of the left paraspinal muscles suggests that, at least in right-handed subjects, these left paraspinal muscle spindle organs play a greater role in the nervous system's determination of lateral rotational velocity than the right paraspinal muscle spindle organs. Since all subjects in the current study were right-handed it cannot be determined;

from the current data the extent handedness may have contributed to the patterns observed, though the possibility is worth noting and testing in the future.

There were some limitations in the current study. Kerr and Worringham suggested that duration of a movement or distance traveled in a movement may give subjects some cues on velocity (Kerr & Worringham, 2002). In this study this effect was limited by requiring subjects to move through their entire range of lateral motion at a relatively slow speed. Such a requirement made both the distance traveled and time large, limiting their usefulness as velocity cues. Other potential cues, such as floor vibration, were reduced by creating a smooth rolling surface for the platform and using padding on the platform to dampen any vibration. Because subjects need to speed up at the beginning of a motion and slow down to stop at the end of a motion, only the central 30% of the motion was analyzed to prevent contamination of end effects. Finally, fatigue could play a role in velocity sense though the randomization of the order of the various conditions likely minimized this effect.

In this study a single local vibratory stimulus applied to the paraspinal musculature at a single frequency was used. Cordo et al. suggested the effects of vibration on velocity sense may vary with the frequency of the application signal and speed of motion (Cordo et al., 1995). While speed of motion was varied in this study, the range may have been too small to observe the effects of speed. Vibration of multiple muscles or vibration at varying amplitudes could also have an effect and should be investigated further. Similarly, the use of occupationally-relevant whole body vibrations may result in different velocity patterns.

This study is a step towards understanding how velocity information is perceived in the lumbar spine during a lateral flexion task. The muscle spindle organs in the paraspinal musculature have been demonstrated to contribute to the sense of lateral trunk velocity as observed by the differences in velocity due to vibration. This effect was found to be stronger when comparing the difference in magnitudes of consecutive right and left movement velocities during vibration of the left side only, suggesting an asymmetry in the role of the muscle spindle organs that should be investigated further.

As mentioned in the introduction, velocity sense, and more broadly proprioception, play a role in both maintaining dynamic stability and reducing variability in trunk motion tasks. The role of the muscle spindle organs in this task suggest that these elements should be investigated further for their potential role in the risk of low back injury. Conditions that may injure or otherwise inhibit the muscle spindle organs, such as muscle fatigue or muscle strain, may also have an effect on the dynamic stability and trunk motion variability (Panjabi, 1992a). Occupational vibration exposure, which has long been known to be a low back injury risk factor, may also have an effect on dynamic stability and trunk motion variability through its effect on the muscle spindle organs (Li & Wilson, 2005). In conclusion, vibration of the paraspinal musculature in the trunk resulted in slower movement velocity overall. Additionally, a directional difference in movement speed was observed that was most predominant when the vibration was applied to the left paraspinal musculature. These results suggest that the paraspinal muscle spindle organs play a role in the ability to sense lateral trunk motion.

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Table.1. A Huynh-Feldt, repeated measures ANOVA was used to examine the effects of the independent variables: Vibration Condition, Target Speed, and Movement Direction on the dependent variable Movement Speed (A.1). In addition to the ANOVA results, further within-subjects, repeated contrasts for the significant main effect of Vibration and the interaction of Vibration and Movement Direction are reported (A.2). Finally, an additional repeated measures ANOVA was performed to examine the left versus right side vibration differences in the DDS (B). Significant results are highlighted.

A.1

Variable	**df**	**Mean Square**	**F**	**Significance (p)**
Vibration Condition	1.979	48.656	9.175	**.001***
Target Speed	1.808	3715.593	89.204	**.000***
Movement Direction	1.000	1.930	0.245	0.628
*Vibration * Target Speed*	2.186	13.712	0.845	0.447
*Vibration * Movement Direction*	2.000	7.696	3.808	**0.033***
*Target Speed * Movement Direction*	1.713	0.369	0.170	0.812

A.2

Variable	**Comparison**	**df**	**F**	**Significance (p)**
Vibration	VL * VOFF	1	7.947	**.012***
	VR * VOFF	1	15.946	**.001***
Vibration & Movement Direction	VL * VOFF	1	5.515	**0.032***
	VR * VOFF	1	0.149	0.705

B

Variable	**df**	**epsilon**	**F**	**Significance (p)**
Vibration Condition	1.000	1.000	6.618	**.020***
Target Speed	1.746	0.873	0.118	0.863
Repeat	1.000	1.000	1.285	0.274
*Vibration * Speed*	2.000	1.000	1.119	0.339
*Vibration * Repeat*	1.000	1.000	0.000	0.994
*Speed * Repeat*	1.943	0.981	1.271	0.294
*Vibration * Speed * Repeat*	2.000	1.000	0.377	0.689

* Indicates significance of $p <= 0.05$

Figure Legends

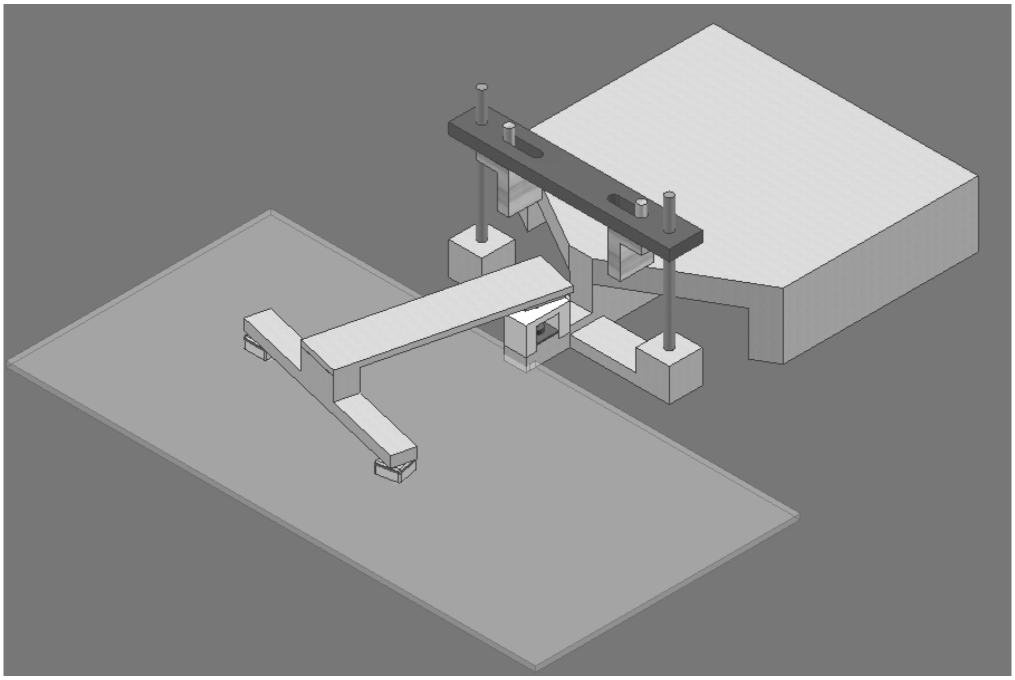
Figure 1. The experimental setup consisted of a two-section platform. A fixed section supported the lower extremities and held the pelvis stationary. The other was a rotating beam supported on one end by omni-directional casters and at the other end by a pin connection. A 4’x8’x1/4” sheet of acrylic provided a smooth surface over which the casters could easily roll. A digital encoder connected to the pin provided feedback on the angular displacement of the rotating portion of the platform. Subjects wore a blindfold while vibrations were applied over the L3 paraspinal musculature via two independent DC motors with an offset weight on the spindle.

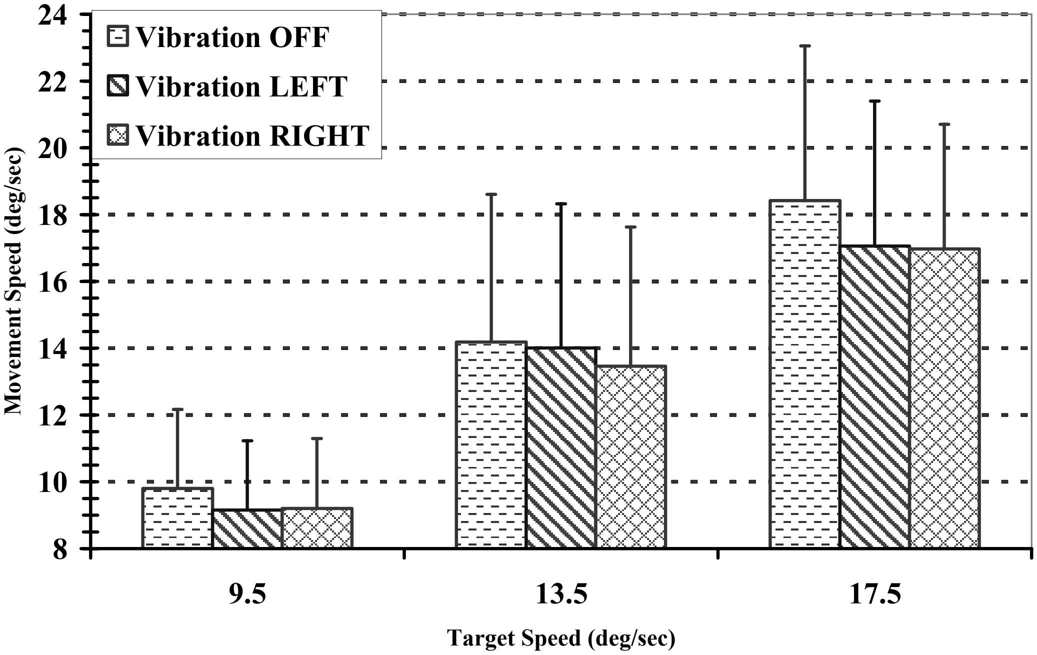
Figure 2. Subjects were trained at three velocities 9.5, 13.5 and 17.5 degrees per second. Subjects were able to maintain these speeds during the assessment trials shown here.

Figure 3. The DDS was calculated as the difference between the lateral flexion velocity between successive right and left motions. A positive DDS indicates faster movement towards the right. Vibration was found to result in a negative DDS when vibration was applied to the left paraspinal musculature. Vibration applied to the right paraspinal musculature resulted in a positive DDS although this was not significantly different from the VOFF condition.

Figure 4. Average movement speeds for each movement direction and vibration condition are represented. A slower than average velocity was observed with the addition of

vibration. A greater interaction of movement direction and vibration condition was observed during the VL condition. This interaction was termed the Directional Difference Speed (DDS). The DDS is represented by the right minus left difference in magnitude of movement velocity.




Vibration OFF
Vibration LEFT
Vibration RIGHT
Movement Speed (deg/sec)
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12
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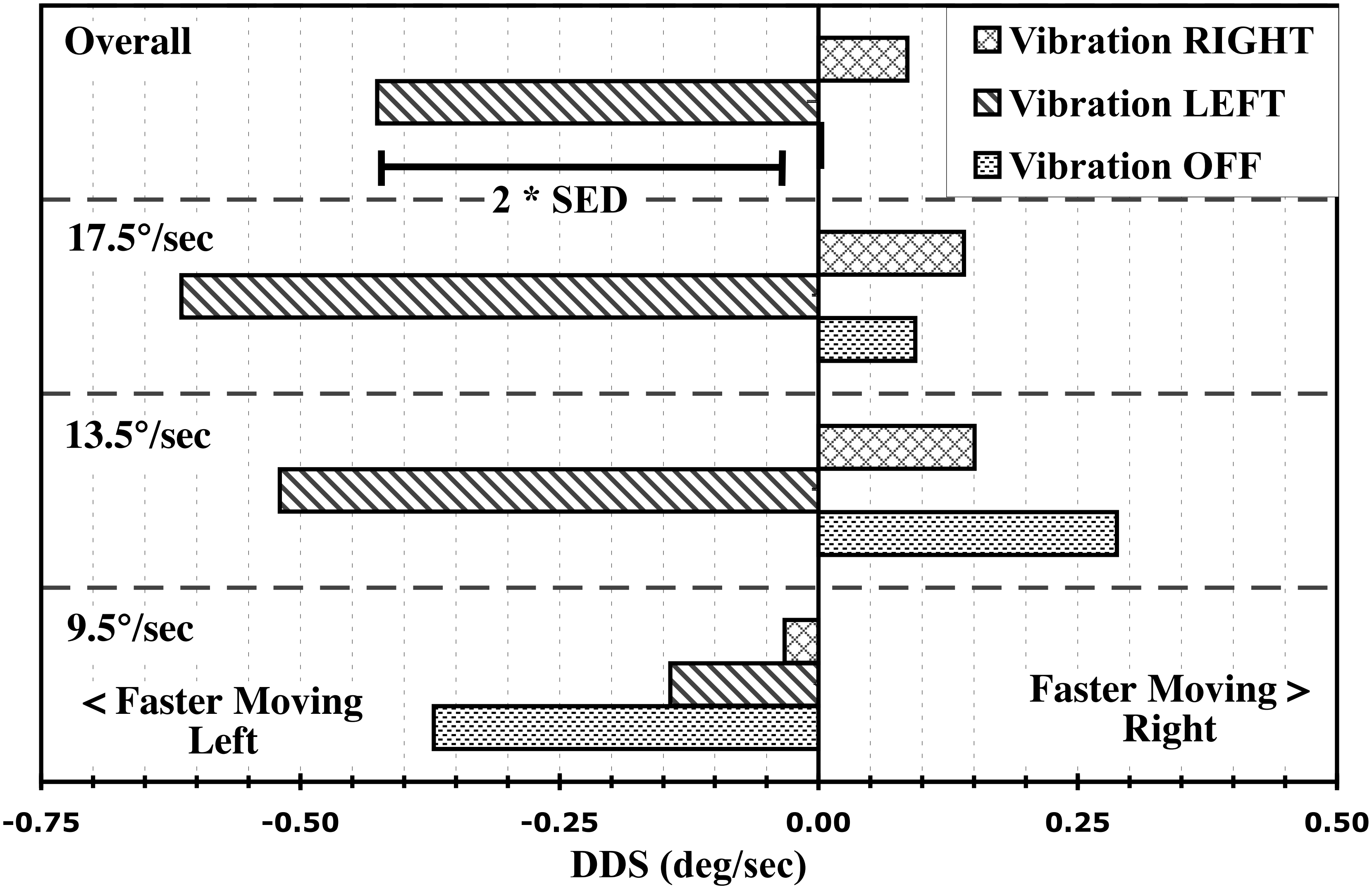
17.5
Target Speed (deg/sec)


Overall
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13.5°/sec
9.5°/sec
Vibration RIGHT
Vibration LEFT
Vibration OFF
2 * SED
< Faster Moving Left
Faster Moving > Right
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-0.50
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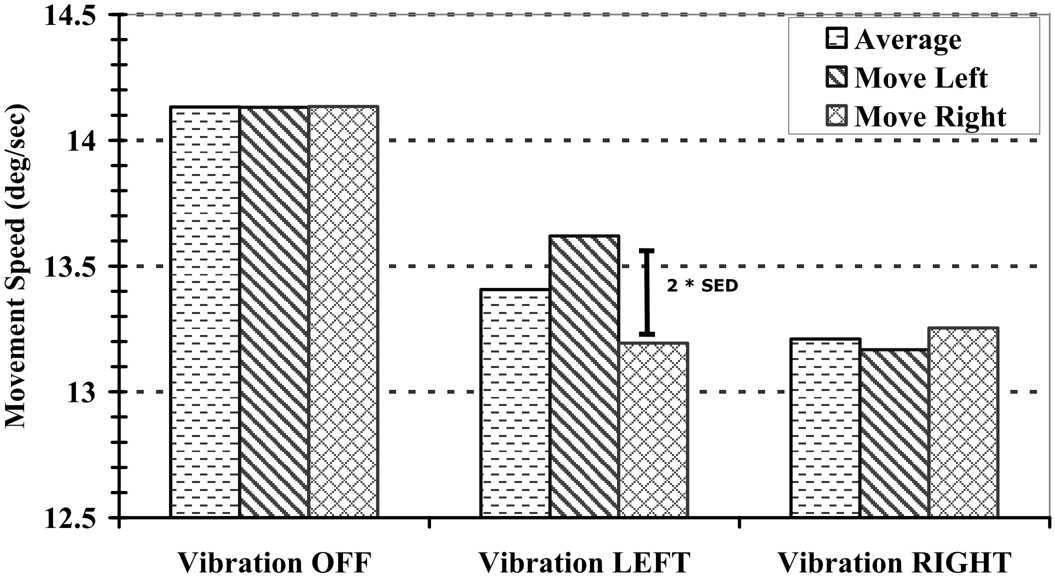
0.50
DDS (deg/sec)



14.5
14
13.5
13
12.5
Movement Speed (deg/sec)
Average
Move Left
Move Right
2 * SED
Vibration OFF
Vibration LEFT
Vibration RIGHT