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The Effects of a Low Back Pain Vibration Modality on Trunk Postural Control

Adam R. Cornwall
Wilfrid Laurier University, corn1130@mylaurier.ca

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By

Adam Cornwall

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Abstract

Introduction: Low back pain (LBP) is prevalent worldwide and is affecting even more individuals as the population ages. There has recently been an increase in production of low back pain (LBP) vibration modality belts that apply localized vibration to the lumbar region of the spine as it has shown to reduce pain. However, vibration is also known to perturb muscle spindles and thus interfere with proprioception. If a LBP vibration modality causes a proprioceptive deficit in the trunk lumbar region it could potentially increase an individual's risk of injury due to poor postural control. Therefore, the effects of a LBP vibration modality on trunk motor control needed to be investigated further.

Methods: 15 participants who had not experienced LBP for longer than 3 days in the previous year were recruited to partake in a control and experimental day approximately one week apart from each other. Each day consisted of 3 conditions including; pre-vibration, post-vibration, and vibration ON. Between each condition participants sat on a standard chair for 15 minutes while wearing the vibration belt and the belt was also worn during the last vibration ON condition. On the control day the vibration belt was worn but not turned on between conditions or during the last vibration ON condition. Each condition consisted of 4 sudden unexpected trunk perturbations following by 3 half- and 3 full-trunk flexion repositioning tasks. Electromyography (EMG) was collected from several trunk muscles to analyze changes in trunk postural control and motion capture was collected to analyze changes in lumbar spine movement.

Results: The magnitude of lumbar flexion caused from the sudden trunk perturbation decreased after sitting for 15-minutes and was exacerbated by vibration. No other significant differences in the variables measured after wearing the vibration belt for 15-

minutes were found. However, profound differences were found during the vibration ON condition. Bilaterally the LES ($p<0.0001$), LEO ($p=0.03$), and REO ($p=0.002$) displayed significantly delayed muscle activation onset latencies. Bilaterally the LES ($p<0.0001$), LTES ($p=0.01$), RTES ($p<0.0001$), EO ($p<0.0001$), LRA ($p<0.0001$), and RRA ($p=0.0001$) all showed significant increases in resting muscle activation pre-perturbation. The LLES ($p=0.0002$), RLES ($p=0.0003$), LTES ($p=0.0008$), RTES ($p=0.03$), LRA ($p=0.02$), and RRA ($p=0.01$) also all displayed significantly reduced muscle activation magnitudes post-perturbation.

Discussion and Conclusion: The increased resting muscle activation pre-perturbation caused from the vibration can be explained as the tonic vibration reflex (TVR) because of vibrations stimulatory effect on Ia afferents. The delayed muscle activation onset latencies that were observed while wearing the vibration belt most likely occurred because of the ability for vibration to create a ‘busy line’ or vibration-locked discharge of the muscle spindles. Proper muscle spindle function is essential for providing critical proprioceptive information on body awareness and functions as a protective mechanism against injury. Additionally, the TVR can also lead to fatigue and subsequent altered trunk motor control. The findings of the current study reveal that impaired trunk motor control when wearing a LBP vibration modality belt needs to be considered due to the potentially greater risk for experiencing an injury to the low back or LBP.

Acknowledgements

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List of Abbreviations

ANOVA	Analysis of Variance
CNS	Central Nervous System
EMG	Electromyography
EO	External Oblique
EPSP	Excitatory Post Synaptic Potential
FFT	Fast Fourier Transformation
GTO	Golgi Tendon Organ
LBI	Low Back Injury
LBP	Low Back Pain
LES	Lumbar Erector Spinae
LFF	Low-Frequency Fatigue
T	Transmission cells
TES	Thoracic Erector Spinae
TVR	Tonic Vibration Reflex
MVC	Maximum Voluntary Contraction
RA	Rectus Abdominis
ROM	Range of Motion
SG	Substantia Gelatinosa
WBV	Whole-Body Vibration

1.0 Introduction

Low back pain (LBP) is prevalent worldwide and is affecting even more individuals as the population ages. Not only does LBP negatively impact an individual's quality of life, it is also a significant financial burden to society as a whole (Martin et al., 2009). Extensive research has been conducted into prevention as well as treatment of LBP but further research is still needed. There is now an increased demand for safer, less harmful, non-pharmacologic alternatives for treatment of LBP. This has led to an increase in production of vibration-based modalities for pain relief, which are mainly supported by the now partially incorrect gate control theory of pain. However, vibration has shown to reduce pain in various circumstances and still has the potential to be an alternative form of treatment to pharmaceuticals (del Pozo-Cruz et al., 2011). The issue now presented with using a LBP vibration based modality is the potential disruptive proprioceptive effects known to be associated with exposure to vibration (Duclos, Maynard, Barthelemy, & Mesure, 2014). If a LBP vibration modality causes a proprioceptive deficit in the trunk region it could potentially increase an individual's risk of injury due to poor postural control. Therefore, the main purpose of this research study was to investigate the potential negative effects of a LBP vibration modality on trunk postural control in healthy individuals. The two tasks that were used as assessments of postural control for this study were chosen to best reflect real life scenarios. The first task was a sudden trunk perturbation that tested individuals' spinal reflex pathway while the second, a trunk repositioning task, tested individuals' voluntary active ability to position their trunk. Overall, LBP vibration based modalities are currently on the market and further research

needs to be conducted on the possible negative effects they may have on trunk postural control.

2.0 Review of the Literature

2.1 Prevalence of Low Back Pain

In 2010 LBP, in relation to years lived with disability, was ranked as the greatest contributor to global disability and 6th as an overall burden to society (Hoy et al., 2014). It is no secret that LBP affects millions of people worldwide given that statistically, 84% of people will experience some form of LBP at some point in their lifetime (Balagué, Mannion, Pellisé, & Cedraschi, 2012). However, not only is LBP globally disabling, it also brings pressure and financial burden to health care systems to diagnose, treat, and manage those experiencing pain. In the U.S. it has been estimated that 35.1 billion dollars is spent annually on LBP health care expenditures (Martin et al., 2009). In addition, LBP is the number one cause of sick leave and lost time from work in the developing world (Pope & Novotny, 1993) resulting in an even greater economic burden in the form of production loss due to inability to work (Maniadakis & Gray, 1999). In the U.S. alone, it is predicted that the total overall cost of LBP comes to a staggering 80 billion dollars annually (Pope, Goh, & Magnusson, 2002). These statistics become more concerning as the average age of the population is globally increasing (Hoy et al., 2014). With an increased prevalence of LBP in older age groups the economic problem is going to continually grow over the upcoming decades (Maniadakis & Gray, 1999). Clearly LBP is a significant debilitative and financial burden to society and further research needs to be done not only on preventative measures but also treatment once symptoms are present.

2.2 Treatment of Low Back Pain: Non-Drug Therapy

Reduced quality of life is a common symptom in individuals experiencing LBP (Bentsen, Hanestad, Rustøen, & Klopstad, 2008) because of the inability to participate in

general positive health behaviours (Briggs et al., 2011). Treatment has been focused on optimizing function and reducing severity of pain because this has led to improvement in physical functioning as well as quality of life (Pallay et al., 2004). In the past, narcotics were a common treatment used for treating LBP. The common known adverse side effects of narcotics resulted in a shift towards using non-steroid anti-inflammatory drugs (NSAIDS) as a more appropriate alternative treatment (Alpert, 2014). However, NSAIDS can only provide temporary relief of pain and also have well-known adverse side effects including abdominal pain, diarrhea, edema, dry mouth, rash, dizziness, headache, tiredness, and gastrointestinal events (Koes, Scholten, Mens, & Bouter, 1997; Ghoname et al., 1999). This is the reason for why there is now a new interest in relieving LBP with safer, non-pharmacologic alternatives, such as vibration.

2.3 Vibration as a Pain Modality: The Gate Control Theory of Pain

It is understood based on the gate control theory of pain that vibration has the ability to reduce pain. The mechanisms behind the reduction in pain is based on the idea that when large fast-conducting fibres are stimulated their afferent signals travel to and excite the substantia gelatinosa, located within that spine, which then inhibits nociceptive small slow-conducting fibre signals (Figure 1) (Melzack & Wall, 1967). Although, large fast-conducting fibres tend to adapt quickly to constant stimuli and will only stay activated by a continuously changing stimuli. This leads into why vibration is able to reduce pain, as it is a technique that overrides the tendency of the fibres to adapt and therefore, continually stimulates the large fibres that inhibit pain signals (Melzack & Wall, 1967). However, it should be acknowledged that numerous experiments and clinical findings after the publication of the gate control theory have made it clear that

various details of the theory are incorrect (Mendell, 2014). This includes discoveries such as: Input from small sensory fibres are not always from pain; the theory does not account for the lingering effect of pain relief seen after large fast-conducting fibre stimulation is removed; and that pain is much more complex than being evoked simply by brain activity reaching a specific threshold but has now expanded to a neuromatrix concept (Mendell, 2014). Nevertheless, the theory still acts as a fundamental basis to understanding pain and even though the proposed mechanisms may not be entirely understood, there are still various studies that have found a reduction in pain from the application of vibration. Nanitsos, Vartuli, Forte, Dennison, and Peck (2009) used a vibration device normally used for massage therapy and applied it to the side of patients faces prior to receiving a dental anesthetic injection and found decreased pain associated with vibration. In another experiment, vibration between 50-150hz was applied to individuals with a variety of pain disorders for a varying amount of time. It was found that when vibration was applied for 1-15 minutes the pain relieving effects of vibration were brief post-vibration. When the vibration was applied for upwards of 45 minutes, there was a longer lasting effect of pain relief even up to several hours post-vibration. It was concluded that vibration between 50-150Hz applied with moderate pressure could relieve musculoskeletal pain in up to 70% of individuals (Lundeberg, Nordemar, & Ottoson, 1984). Therefore, even though various details of the gate control theory have been disproven, vibration has proven to reduce pain in a variety of circumstances.

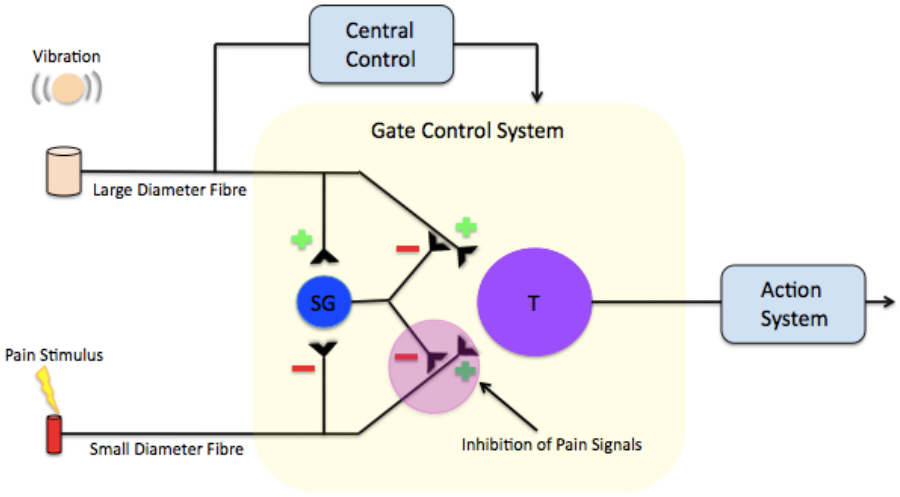


Figure 1 Theoretical mechanism behind the gate control theory of pain. Small diameter fibre signals are inhibited indirectly by activation of large diameter fibres that stimulate the substantia gelatinosa (SG) that then inhibit pain signals (indicated by purple shade). Therefore the pain signals cannot reach transmission (T) cells in the dorsal horn that would send pain signals to the CNS and thus, results in decreased pain perception (adapted from Mendell, 2014).

2.4 Vibration Treatment for Low Back Pain

Vibration is now being explored as a possible modality for the treatment of LBP. Del Pozo-Cruz et al. (2011) explored whole body vibration therapy as a possible mechanism for reducing chronic non-specific LBP. Individuals experiencing chronic non-specific LBP underwent a 12-week vibration therapy protocol with a total of 24 sessions. The vibration group proved to be statistically significant in a variety of pain measurements and it was concluded that vibration may be a feasible pain modality that could possibly hold up as a novel, more safe, physical therapy for those experiencing LBP (del Pozo-Cruz et at., 2011). Lundeberg, Ottoson, Hakansson, and Meyserson (1982) speculated that to maximize pain reduction when using vibration it needs to be applied to the local large fast-conducting fibres closest to the pain affected area. Various specific localized vibration modalities have now been created as an alternative therapy for LBP such as vibration belts worn around the torso, massage chairs, and massage

handheld devices. However, the effects of vibration on the postural control system have not been considered.

2.5 Vibration Disrupts Proprioceptive Feedback

Various LBP vibration modalities have been created that are recommended to be applied to the lower back for a sustained period of time. Within the lower back the lumbar erector spinae (LES) is the most superficial group of muscles that are essential for postural control and extension of the trunk. The LES, like most skeletal muscles, contain fundamental somatosensory receptors that are crucial for providing sensory feedback to the central nervous system (CNS) on perceived muscle length and joint movement. These receptors are commonly known as muscle spindles. They consist of several intrafusal muscle fibres that respond differently based on dynamic or static actions. During a dynamic movement efferent dynamic fusimotor gamma motoneurons stimulate nuclear Bag_1 fibres that then increase stiffness in the polar regions of the spindle. This results in increased stretch-sensitivity of the muscle spindle by increasing tension on the Ia afferent located in the equatorial (center) region of the spindle. During a static contraction static efferent fusimotor gamma motoneurons stimulate nuclear Bag_2 and chain fibres that then increase the firing rate of both Ia and II afferents at a given muscle length. Therefore, because muscle spindles extend over the length of a muscle, they are able to contract and relax in sync with extrafusal muscle fibres. As the muscle length changes they are able to constantly relay this information to the CNS through both Ia and II afferents and thus, are responsible for providing information on change in muscle length and velocity (Banks, 2015). Muscle spindles are large fast-conducting fibres and are therefore able to detect minimal changes in muscle length (Powers & Howley, 2012). This allows for vibration to

be a very powerful muscle spindle stimulus because it causes minimal but constant changes in the length of the muscle. When vibration is applied to a muscle tendon it causes an almost constant illusory movement in the direction that corresponds with the rotation of the joint if the vibrated muscle was lengthening (Roll & Vedel, 1982). This illusory movement experienced from vibration supports that fact that muscle spindles monitor muscle length and provide information on joint movement to the CNS. This is important because proprioception of muscle lengthening is greatly involved in overall body kinesthesia and if its feedback is altered or insufficient, there will be an altered perception of ones muscle length and joint position (Roll & Vedel, 1982). The main point to be emphasized is that when a low back vibration modality is applied to the lower back, it may cause an informational perturbation on the length of the superficial LES that will result in altered trunk postural control. There is also some evidence to suggest that vibration may also affect cutaneous mechanoreceptors involved in proprioception (Weerakkody & Gandevia, 2009). Although, because of muscle spindles known primary function and sensitivity to vibration they are more likely to be the primary cause for motor impairment from vibration (Ribot, Roll, & Gauthier, 1986).

The excitatory perturbation effect from vibration is known to occur during the initial 20-30 seconds from when the vibration is applied to the muscle. On the other hand, beyond 30 seconds, vibration has been shown to actually have an inhibitory effect on muscle spindles. Prolonged vibration in multiple leg muscles has shown to cause a decrease in resting discharge rate of Ia afferents that project from muscle spindles (Ribot-Ciscar, Rossi-Durand, & Roll, 1998). A decreased resting discharge rate is associated with an increase in strength of stimuli required to activate muscle spindles. Because

muscle spindles are the primary sensors of the monosynaptic reflex arc, when their resting discharge rate is decreased, inhibition of the reflex also occurs (Eccles, Schmidt, & Willis, 1962). Therefore, the monosynaptic short-latency stretch reflex that protects muscles from injury from a sudden increase in length becomes delayed after prolonged vibration. A delay in the short-latency stretch reflex has been observed in the soleus after 15 minutes of prolonged vibration at 90Hz. It has been suggested that the delayed stretch reflex might also be due to a 'busy line' effect that causes a vibration-locked discharge to muscle spindles that makes them less responsive to muscle stretch (Bove, Nardone, & Schieppati, 2003). Eccles, Schmidt, and Willis (1962) also suggested vibration causes inhibition of the monosynaptic reflex because of depression in the excitatory post-synaptic potential (EPSP) caused from pre-synaptic depolarization. A depression in EPSP would cause a reflexive delay because transmission of the afferent signal would be prolonged due to an increase in time required to reach post-synaptic depolarization. In addition, Hayward, Nielsen, Heckman, and Hutton (1986) attributed the delay to an autogenic inhibition by more selective activation of Ib afferent fibres. It was further proposed that the selective prolonged stimulation from high frequency vibrations increased the electrical thresholds of the muscle spindle fibres. If the electrical threshold of muscle spindle fibres is increased a stronger stimuli is required to activate the fibres and would also result in a reflexive delay. Last, Curtis and Eccles (1960) proposed that prolonged stimulation causes a depression in reflexes because of depletion in transmitters at Ia afferent synapses. Decreased transmitter concentration would result in a delay because of the increased latency time to post-synaptic depolarization. There is also evidence that under constant stimulation intrafusal muscle fibres can experience glycogen

depletion and consequently fatigue. Therefore, it is also possible for fatigue to occur when muscle spindles are exposed to prolonged stimulation which would reduce spindle stretch-sensitivity and potentially be responsible for the delay seen in the stretch reflex (Banks, 2015). Furthermore, there is evidence that vibration may not only affect the targeted muscle. Since synergistic muscles have potential neural connections between each other, altered activation of synergistic muscles to the vibrated muscle has also been speculated (Shinohara, 2005). In summary, it is understood that prolonged application of vibration causes a depression in the monosynaptic short-latency stretch reflex that is explained by several mechanisms including: decreased Ia afferent resting discharge rate, increased electrical threshold of Ia afferents, a 'busy line' vibration-locked effect, depletion of transmitters in Ia afferent synapses, depressed EPSP, and glycogen depletion/fatigue. When vibration is applied to the low back for pain relief for a prolonged period of time, it is anticipated that depression of the LES stretch reflex should occur. Depression of the stretch reflex may cause a substantial increase in muscle response time to a rapid stretch, which can easily occur from a sudden trunk perturbation.

2.6 Motor Control

Motor control of the human body is extremely complex but can be segregated into three levels based on the location information is processed and the pathway from which the following response is produced. The first level consists of the spinal reflex and is the fastest motor response. This is because the sensory neurons synapse in the spinal cord and avoid a delay that would occur if the signals had to pass through the brain. It is crucial for reflexive responses to be quick because in many cases, reflexes protect the body from injury. The second level of motor control is known as the brain stem pathway.

In short, the brain receives and interprets information from the vestibular, visual, and somatosensory systems and then signals the most appropriate motor response. The third level of motor control is known as cognitive programming and consists of central voluntary commands based on repeated and stored memories (Panjabi, 1992). These levels do not function separately and are always working simultaneously to produce appropriate muscle actions and responses.

2.7 Assessing the Spinal Reflex of the Trunk: An Unexpected Trunk Perturbation

Radebold, Cholewicki, Polzhofer, and Greene (2001) assessed individual's trunk motor control and more specifically, the spinal reflex of trunk musculature using a trunk perturbation in a semi-seated, cable and pulley system. The semi-seated position was selected to isolate the trunk response by eliminating lower extremity postural control responses. This methodology was chosen to investigate trunk postural control through analysis of trunk muscle response latencies from a sudden perturbation, which reflects the stretch reflex response. Radebold et al. (2001) concluded that individuals experiencing LBP showed a delayed muscle response time to an unexpected perturbation due to a localized proprioceptive deficit in the trunk muscles. In addition, Gregory, Brown, and Callaghan (2008) found that when acute LBP developed due to prolonged standing there is also changes in trunk muscle activation patterns. It was found that once discomfort developed from prolonged standing individuals showed an increased number of responsive extensor muscles as well as an increased response in their abdominal muscles, which indicates an increase in coactivation of trunk muscles. Individuals with LBP have also demonstrated a pattern of coactivation following a perturbation where agonist trunk muscles maintain activation longer, indicating a delayed shut-off response time, while the

antagonist trunk muscles displayed an appropriately timed activation response (Cholewicki et al., 2002). Therefore, both chronic and acute LBP from standing are associated with altered trunk muscle responses to an unexpected trunk perturbation. These altered muscle responses seen in LBP individuals have shown muscle activation delays upwards of 31ms longer compared to healthy individuals. This is important because a delay in trunk muscle response latencies to a sudden perturbation increases the vulnerability of the spine to injury. Aside from previous history of LBP being the single best predictor for experiencing a future low back injury (LBI), a delayed muscle reflex to a sudden perturbation has also been shown to be a significant predictor (Cholewicki et al., 2005). For that reason, it is important to investigate the effects of a vibration-based modality on the trunk spinal reflex.

2.8 Unexpected Trunk Perturbation & Vibration

If vibration causes a localized deficit in proprioception that results in delayed muscle response latencies it may also increase an individual's susceptibility to injury while wearing the modality or shortly afterwards. Both Wilder et al. (1996) and Li, Lamis, and Wilson (2008) analyzed the effects of seated whole-body vibration (WBV) on trunk muscle response latencies to trunk flexion. Both studies found that after exposure to WBV individuals showed increased muscle response latencies and concluded that WBV impaired trunk postural control and spinal stability. Therefore, there is evidence that WBV will increase muscle response latencies however, it is unknown whether localized vibration to the low back will have a similar effect.

2.9 Assessing Voluntary Trunk Postural Control: Trunk Repositioning

Gill and Callaghan (1998) assessed proprioception in LBP individual's based on performance of a standing trunk repositioning task. The repositioning task was designed to assess proprioception during active/voluntary control of the trunk. Proprioception was assessed based on repositioning error from a target trunk position that participants were asked to reproduce. Gill and Callaghan (1998) concluded that individuals with LBP have differences in proprioception compared to healthy individuals when performing a trunk repositioning task. Since then, trunk repositioning has been investigated extensively in the LBP population and numerous studies have concluded that individuals with LBP have a proprioceptive deficit during an active trunk repositioning task (Brumagne, Cordo, Lysens, Verschueren, & Swinnen, 2000; Newcomer, Laskowski, Yu, Johnson, & An, 2000; O'Sullivan et al., 2003). However, within the literature there is also conflicting evidence that LBP individuals do not demonstrate a deficit in proprioception during a trunk repositioning task (Timm, 1999; Descarreaux, Blouin, & Teasdale, 2005; Asell, Sjölander, Kerschbaumer, & Djupsjöbacka, 2006). It is speculated that these inconsistent findings may be because of a large variance within the LBP population as well as the use of different methodologies between studies. For example, Silfies, Cholewicki, Reeves, and Greene (2007) found that LBP is not associated with poor trunk repositioning in the transverse plane but concluded it is possible that LBP may affect trunk repositioning in other planes. Afterward, Lee, Cholewicki, Reeves, Zezulak, and Mysliwiec (2010) investigated the differences between patients with LBP and healthy controls and found that trunk repositioning errors did not differ between the LBP patients and healthy controls in all three planes. In addition, Silfies et al. (2007) also concluded that there is no

relationship between trunk repositioning ability and low back injury (LBI) risk. Taken as a whole, it remains very controversial whether LBP is associated with a deficit in trunk repositioning and there has been no relationship found between a deficit and the risk of experiencing a future LBI. Although, it is clear that there are implications and risk involved when a deficit in voluntary trunk positioning is present. The trunk repositioning task still remains as a valid task for measuring active proprioception of the trunk and has been used to assess proprioception under various conditions such as vibration.

2.10 Trunk Repositioning & Vibration

The perturbing effects of vibration when applied overtop of the skin on the low back has been investigated in numerous studies. Hidalgo, Gobert, Bragard, & Detrembleur (2013) analyzed trunk repositioning under multiple disruptive proprioceptive conditions including vibration. They found that vibration at 50Hz applied for three minutes on the skin over the L3 region significantly altered repositioning ability in healthy participants. Li, Lamis, and Wilson (2008) exposed healthy individuals to WBV while seated for twenty minutes and found a 1.58-fold increase in repositioning error post-vibration. Last, Brumagne, Lysens, and Verschueren (1999) applied vibration at 70Hz to the low back for approximately five seconds and found that the vibration caused a significant muscle lengthening illusion that led to participants significantly undershooting the target position. These findings support that muscle spindles role to provide correct proprioceptive feedback is essential for accurate active trunk positioning. Overall, there is significant evidence that vibration has a detrimental effect on trunk repositioning during various durations and frequencies. However, to the knowledge of the researcher, there have been no studies that have used a vibration-based modality as the

source of vibration. It is important to investigate this phenomenon further as LBP vibration-based modality products are currently on the market. If vibration from a LBP modality alters trunk proprioception in a similar fashion to the previously mentioned studies, the effects and possible risks need to be acknowledged.

2.11 Concluding Remarks

In summary, the present study investigated the effects of a LBP vibration modality on trunk postural control. LBP is increasing in prevalence and there is a growing demand for non-pharmacologic alternatives, which has led to the production of various vibration-based modalities. Vibration has been used as a pain relief modality that is supported by the gate control theory of pain, which has various aspects that have been disproven, but nevertheless has shown to reduce pain in some circumstances. Two components of trunk postural control, the spinal reflex and cognitive programming, have been assessed in individuals with LBP and identified postural deficiencies have been correlated with an increased risk of injury. Analysis of trunk muscle response latencies to a sudden perturbation has been used to assess the spinal reflex while a trunk repositioning task has been used to assess voluntary cognitive programming. There have been no studies, to the knowledge of the researcher, that have investigated the relationship between both tasks when proprioception of the low back has been perturbed by vibration. If a deficiency in proprioception is the underlying cause of reduced performance in the sudden perturbation or trunk repositioning task, then a relationship should be present. Finally, this study added to the literature on the effects of vibration on postural control under distinct characteristics, duration, and recovery time post-vibration.

3.0 Main Purpose

The main purpose of this research project was to investigate the effects of a LBP vibration-based modality on trunk postural control in healthy controls. The effects on trunk postural control were investigated during as well as post-vibration. Trunk postural control was assessed based on trunk muscle response characteristics to a sudden trunk perturbation as well as performance in a trunk repositioning task.

4.0 Hypothesis

It was hypothesized that healthy controls would show significantly delayed muscle response latencies to a sudden trunk perturbation and significantly increased trunk repositioning error while wearing the LBP vibration modality. It was expected that muscle response latencies to a sudden trunk perturbation would be delayed to a lesser extent post-vibration in contrast to during vibration but still significantly delayed compared to pre-vibration. It was also expected that trunk repositioning error would be increased post-vibration but to a lesser extent than during vibration. These hypotheses were based on the premises that localized vibration to the lumbar region of the spine would perturb muscle spindles and consequently interfere with trunk postural control.

5.0 Methodology

5.1 Participants

	Male (n=7)	Female (n=8)
Age (years)	22.28 (3.69)	22.37 (1.40)
Height (m)	1.77 (0.03)	1.67 (0.04)
Mass (kg)	70.83 (6.12)	61.95 (5.24)

Table 1: Average (standard deviation) age, height, and mass, for male and female participants.

The present study had a total of 15 healthy participants. They were required to have never experienced low back pain that had lasted more than three consecutive days in the previous year and had no previous history of a neuromuscular, postural, visual, vestibular, skeletal, or musculoskeletal disorders. Pregnant individuals were also excluded. There were no sex specific requirements as both tasks in this study have shown to have no sex-based differences (Radebold et al., 2001; Newcome et al., 2000). All participants read and signed an informational consent form providing they understood the experiment and exclusion criteria. They were also required to provide other parameters such as age, height, and weight.

5.2 General Overview of Research Experiment

Each participant underwent both a control and experimental day that was selected in a randomized fashion. Collection periods were scheduled approximately one week apart from each other. Participants were asked to come to the research lab with a change of sport shorts and a t-shirt. Electromyography (EMG) electrodes were placed on specific muscle bellies and then maximum voluntary contractions (MVC) were recorded. Motion capture sensors were also positioned on specific vertebrae to record trunk displacement (details below).

The experimentation began with two motor control tasks: a standing perturbation and a trunk repositioning task. To create a trunk perturbation each participant held a

container away from his or her body (Figure 2) (Gregory et al., 2008). Participants were asked to pay as little of attention as possible to any perturbation cues by relaxing and focusing their eyesight directly forward. There was a sheet in front of the participants face to avoid possible peripheral visual cues. The amount of weight used to cause the perturbation was approximately 6.78kg and was dropped from approximately 2cm based on previous work that has shown that this weight and height will cause a significant trunk muscle response (Gregory et al., 2008). The magnitude of each perturbation was controlled by sufficient practice before collection began as well as examination of pilot data for relative consistency. Each participant experienced a total of five perturbations. The first trial acted as a practice trial for participants to experience the weight of the perturbation and was not unexpected. Then a following four perturbations were unexpected and recorded for further analysis. The weight was randomly dropped from a height of approximately two centimeters into the container within a ten second window to ensure the perturbation was as unexpected as possible. Muscle activation onset latency, muscle activation magnitude, muscle activation pre-perturbation, and trunk displacement were calculated for each perturbation. The time when the perturbation was applied was determined using an accelerometer that was attached to the container.

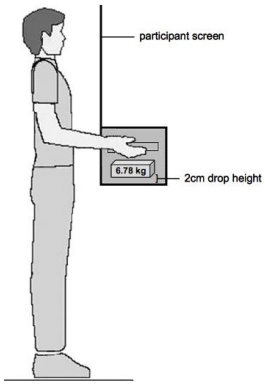


Figure 2 Trunk perturbation setup (adapted from Gregory et al., 2008).

The participants then performed a standing trunk repositioning task. The participants were told to focus on only bending at the trunk while keeping their legs as straight as possible (Figure 3). To begin, participants were taken through their complete trunk range of motion, which was recorded for normalization purposes (Newcomer et al., 2000). Each participant was then instructed to bend to a predetermined target position at approximately 45° from the horizontal. The researcher measured this angle with a manual goniometer. Participants were told to remember this target position. They were then instructed to reproduce the target position by slowly bending forward from a neutral standing position and then held their trunk position for three seconds once they perceived they had achieved the target position. They were then told to slowly extend back to their neutral standing position and hold again for three seconds. They were required to reproduce this target position three times with brief breaks in between trials for each condition. Then they were required to perform a very similar task but instead of returning to their neutral standing posture after being shown the target position they continued to move into complete trunk flexion. Then they were then asked to reproduce the target position as they extended back into their neutral standing position holding at their perceived reproduction of the target position for 3 seconds. They also performed this full flexion trunk repositioning task 3 times per condition. Participants were instructed to keep their eyes closed throughout the repositioning task to remove visual cues. Trunk repositioning error was calculated as the absolute difference between the target position and the participant's perceived target position. Repositioning error was also determined

based on relative error as well as percent error from the target position. Whether the perceived position was over- or underestimated was also recorded.

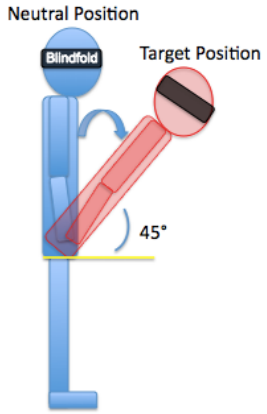


Figure 3 Example of the trunk repositioning task. Participants were required to hold for 3 seconds once they perceived they had matched the target position.

The trunk perturbation and trunk repositioning tasks were performed under three different conditions in a repeated measures format (Figure 4). Both tasks were performed pre-vibration and thus, were used as the baseline measures. On the experimental day, participants then sat in a standard desk chair for 15 minutes with the vibration modality on. The trunk perturbation and repositioning tasks were then performed again as the post-vibration condition. The participants then sat again in a standard desk chair again with the vibration modality on for 15 minutes. After 15 minutes the participants performed the trunk perturbation and repositioning tasks with the belt worn and the vibration ON which was the third condition (Figure 4). On the control day participants wore the vibration belt during both 15 minute periods of sitting as well as during the third condition; however the vibration belt was never turned on. This was done to ensure both the control and experimental days were identical aside from the vibration exposure. The vibration ON

condition collection period was positioned after the post-vibration condition to avoid any possible learning effects that could affect the results in the post-vibration condition. The vibration was at a frequency of approximately 53Hz and was worn around the torso of participants positioned so the vibration applicators were at the lumbar region of the spine.

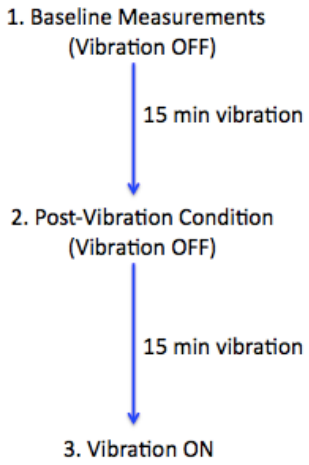


Figure 4 Procedure that participants followed during experimentation. At each condition the trunk perturbation and repositioning tasks were performed.

5.3 Data Collection

5.3.1 EMG Collection

Muscle activation was collected during the perturbation trials. Prior to applying EMG electrodes, the skin was cleaned with 70% isopropyl-rubbing alcohol and shaven if necessary. Muscle activation was collected using pre-gelled EMG Ag-AgCl electrodes (Ambu Blue Sensor, Denmark) with an inter-electrode distance of 3cm. Bilaterally, electrodes were positioned on four muscles: rectus abdominis (3cm lateral to the umbilicus), lumbar erector spinae (3cm lateral to L3 spinous process), thoracic erector spinae (5cm lateral to T9 spinous process), and the external oblique (approx. 15cm lateral

to the umbilicus) (McGill, 1991). A ground electrode was placed unilaterally on the left anterior superior iliac spine of the pelvis. All EMG was amplified (Bortec, Calgary, Alberta) and bandwidth filtered from 10-1000Hz, converted with a 16-bit A/D board, and sampled at 2048Hz.

5.3.2 Kinematics

Lumbar and thoracic trunk kinematics were recorded during both the trunk perturbation and repositioning tasks. Kinematic data was collected with an electromagnetic motion capture system (Liberty, Polhemus, Colchester, Vermont) with three sensors positioned between spinous processes C7/T1, T12/L1, and L5/S1. Sensors were firmly secured with double sided tape and were positioned when the participant was in a slight flexed posture to minimize sensor displacement from skin movement. All kinematic data was sampled at 32Hz.

5.3.3 Calibrations

After electrode setup, participants performed multiple MVCs that were used to normalize EMG data for analysis. Prior to the MVCs, EMG activity was checked and adjusted accordingly using an oscilloscope to ensure sufficient amplification and signal. To collect an MVC for the back extensor musculature, participants positioned themselves lying with their torso suspended over the edge of a physiotherapy table while a research assistant applied resistance downward. To collect abdominal MVCs a modified resisted sit-up protocol was used (Gregory et al., 2008). During all MVCs the researcher constantly encouraged participants to give their maximal effort. Last, once the motion capture sensors were setup, participants performed their full range of motion (ROM) of their trunk by undergoing a full flexion-extension trial before returning to their neutral

position. This provided information on each participants maximal spinal ROM in the lumbar and thoracic regions.

5.4 Data Processing

5.4.1 EMG Muscle Activation

EMG collected from the perturbation trials were used to determine muscle activation onset caused from the unexpected trunk perturbation. To determine baseline muscle activity, raw EMG was rectified and passed through a 2nd order low-pass Butterworth filter with a cut-off frequency of 2.5Hz (Brereton & McGill, 1998). Then average muscle activation during the 50ms prior to the application of the sudden load was calculated. The baseline muscle activation was then subtracted from a 375ms muscle response activation window post-perturbation to determine changes in muscle activity (Figure 5) (Gregory et al., 2008). Last, to determine muscle onset time following the perturbation, the rectified signal was dual-pass Butterworth filtered (low-pass 2nd-order with a 50 Hz cut-off) (Hodges & Bui, 1996). This allowed for greater accuracy for determining muscle onset because of the higher cut-off frequency. The muscle activation threshold was set at the point when muscle activity exceeded the baseline muscle activity plus three standard deviations (Gregory et al., 2008) for a minimum duration of 25ms (Cholewicki et al., 2002). The muscle offset threshold was when muscle activity fell below the baseline muscle activity plus three standard deviations for longer than 44ms (Cholewicki et al., 2002). Only muscle activation responses that fell between 15-150ms post-perturbation were considered a reflexive muscle response to the stimulus because a reflex cannot occur earlier than 15ms and muscle activity beyond 150ms is considered to be voluntary (Cholewicki et al., 2005). The actual muscle activation latency time was

calculated as the difference between the time of application of the unexpected perturbation, determined from the accelerometer, to the calculated muscle onset time. Maximum muscle activation magnitude was determined as the peak activity recorded post-perturbation from the more representative, linear enveloped EMG signal.

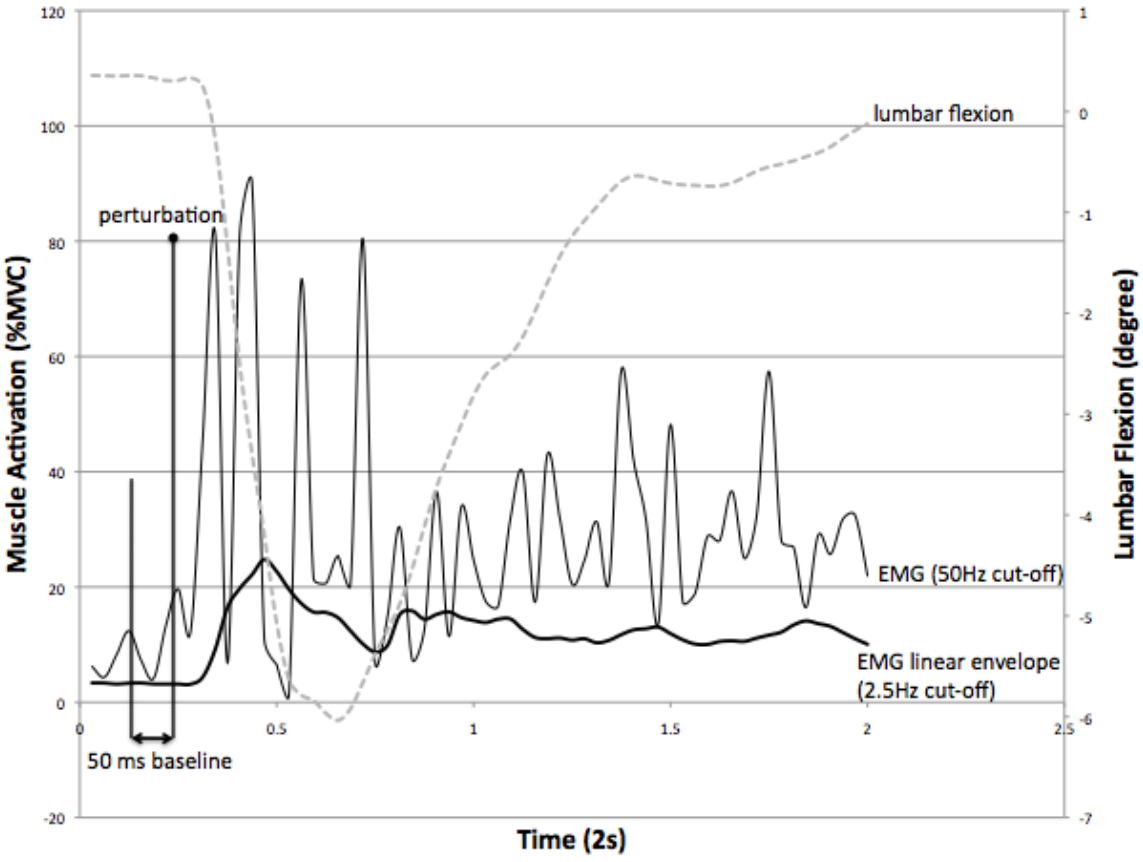


Figure 5: Example of EMG analysis and motion capture used to determine muscle activation onset, magnitude, and lumbar flexion. The dark thin line represents the EMG filtered with a cut-off frequency of 50Hz to determine muscle activation onset. The dark thick line represents the EMG filtered with a cut-off frequency of 2.5Hz to determine muscle activation magnitude. The dashed line represents the motion of the lumbar region of the spine where negative values are flexion and positive values are extension relative to each participant's neutral standing posture.

During the vibration ON condition (condition 3) the motion artifacts produced from the LBP vibration-modality on the surface of the skin produced significant noise and could not be considered negligible. If the motion artifacts caused from the vibration were not removed the muscle responses would have been inaccurate. To identify the applied vibration stimulus frequency and its harmonics, EMG was collected before and

during vibration application during a quiet sitting trial. A fast fourier transform (FFT) was used to identify motion artifacts caused by the surface vibration. Noise was then removed using a high-pass 100Hz cut-off filter (Staudenmann, Potvin, Kingma, Stegeman & van Dieën, 2007) as majority of this noise was below 100Hz. Some true EMG was filtered out during this process but the filtering was essential in order to use the EMG. Staudenmann et al. (2007) showed that using a high-pass filter with a cut-off frequency of 100Hz is still an acceptable way to filter EMG when appropriate because majority of EMG that represents force falls above 100Hz. Using a high-pass filter with a cut-off frequency of 100Hz was clearly beneficial to remove noise artifacts so the remaining EMG represented muscle activity. This filter was used on EMG for the third condition of both days even though vibration artifacts would not have been present on the control day. This was done to allow for comparison between days to avoid any discrepancy.

5.4.2 Kinematic Trunk Displacement

Trunk kinematic data was dual-pass filtered with a low-pass Butterworth filter (4^{th}-order with a cut-off of 6Hz). Trunk displacement caused by the perturbation was calculated as the difference between the lumbar spine angle prior to the application of the trunk perturbation to the maximal lumbar deflection reached post-perturbation. Maximal trunk deflection was expected to be reached around 250ms post-perturbation (Cholewicki, Simons, & Radebold, 2000).

During the trunk repositioning task, participants were assessed based on their ability to accurately and consistently reproduce a target position. Trunk repositioning was also assessed based on absolute, percent, and relative repositioning error (O'Sullivan et

al., 2003). The magnitude of repositioning error was the difference in angle between the target position and the actual position participants' perceived as the target position.

6.0 Statistical Analysis

To determine the effect of prolonged vibration exposure on trunk motor responses to a sudden perturbation and repositioning task, a 2x2 repeated measures analysis of variance (ANOVA) was conducted on day (control versus experimental) and condition (pre- versus post-vibration). To determine the effect of vibration exposure on both the sudden unexpected trunk loading and repositioning tasks, a one-way repeated measures ANOVA was conducted that compared the experimental day when the LBP vibration modality belt was turned on to the control day when the belt was worn but turned off. An alpha level of 0.05 was used as the measure of significance.

7.0 Results

In total, there were 15 participants that were tested in this research project. Each participant underwent a control and experimental day (approximately 1 week apart, randomized) consisting of a total 36 trunk repositioning trials and 24 sudden trunk perturbation trials.

7.1 The Effects of Concurrent Vibration on Trunk Motor Control

7.1.1 Sudden Unexpected Trunk Perturbation

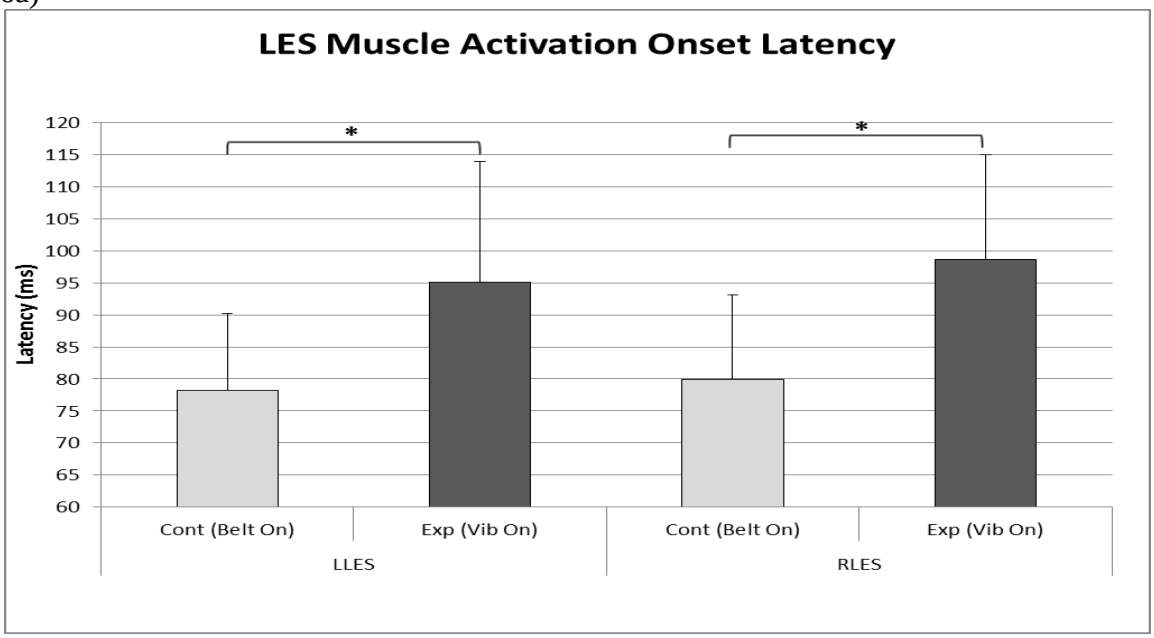
7.1.1.1 The Effect of Concurrent Vibration on Lumbar Trunk Displacement Post-Perturbation

There were no significant findings using a one-way repeated measure ANOVA in relation to the effects of concurrent vibration on trunk displacement post-perturbation.

7.1.1.2 The Effect of Concurrent Vibration on Trunk Muscle Activation Onset Latencies

When participants wore the LBP vibration belt turned on the LLES/RLES ($p<0.0001$) (Figure 6a), LEO ($p=0.03$), and REO ($p=0.0002$) (Figure 6b), displayed significantly delayed muscle activation onset latencies in contrast to when the belt was worn but turned off. Furthermore, bilaterally neither the RA nor the TES muscles showed any significant difference in respect to the effects of concurrent vibration on muscle activation onset latencies to a sudden unexpected trunk perturbation.

6a)



6b)

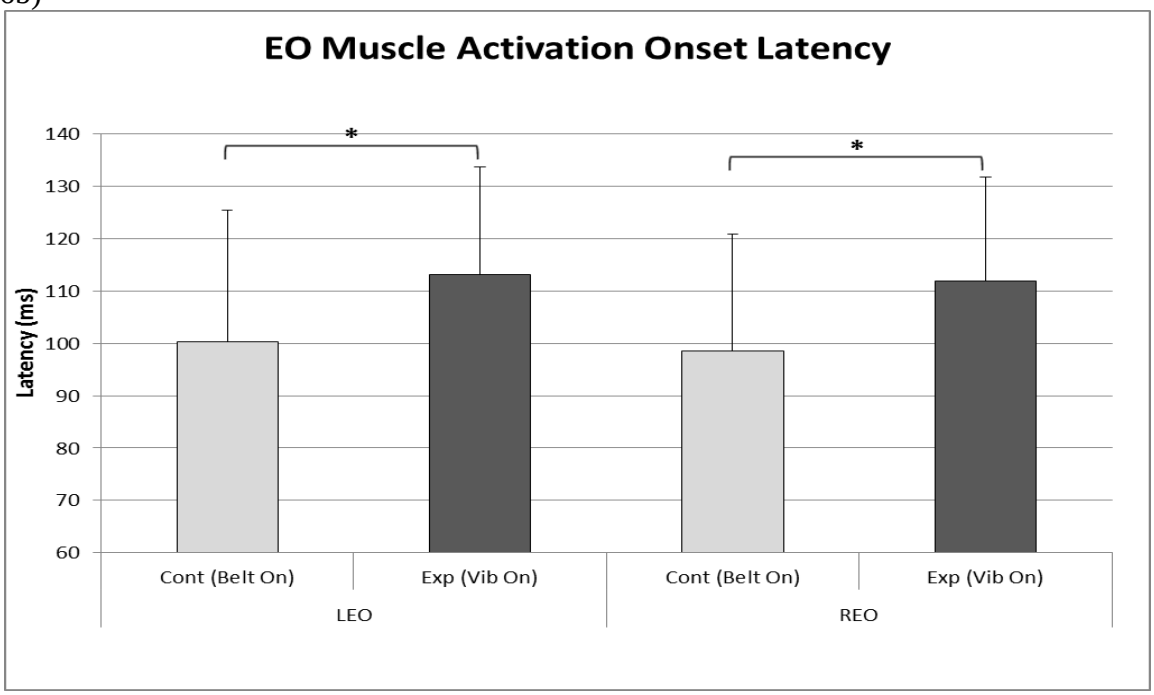
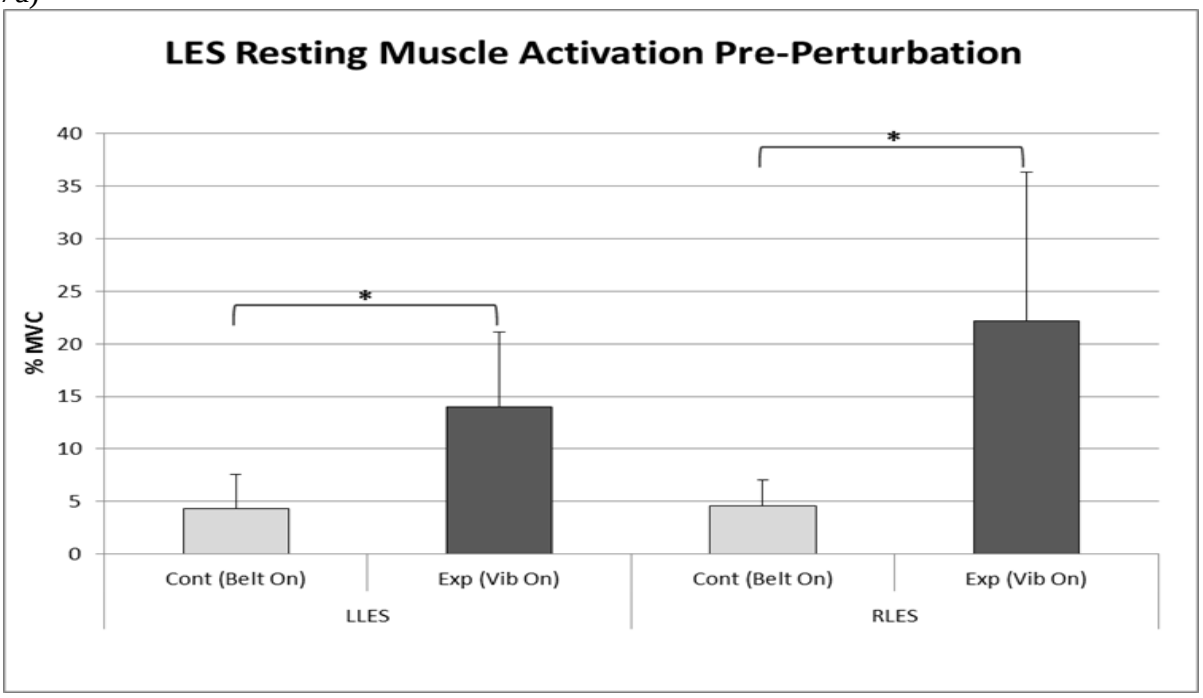


Figure 6: 6a) LLES muscle activation onset latency. 6b) EO muscle activation onset latency. When participants were wearing the LBP vibration modality belt turned on during a sudden trunk perturbation the LLES, RLES, LEO, and REO, showed significantly delayed mean muscle activation latencies. Standard deviation bars are shown.

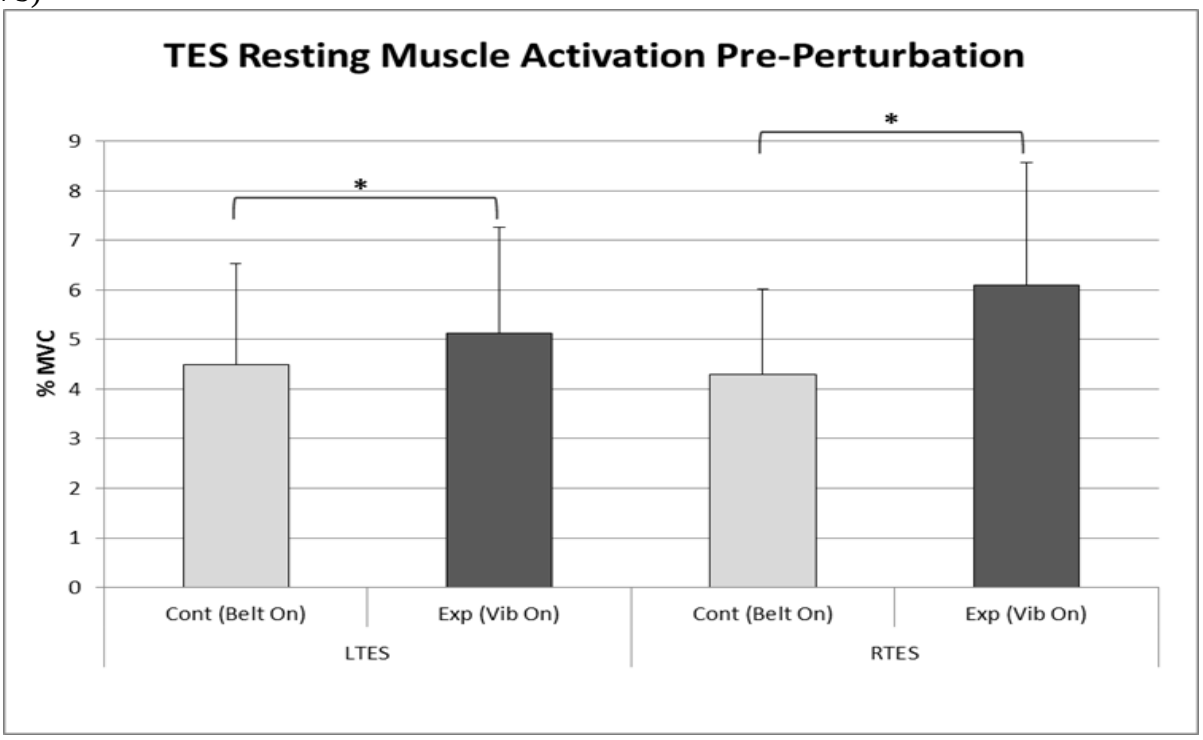
7.1.1.3 The Effect of Concurrent Vibration on Trunk Muscle Activation Both Pre- and Post-Perturbation

Bilaterally, the resting muscle activation pre-perturbation was significantly greater when participants were exposed to concurrent vibration in the following muscles: LLES/RLES ($p<0.0001$) (Figure 7a), LTES ($p=0.01$), RTES ($p<0.0001$) (Figure 7b), LEO/REO ($p<0.0001$) (Figure 7c), LRA ($p<0.0001$), and RRA ($p=0.0001$) (Figure 7d). Additionally, concurrent vibration exposure resulted in significantly reduced muscle activation magnitudes post-perturbation in the LLES ($p=0.0002$), RLES ($p=0.0003$) (Figure 8a), LTES ($p=0.0008$), RTES ($p=0.03$) (Figure 8b), LRA ($p=0.02$), and RRA ($p=0.01$) (Figure 8c). Last, a significant condition*day interaction was found for the LEO resting muscle activation pre-perturbation where the muscle showed a decrease in muscle activation on the experimental day ($p=0.04$). The REO muscle did not show any significant difference in muscle activation magnitude post-perturbation when exposed to vibration.

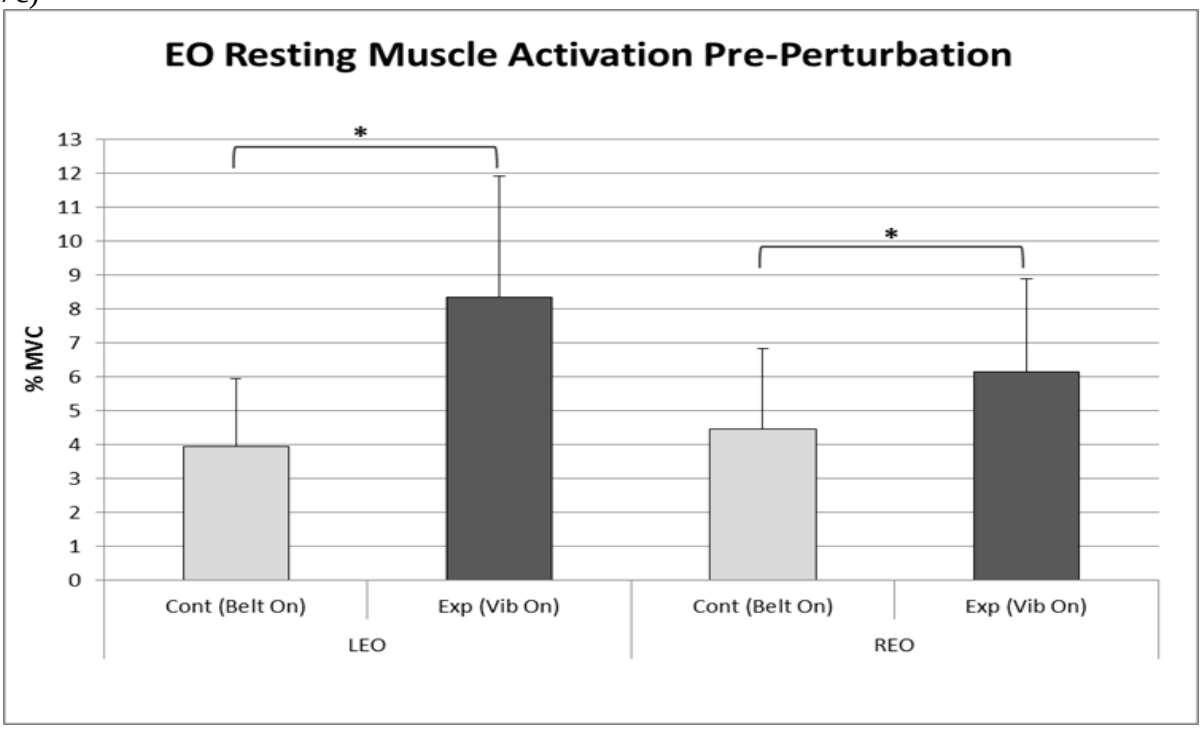
7a)


LES Resting Muscle Activation Pre-Perturbation
% MVC
40
35
30
25
20
15
10
5
0
*
*
Cont (Belt On)
Exp (Vib On)
Cont (Belt On)
Exp (Vib On)
LLES
RLES

7b)


TES Resting Muscle Activation Pre-Perturbation
% MVC
9
8
7
6
5
4
3
2
1
0
*
*
Cont (Belt On)
Exp (Vib On)
Cont (Belt On)
Exp (Vib On)
LTES
RTES

7c)



7d)

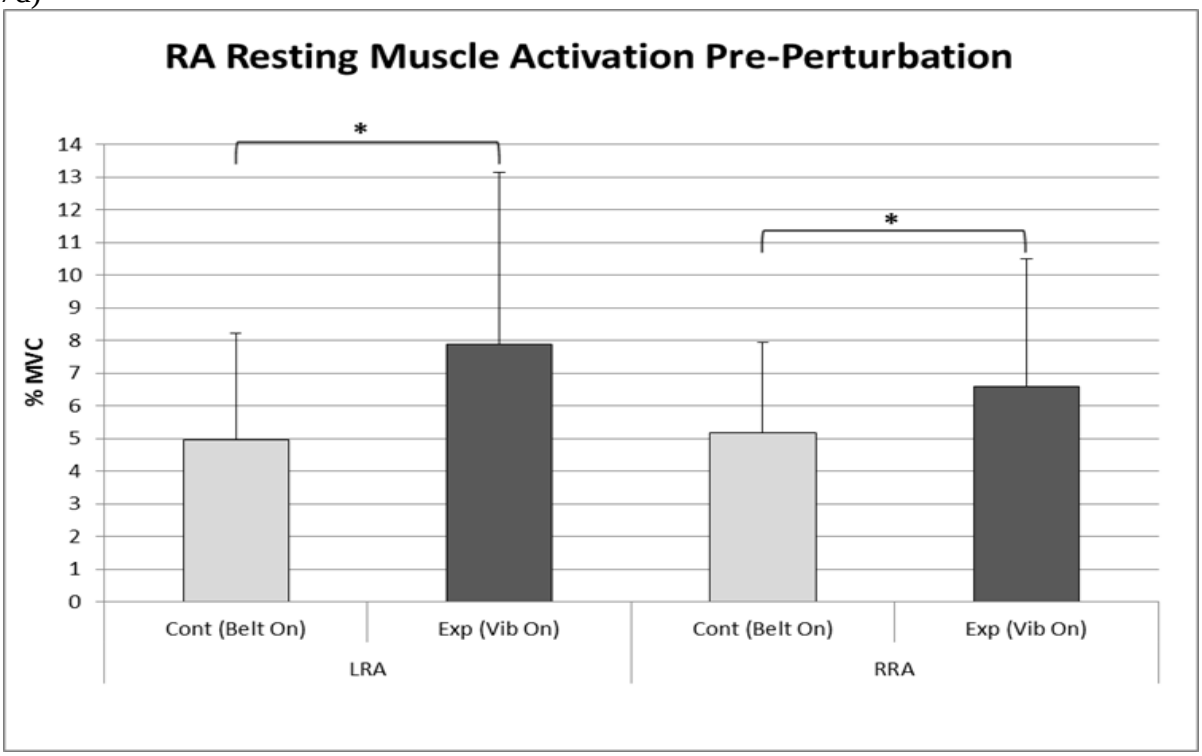
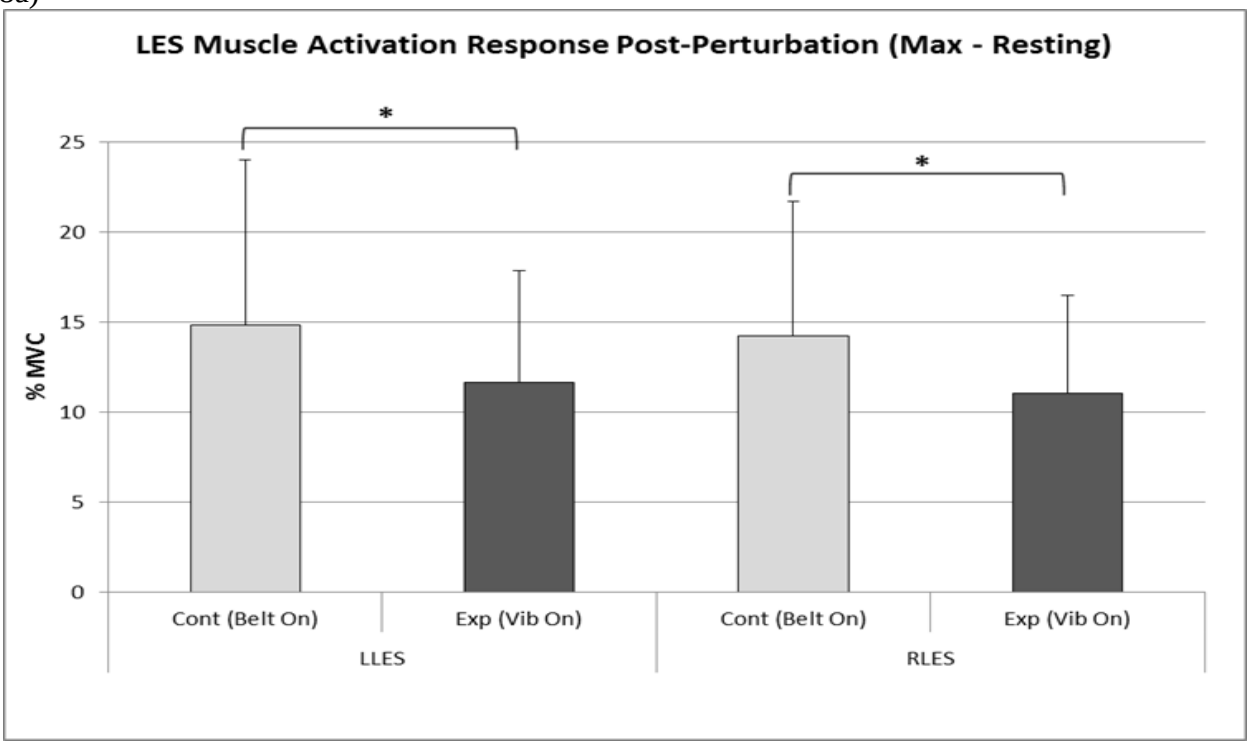
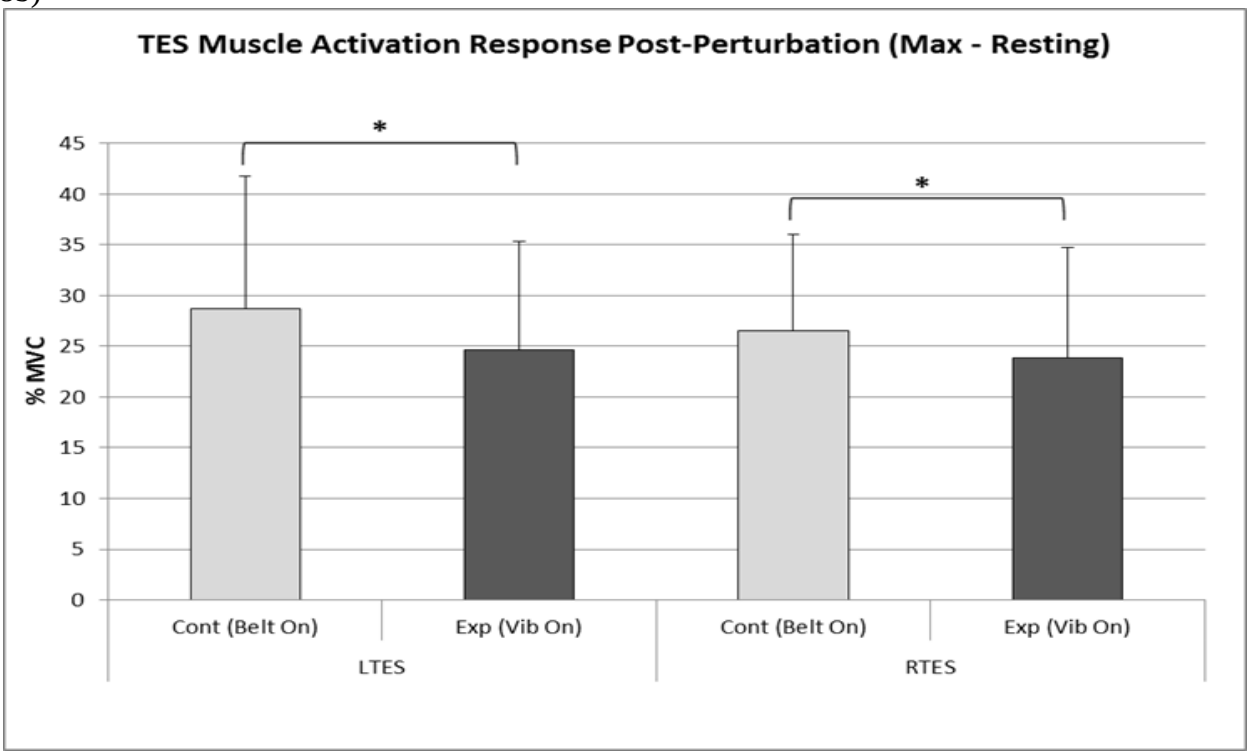


Figure 7: 7a) LES resting muscle activation pre-perturbation. 7b) TES resting muscle activation pre-perturbation. 7c) EO resting muscle activation pre-perturbation. 7d) RA resting muscle activation pre-perturbation. Bilaterally the LES, TES, EO, and RA resting muscle activations were significantly greater when the LBP vibration modality belt was turned on compared to when it was worn but turned off. Standard deviation bars are shown.

8a)


LES Muscle Activation Response Post-Perturbation (Max - Resting)
% MVC
25
20
15
10
5
0
*
*
Cont (Belt On)
Exp (Vib On)
Cont (Belt On)
Exp (Vib On)
LLES
RLES

8b)


TES Muscle Activation Response Post-Perturbation (Max - Resting)
% MVC
45
40
35
30
25
20
15
10
5
0
*
*
Cont (Belt On)
Exp (Vib On)
Cont (Belt On)
Exp (Vib On)
LTES
RTES

8c)

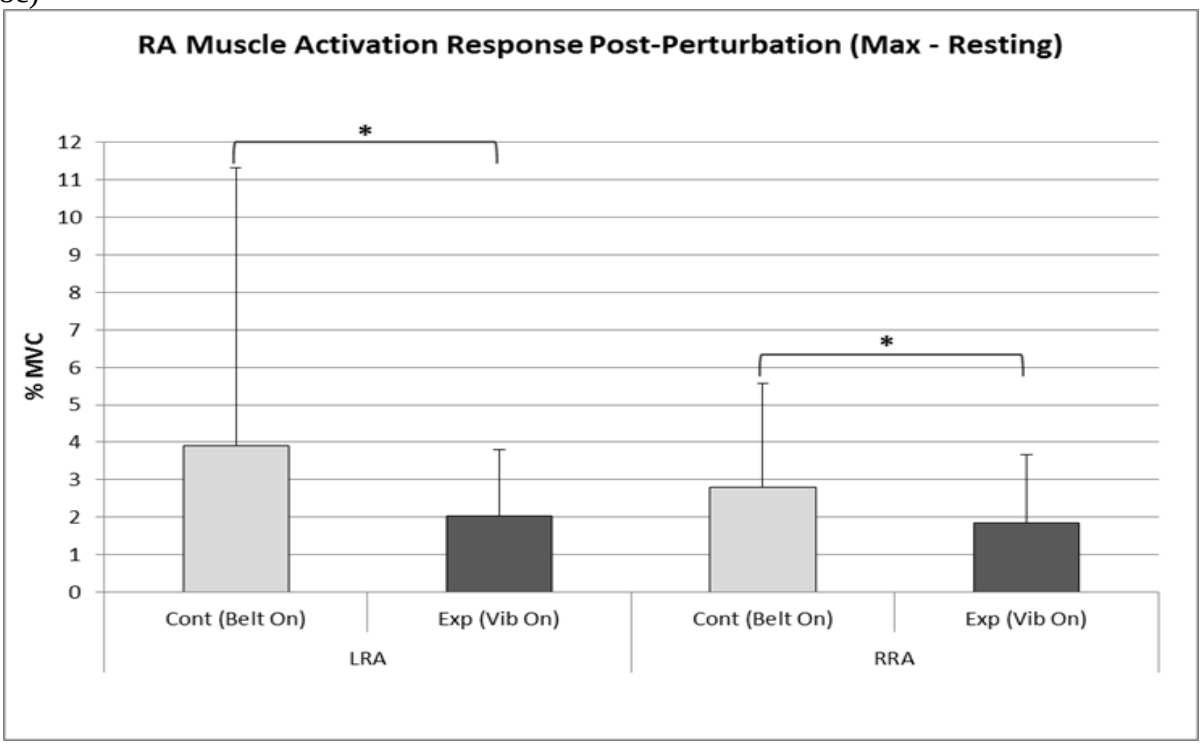


Figure 8: 8a) LES muscle activation response post-perturbation. 8b) TES muscle activation response post-perturbation. 8c) RA muscle activation response post-perturbation. When participants wore the LBP vibration modality belt, bilaterally the LES, TES, and RA muscle activation responses were significantly reduced during the vibration ON condition in comparison to when the belt was worn but turned off. Standard deviation bars are shown.

7.1.2 Trunk Repositioning Task

There were no significant findings found for all of the variables analyzed for the trunk repositioning task. Wearing the LBP vibration modality belt turned on had no apparent significant effect on the repositioning task used in this experiment.

7.2 The Effects of Sitting With and Without Vibration on Trunk Motor Control

A significant main effect in condition means that regardless of day there was a significant difference between the pre- versus post-vibration conditions when compiled together. If there is no significant interaction between control and experimental day then it can be concluded that vibration had no effect. However, this leaves the 15 minutes of sitting as the only other potential contributing factor that caused significant differences in

variables between pre- and post-vibration regardless of the day. Therefore, when a main effect in condition was found the difference was attributed to the 15 minutes of sitting.

7.2.1 Sudden Unexpected Trunk Perturbation

7.2.1.1 The Effect of Sitting on Lumbar Displacement Post-Perturbation

There was a significant main effect in condition found in the degree of lumbar trunk flexion post-perturbation ($p=0.003$). In addition, a significant condition*day interaction was found ($p=0.04$)(Figure 9). Therefore, because a significant interaction was found the significant main effect on condition can be disregarded. A post-hoc tukey analysis was performed and the lumbar flexion that occurred post-perturbation was only significantly less on the experimental day ($p<0.0001$).

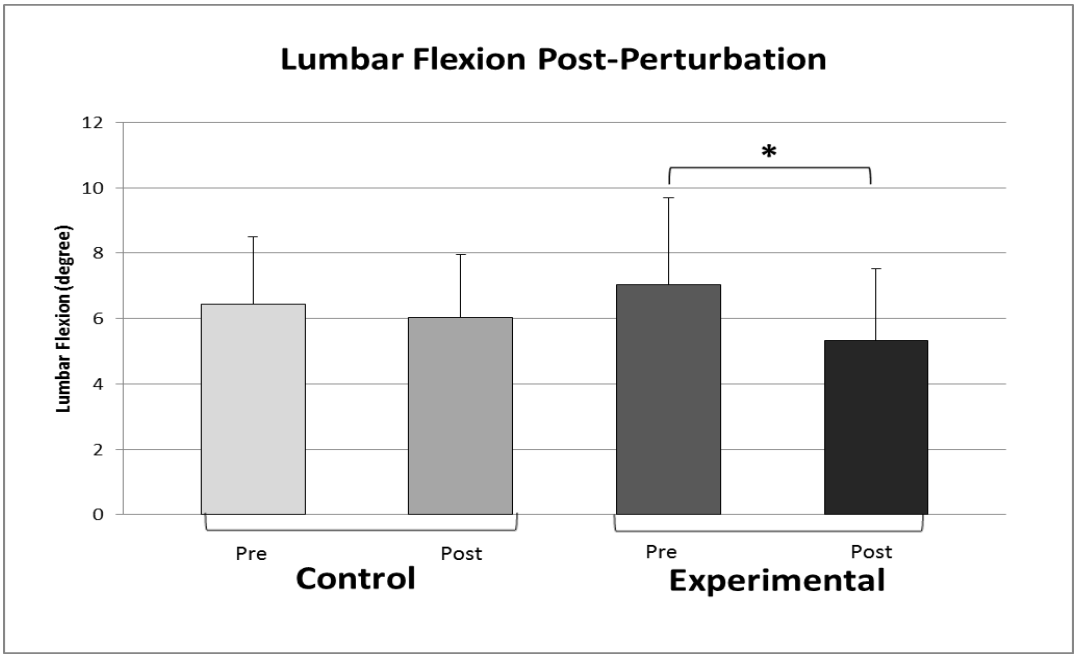


Figure 9: A post-hoc tukey analysis was performed following the significant interaction and it was determined that only on the experimental day did participants go into significantly less lumbar flexion following the sudden perturbation. Standard deviation bars are shown.

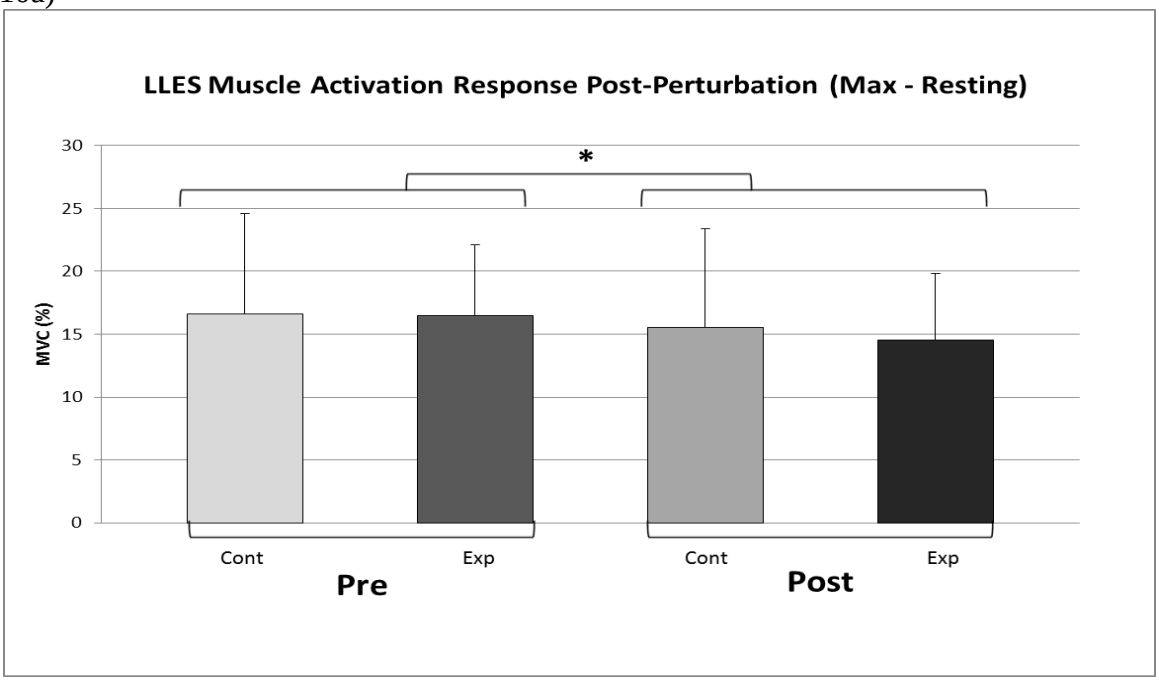
7.2.1.2 The Effect of Sitting on Trunk Muscle Activation Onset Latencies

There were no significant findings found in relation to the effects of sitting or the post-vibration condition on trunk muscle activation onset latencies.

7.2.1.3 The Effect of Sitting on Trunk Muscle Activation Pre- and Post-Perturbation

A significant main effect in condition was found for both the LLES ($p=0.0003$) (Figure 10a) and RLES ($p=0.02$) (Figure 10b) max muscle activation post-perturbation. Bilaterally the LES muscle activation magnitudes were significantly lower after a 15-minute bout of sitting despite vibration exposure on the experimental day. In addition, the REO also showed a significant main effect in condition in respect to max muscle activation post-perturbation ($p=0.03$). Last, a significant main effect in condition was also found for the LRA resting muscle activation pre-perturbation ($p=0.01$). Both the REO (muscle activation post-perturbation) and LRA (resting) displayed reduced muscle activation after a 15-minute bout of sitting. No other significant findings were found for all other analyzed muscles in regards to muscle activation pre- and post-perturbation.

10a)



10b)

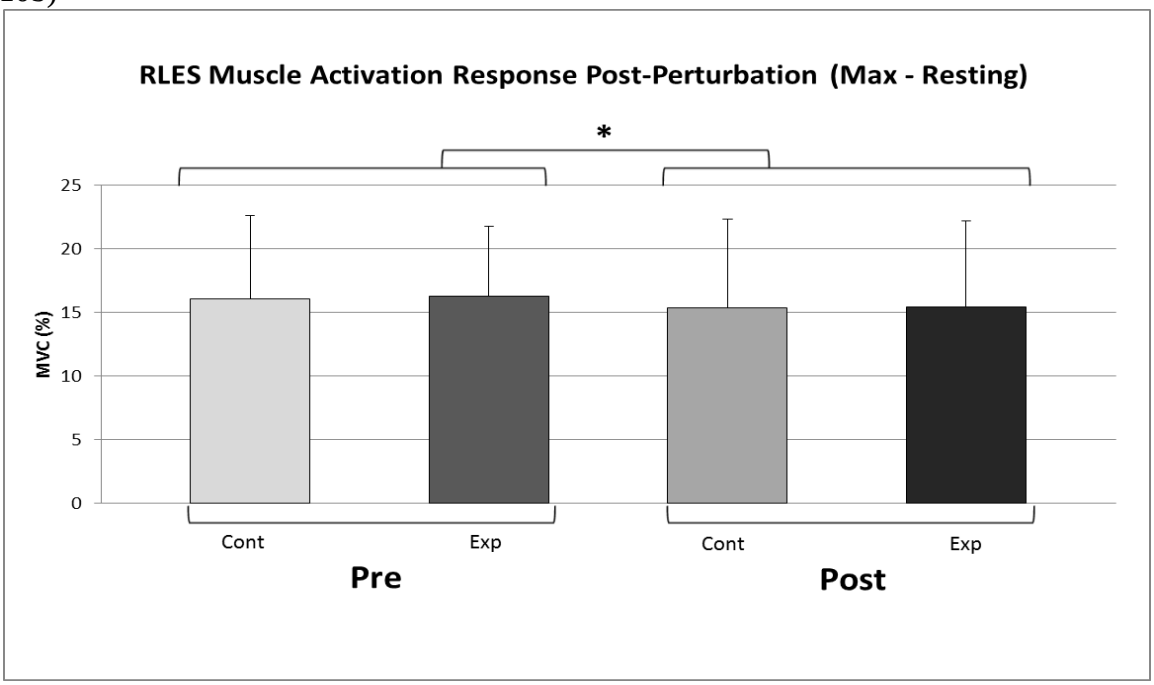


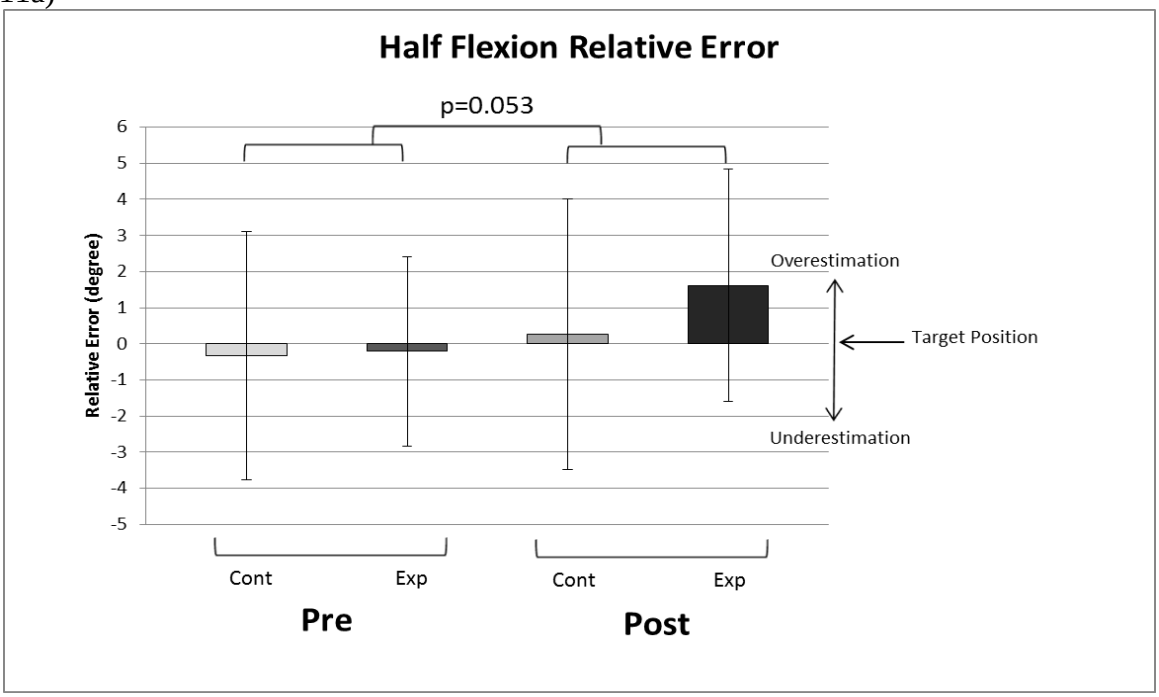
Figure 10: 10a) LLES muscle activation response post-perturbation. 10b) RLES muscle activation response post-perturbation. A significant main effect in condition was found for both the LLES and RLES in respect to mean muscle activation post-perturbation normalized to %MVC. Bilaterally the LES max muscle activation post-perturbation was significantly less post 15 minutes of sitting regardless of vibration exposure. Standard deviation bars are shown.

7.2.2 Trunk Repositioning Task

7.2.2.1 The Effect of Sitting on Relative Trunk Error

A trend towards a significant main effect of condition (pre- versus post-vibration) was found in relation to relative error during the half flexion ($p=0.053$) (Figure 11a) and full flexion repositioning tasks ($p=0.055$) (Figure 11b). There was a trend towards a more positive mean relative error after a 15-minute bout of sitting indicating that in spite of vibration exposure on the experimental day, participants on average overestimated the target position. Note that during the half flexion task participants are moving to the target position from a standing posture and during the full flexion task participants are moving to the target position from a full trunk flexion posture. Therefore, in both tasks participants overestimated the target position but the actual directional error is opposite to one another.

11a)



11b)

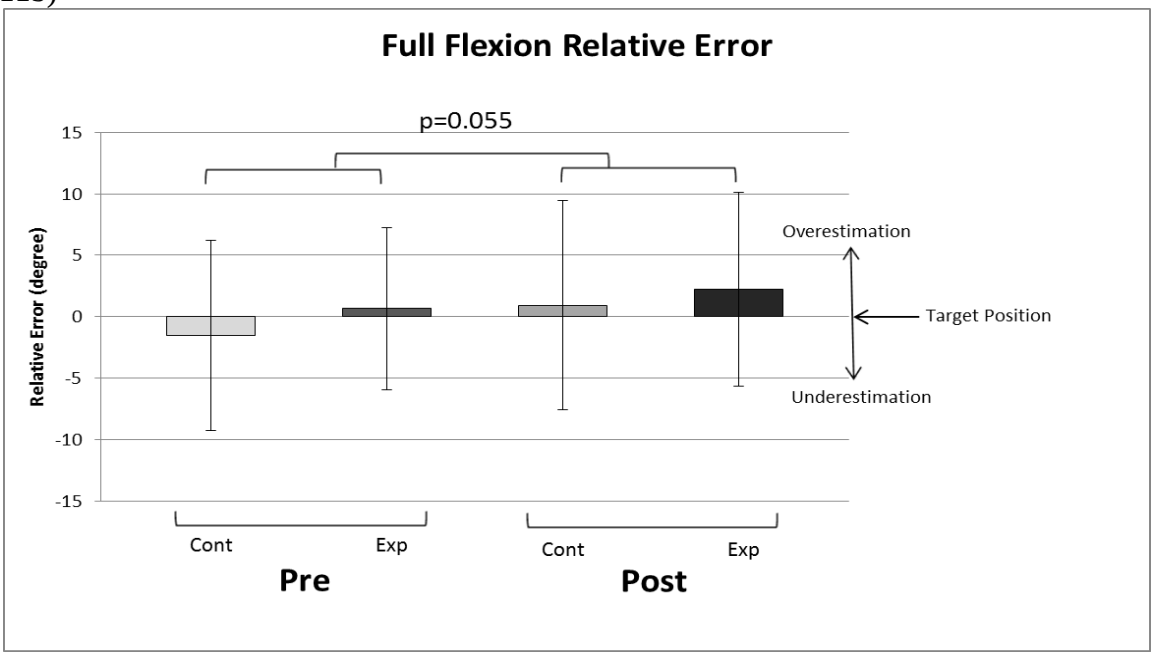


Figure 11: 11a) Half flexion relative error. 11b) Full flexion relative error. A trend towards a significant main effect of condition was found between pre- and post-vibration for both half and full flexion mean relative error during the trunk repositioning task. During both tasks participants overestimated the target position. Standard deviation bars are shown

8.0 Discussion

8.1 Purpose and Hypothesis

The therapeutic use of vibration as a LBP modality has gained evidence as an effective acute treatment (Del Pozo-Cruz et al., 2011). However, vibration is known to be a strong stimulus to proprioceptive structures and further implications need to be taken into consideration. The purpose of this experiment was to investigate the effects of a LBP vibration modality belt on trunk motor control in healthy individuals. Trunk voluntary control was assessed using a trunk repositioning task and the spinal stretch reflex was assessed using a sudden expected trunk perturbation task. It was hypothesized that the localized vibration exposure to the LES muscle group would interfere with proprioceptive mechanisms resulting in delayed muscle activation onset latencies (stretch reflex) to a sudden trunk perturbation. It was also hypothesized that vibration would increase the amount of estimated error from the target position when performing a trunk repositioning task.

8.2 Main Findings

The current study found that sitting for 15-minutes with localized vibration applied to the LES did not significantly alter trunk motor control once the vibration was turned off. Lumbar trunk flexion post-perturbation was the only exception, which showed a significant decrease post-vibration. However, profound differences were found when the trunk motor control tasks were performed with the vibration turned on compared to when it was turned off. Most notably, resting muscle activation of the trunk musculature was significantly increased when vibration was turned on. This increased muscle activation caused from vibration can most readily be explained as the tonic vibration

reflex (TVR) that states that the stimulatory effect of vibration on Ia afferents causes increased muscle activity (Santos et al., 2008). There are several important implications of these findings. For that reason the effects of concurrent vibration on trunk motor control tasks will be discussed first.

8.3 The Effects of Concurrent Vibration on A Sudden Trunk Perturbation

8.3.1 Concurrent Vibration Increased Resting Muscle Activation Pre-Perturbation

When participants wore the vibration belt turned on, the resting muscle activation pre-perturbation of the LES, TES, EO, and RA, were all significantly greater in contrast to when the belt was worn and turned off. Most notably, based on averages, the LES muscle group showed the highest increase in resting muscle activation from 4.45 to 18.09 (%MVC). This is likely because the direct point of application of the vibration from the LBP modality belt is at the lumbar spine region. However, not only was the LES muscle group affected from the vibration. The average resting muscle activation in percent MVC of the TES, EO, and RA, all showed significant increases from 4.40-5.61%, 4.20-7.25%, and 5.07-7.22% respectively. It is speculated that this vibration effect across both the EO and RA muscle groups occurred because the vibration belt was completely wrapped around participants' abdominal region. Even though the vibration applicators are located in the back of the belt to apply vibration to the lumbar region of the spine, the vibration may have travelled throughout the entirety of the belt resulting in vibration exposure to the entire trunk region. This explanation is supported by the fact that EO muscles exhibited a lesser increase in muscle activation compared to the LES but a greater increase in comparison to the RA. In all likelihood this is because the EO muscles are located in closer proximity to the source of vibration whereas the RA muscles are further

away. As vibration transmits from its source it begins to diminish quickly as it travels due to dampening. It is then reasonable to assume a weaker vibration stimulus further from the source.

The TES also displayed an increased, but marginally smaller, resting muscle activation even though there was no direct contact with the vibration belt. It is speculated that the vibration may have transmitted through anatomical structures such as skin and muscle tissue and was then able to affect adjacent muscles but to a lesser extent (Friesenbichler, Lienhard, Vienneau, & Nigg, 2014). Vibration has shown to transmit most effectively through soft tissue structures if applied at the corresponding resonance frequency of soft tissue. If vibration is applied at a greater frequency than a tissues resonance frequency there is a significant reduction in vibration transmissibility (Friesenbichler et al., 2014). Although the resonance frequency of the trunk is much lower than 53Hz, shown to be in the range of 4-8Hz, it is possible that the vibration frequency fell into higher frequency harmonics of the trunk tissue resonance frequency (Hill, Desmoulin, & Hunter, 2009). Zaidell, Mileva, Sumners, & Bowtell, (2013) also suggested that motor units synchronize to the frequency of vibration and its sub-harmonics. Therefore it could be possible that the vibration caused the TES muscle tissue to resonate at some harmonic frequency. Alternatively the vibration may have simply not been significantly dampened due to the very close proximity of the TES to where the belt was worn. In addition, previous research has found that prolonged localized vibration has also shown to have similar vibration effects across synergistic muscles (Shinohara, 2005). Therefore, it is also possible that the effects of vibration in the LES transferred to the TES muscle group through shared neural circuitry. Overall, the application of vibration at

53Hz using a LBP vibration modality belt for 15 minutes resulted in increased muscle activity of multiple trunk muscles in contrast to a control day.

8.3.1.1 The Tonic Vibration Reflex – A Possible Explanation for Increased Muscle Activity with Vibration

The significant increase in resting muscle activation found in all measured muscles can be explained as the TVR. Vibration between 30-120Hz applied to skeletal muscle has been shown to induce the TVR (Santos et al., 2008), which is characterized by an increase in resting muscle activity to greater than 5%MVC (Shinohara, 2005). A threshold of <5%MVC has been used in previous studies to ensure muscle spindles have been effectively activated from vibration in smaller muscles in the hand (Shinohara, 2005). This phenomenon can be simply explained by extensive evidence demonstrating that vibration is a powerful stimulus to Ia afferents (Rittweger, 2010). Stimulated Ia afferents then activate homonymous motor units and subsequently increase muscle activity and tension of the vibrated muscle (Shinohara, 2005). There has been speculation that the TVR may occur because the vibration stimulus may cause a positive feedback loop where gamma neurons continually stimulate intrafusal muscle fibres that enhance spindle stretch-sensitivity and subsequently increasing the firing rate of Ia afferents in response to the vibration stimulus (Banks, 2015). This may explain why the synchronous firing of motor units caused from vibration stimulation has demonstrated a long-lasting effect for over 15 minutes (Park & Martin, 1993). In addition, cutaneous mechanoreceptors have also been shown to contribute to the TVR (Abbruzzese, Hagbarth, Homma, & Wallin, 1978). For that reason, the stimulating effects of vibration on both muscle spindle Ia afferents and cutaneous mechanoreceptors causing increased

muscle activation known as the TVR can explain the rise in muscle activation found when wearing the LBP vibration modality for 15 minutes.

The stimulating effects of vibration at 53Hz from the belt fell into the range of frequencies known to cause the TVR. This appears to be the most reasonable explanation for the increase in resting muscle activity found as 7 of the 8 muscles collected displayed less than 5%MVC with no vibration and greater than 5%MVC with vibration. Only the RRA showed slightly greater than 5%MVC with no vibration, however, this may be due to activation required for postural stability while standing and holding a bucket. Therefore, it should be noted that the EMG recordings were not a true measurement of resting muscle activation because some level of activation is required to maintain postural stability in an upright standing posture. Previous research by Ringheim, Austein, Indahl, and Roeleveld (2015) investigated trunk muscle activation when standing in a neutral posture and found that RA muscle activity can range from 2.5-5.5%MVC. Therefore the additional muscle activity found can be attributed to the maintenance of postural control.

The current study found a stronger effect of the TVR compared to previous literature. Åström, Lindkvist, Burström, Sundelin, and Karlsson (2009) targeted the trapezius muscle with vibration of 10Hz and only saw an increase in resting muscle activation from 3.8 to 5%MVC. This discrepancy in muscle activity most likely occurred because a lower frequency of vibration was used than what has been shown to elicit the TVR (Adamo, Martin, & Johnson, 2002; Santos et al., 2008). In addition, Zaidell et al. (2013) applied vibration with a frequency of 50Hz to elicit the TVR in the soleus and found the reflex to be enhanced when the leg was loaded. Therefore the stronger TVR seen in the current study may have also been because the trunk musculature was loaded in

order to maintain the weight of the upper body in an upright standing posture. Overall, the present study found a more prominent TVR in comparison to previous research but can be attributed to variations in frequencies used and the enhancing effects on the TVR when a muscle is loaded.

8.3.2 Concurrent Vibration Decreased Muscle Activation Post-Perturbation

When participants wore the LBP vibration modality belt turned on the LES, TES, and RA, displayed significantly lower increases in muscle activation magnitude post-perturbation. Given that the pre-perturbation activation levels were already higher with vibration, it is presumed that a comparatively smaller change in muscle activation was needed in response to the perturbation.

The LES, RA, and EO, also reached higher peak muscle activation magnitudes post-perturbation on the experimental day. Although not statistically significant, this may be meaningful because more muscle activity and inherently greater force was required to re-stabilize the trunk post-perturbation. Slota, Granata, and Madigan (2008) found increased instability of the trunk when performing an unstable sitting task after WBV. This increased spinal instability was attributed to a reduction in passive stiffness in the trunk. WBV has shown to accelerate creep deformation in intervertebral discs and subsequently affect postural control and spinal stability of the trunk (Slota et al., 2008). Several other studies have also speculated that vibration can cause significant changes in the mechanical and viscoelastic properties of the lumbar intervertebral disc leading to spine instability (Wilder, Pope, & Frymoyer, 1988; Arora, Graham, & Grenier, 2015). Therefore, if the spine was less stable prior to the perturbation, greater muscle activation and inherently force would have been required to re-stabilize the trunk.

Trunk stiffness was not measured in the present study so it cannot be assumed that trunk instability actually occurred. Previous research by Brown and McGill (2010) demonstrated that increased trunk muscle activity is directly proportional to increased trunk stiffness. As previously mentioned, vibration caused an increase in resting muscle activity and therefore an increase in trunk stiffness should have also occurred. If the trunk was stiffer prior to the perturbation then the trunk would have went into less flexion post-perturbation. This contradicting evidence for trunk stiffness and stability may explain why there were no significant findings for the trunk deflection post-perturbation. These factors may have counteracted each other resulting in no difference between the vibration on and off conditions.

8.3.3 Concurrent Vibration Delayed Muscle Activation Onset Latencies

Bilaterally the muscle activation onset latencies of the LES (17.74ms) and EO (13.14ms) were significantly delayed when the LBP vibration modality belt was turned on. Though not statistically significant, on average the TES and RA also displayed delayed muscle activation onset latencies (Appendix A). It is speculated that the LES and EO were more affected due to their proximity to the source of vibration.

There have been several speculations as to why prolonged vibration to muscle spindles causes a delayed spinal stretch reflex. One notion being that the prolonged repetitive stimulation of the vibration on Ia afferents causes a decreased resting discharge rate and thus, depressing Ia afferents (Ribot-Ciscar et al., 1998). This would cause the muscle spindles to become less responsive to stimulation. However, because the TVR was present it is unlikely that the muscle spindles were depressed. Another speculation by Bove et al. (2003) is that the stretch reflex is delayed due to a vibration ‘busy line’ effect

that causes a vibration-locked discharge of muscle spindles that makes them less responsive to muscle stretch. This seems to be a plausible explanation for the delayed reflex found given that when the perturbation occurred the Ia afferents would have been synchronously firing with the vibration frequency. Thus, when the Ia afferent was presented with a second stimulus it may take it longer to detect, activate, and create an appropriate response because it would have been preoccupied continually responding to the vibration stimulus. This would ultimately result in the delayed muscle activation response latency observed. Alternatively, Shinohara (2005) hypothesized that prolonged sustained force caused by the TVR may result in failure in the excitation-contraction coupling mechanism similar to what occurs under prolonged low-force contractions (Enoka & Stuart, 1992). Similar MVC force reductions have been observed between prolonged voluntary muscle contractions and heightened muscle activity from the TVR. Kouzaki, Shinohara, and Fukunaga (2000) found a reduction in MVC force by nearly 10% during a knee extension task by eliciting the TVR with 30Hz vibration for 30 minutes. A prolonged contraction as low as 2.5%MVC for 60 minutes has shown to reduce maximum force during an MVC (Shinohara, 2005). Therefore, it is possible that failure in the excitation-contraction coupling mechanism resulted in the delayed stretch reflex observed. There has also been speculation that the golgi tendon organs (GTO) may also play a role in the inhibition of stimulated Ia afferents (Shinohara, 2005). Although, Shinohara (2005) concluded that GTOs playing a role in the inhibition of Ia afferents is unlikely as the effect was not apparent uniformly across muscles. Therefore, the delayed muscle activation onset latencies observed can be attributed to either the ‘busy line’

phenomenon, and/or due to failure in the excitation-contraction coupling mechanism (Bove et al., 2003; Shinohara, 2005).

Bove et al. (2003) applied vibration at 90Hz for 15 minutes to the soleus and found a significantly delayed stretch reflex by roughly 3ms on average. Similarly, Arora and Grenier (2013) applied WBV at 3Hz for 45 minutes and found an average delay of roughly 7ms in the LES. These findings are both very small delays in relation to the current study. However, Li et al. (2008) measured time to peak LES muscle magnitude after exposure to WBV of 5Hz for 20 minutes and found an increased delay of 23ms. This discrepancy in delays can most likely be attributed to the amount of variability in the effects vibration can have at differing frequencies, amplitudes, duration, mode of application, as well as on varying muscles (Bove et al., 2003; Krajnak et al., 2012; Li et al., 2008; Santos et al., 2008). In addition, the majority of studies analyze the effects of vibration on less complex structures than the lower back. The lower back contains multiple musculotendinous layers and degrees of freedom that make it a much more complex structure in contrast to a single monoarticular muscle (Boucher, Normand, & Descarreaux, 2013). Overall, the present study found greater delayed muscle activation latencies compared to previous studies likely due to variability between study protocols and vibration exposure type.

8.3.4 The Effects of Concurrent Vibration on a Trunk Repositioning Task

There were no significant differences in performance of the trunk repositioning task when vibration was applied to the lumbar spine region. Hidalgo et al. (2013) and Brumagne et al. (1999) found that localized vibration applied to the lumbar spine region can increase trunk repositioning error from a target position. Li et al. (2008) also found an

increase in trunk repositioning error after 20 minutes of WBV. The current study may have not found a similar detrimental effect of vibration because of differences in protocols. The previous studies mentioned isolated the trunk using a sitting trunk repositioning task whereas the current study used a standing trunk repositioning task. Additional joints including the ankle and knee provide proprioceptive feedback to maintain postural control when standing. If the vibration compromised LES proprioceptive feedback other sources of proprioceptive feedback from the lower extremities may have been able to provide sufficient kinesthetic information to the CNS. Therefore a similar deficit may have not been seen due to compensation from other joint segments.

8.4 Post-Vibration Effects on Trunk Motor Control

No significant findings were found with respect to the sudden unexpected trunk perturbation or repositioning task post-vibration. This can most likely be attributed to the fact that muscle spindle Ia afferents are fast-conducting and inherently fast-adapting. Therefore once the vibration was turned off, there was only a small window of time before the effects of vibration wore off (Wilder et al., 1996). Previous research has found that the effects of vibration diminish in less than 50 seconds (Arora & Grenier, 2013). To examine this further a related t-test was used to determine if the response to the first trunk perturbation trial after the vibration was removed was different than the last (4^{th}) perturbation trial post-vibration. No significant differences were found suggesting that the muscles spindles had likely fully recovered from the vibration exposure before the post-vibration testing had begun.

8.5 The Effects of Sitting on Trunk Motor Control

8.5.1 The Effects of Sitting on Trunk Muscle Activation Post-Perturbation

The LES showed significantly reduced muscle activation post-perturbation on both the control and experimental day indicating that 15 minutes of sitting, opposed to the vibration, may be the cause of this change. It is hypothesized that the reduced muscle activation found could have potentially occurred because when sitting the LES is in a semi-stretched position compared to when standing. Kallio, Linnamo, and Komi (2004) found that lengthening the soleus muscle before a sudden stretch can reduce the muscle response amplitude. It was hypothesized that a lengthened muscle may cause an increase in the inhibitory activity of GTOs, which would result in reduced muscle tension and inherently muscle activation. Cramer et al. (2005) found a decrease in EMG amplitude from the stretch reflex after repeated passive stretching in several lower extremity muscles. In relation to the present study, if the LES were slightly stretched while sitting for 15 minutes, it may have been possible that the LES muscle tissue experienced creep, making it less responsive to stretch. Additionally, this may have also increased the inhibitory effect of GTOs contributing to the reduced muscle activation seen.

8.5.2 The Effects of Sitting on Lumbar Displacement Post-Perturbation

On both the control and experimental day the trunk went into less lumbar flexion post-perturbation after sitting for 15-minutes. On the experimental day the trunk went into significantly less lumbar flexion compared to the control day. It is unknown as to why the trunk deflected into less lumbar flexion after sitting for 15 minutes with and without vibration. Based on all the variables collected and analyzed there is no clear explanation for this finding. One speculation could be that participants began to anticipate

the unexpected perturbation. Lumbar flexion pre-perturbation did move into slightly more extension during the post-vibration testing period. It can be assumed that the participants' may have extended their trunk in anticipation of the sudden load. However, lumbar flexion pre-perturbation was not significantly different from pre- to post-vibration.

8.5.3 The Effects of Sitting on Trunk Repositioning Relative Error

When performing both the half- and full-trunk flexion repositioning tasks on both the control and experimental day participants overestimated the target position after sitting for 15 minutes. This was demonstrated by significant changes in relative error. During the half-flexion task, as participants approached the target position, they perceived their LES muscle length to be shorter than its true length leading to an overestimation. During the full-flexion task, as participants approached the target position, they perceived their LES muscle length to be longer than its true length resulting in an overestimation. Therefore, the effect observed was dependent on whether the muscle was shortening or lengthening. It is unknown what could be causing this increased repositioning relative error following an acute bout of 15-minutes of sitting. However, it has been speculated that 60 minutes of sitting may have the potential to influence back muscle postural balance and even cause fatigue (Santos et al., 2008). This may be important as LES fatigue has been shown to affect trunk repositioning performance (Boucher et al., 2012). However, it is unlikely that an acute bout of sitting for 15 minutes would cause significant muscular fatigue.

The Increased relative error observed after 15 minutes of static sitting may have been due to creep of soft tissues. Creep has been shown to desensitize muscle spindles making them less responsive to stretch. A greater stimulus or degree of stretch is then

required to activate and initiate muscle spindle firing (Sánchez-Zuriaga, Adams, & Dolan, 2010). Therefore proprioceptive feedback from muscle spindles may have been compromised resulting in the increased relative error observed. Magnusson et al. (1990) demonstrated that acute bouts of sitting for 5 minutes can induce creep in intervertebral discs resulting in decreased vertical height. Additionally, creep can occur in soft tissues such as tendons, muscles, ligaments, and fascia when subject to stretch (Sánchez-Zuriaga et al., 2010). Creep has shown to occur in the lumbar soft tissue under short durations of stretch or from frequent cycles of flexion. Supporting the trunk mass alone while performing a trunk flexion task can cause creep in the lumbar spine and an additional external load is not necessary (Bazrgari et al., 2011). Therefore, repetitively going into trunk flexion during the trunk repositioning task throughout the experiment in combination with 15 minutes of sitting may have induced creep in soft tissues in the lumbar region. This serves as another possible explanation as to why increased relative error occurred.

8.6 Clinical Relevance of Findings

8.6.1 The Effects of Vibration on Trunk Muscle Fatigue

Several definitions of muscular fatigue appear in the literature but for the purpose of this study fatigue will be defined as “an exercise-induced reduction in maximal voluntary muscular force” (Gandevia, 2001). However, muscular fatigue can also be detected through EMG activity as it is characterized specifically by a decrease in mean frequency with a simultaneous increase in amplitude (Åström et al., 2009). Even though fatigue was not measured in this study, it is known that there is a type of fatigue quantified by low-frequency stimulation of muscles. This type of fatigue has been labeled

as low-frequency fatigue (LFF) (Adamo et al., 2002). LFF is supported by the Cinderella hypothesis, which states that motor units with low activation thresholds maintain activated from low to maximal muscle activation magnitudes and without sufficient rest periods will experience metabolic overload, fatigue, and subsequent pain perception (Adamo et al., 2002). Therefore, a vibration induced increase in facilitatory drive and subsequent TVR may cause low activation threshold motor units to be continuously firing and sequentially lead to fatigue. Several studies have found that the increase in muscle activity caused from repetitive 1 minute cycles or sustained 30 minutes of vibration exposure can contribute to muscle stress, reduced MVC force, and can accelerate muscle fatigue (Martin & Park, 1997; Kouzaki, Shinohara, & Fukunaga, 2000; Park & Martin, 1993). In addition, sustained low force exertions at 5%MVC combined with vibration have shown to exacerbate fatigue due to failure in the excitation-contraction coupling mechanism (Adamo et al., 2002). Furthermore, Hansson, Magnusson, and Broman (1991) found that LES fatigue was accelerated and amplified after exposure to WBV at 5Hz. Therefore, even though back muscles are well equipped for prolonged postural loading/sustained muscle contractions, there is sufficient evidence suggesting that prolonged vibration exposure can lead to muscle fatigue and can accelerate the fatiguing process when maintaining low levels of muscle activation required to maintain an upright posture (Fallentin, Maikala, Banks, Obrien, & Rivard, 2012).

If wearing the LBP vibration modality belt for a prolonged period of time can induce fatigue in the trunk muscles, there are several implications that should be considered. To begin, fatigued back muscles have shown to result in diminished control of trunk movements, altered coordination of trunk muscle activities, and reduced ability

to accurately produce a target force (Boucher, Abboud, & Descarreaux, 2012; Parnianpour, Nordin, Kahanovitz, & Frankel, 1988; Sparto et al., 1997). Most importantly, excessive fatigability of the LES muscles has been shown to be a predictor for experiencing a first episode of LBP as well as long-term back-related disability (Biering-Sorensen, 1984; Enthoven, Skargren, Kjellman, & Öberg, 2003). Thus, trunk motor control can be compromised after vibration exposure due to the risk of fatigue leaving the spine at a greater risk for injury (Santos et al., 2008). If a vibration modality belt is worn for a prolonged period of time, there is significant evidence to suggest that vibration may cause LFF of the LES and consequently increase individuals' susceptibility of experiencing LBP. If an individual was to wear the vibration belt and afterwards immediately perform a strenuous activity such as lifting something heavy or experience an unexpected perturbation, they may be putting themselves at a high risk for injury. Based on this study it is unknown if fatigue of the LES muscles occurred after wearing the vibration belt for two short 15-minute intermittent periods. Regardless, potential precautionary measures should be put into practice to avoid fatiguing of back muscles by limiting amount of time the vibration belt is worn or by giving ample time for recovery after vibration exposure.

It should be noted that individuals who experience chronic LBP have adapted postural control strategies and may respond differently compared to healthy controls. Individuals with chronic LBP have shown a reweighting of their proprioceptive input away from their low back by increasing the gain of other joints (ex. ankle). Therefore, it can be speculated that they may be less affected by localized vibration exposure to the lumbar region and the present results may not be transferable to those who experience

chronic LBP (Brumagne, Cordo, & Verschueren, 2004). Although, individuals who experience acute LBP, for example from prolonged standing, have not demonstrated proprioceptive reweighting (Gregory et al., 2008). For that reason the results of the present study are most likely transferable to individuals who experience acute LBP. This is important because it may be more likely for individuals who are experiencing acute LBP to use this vibration modality as it only provides short-term pain relief. Individuals who experience chronic LBP are more likely to seek professional help and be given more long-term pain relief modalities. Therefore, the transferability of the results in the present study need to be considered as the tests were performed on healthy controls but, the findings are most likely transferable to the target audience that would use this modality.

8.6.2 The Effects of Vibration on Trunk Postural Control

Compromised trunk postural control when wearing the vibration belt is a serious implication that should be taken into consideration. Delayed muscle activation onset latencies have been shown to be a significant predictor for a future LBI (Cholewicki et al., 2005). Therefore, based on these findings it is important for individuals to not put themselves in high-risk situations for a sudden perturbation when wearing the vibration belt. It is important to understand that if an individual was to experience a sudden trunk loading while wearing the belt they may be at a high risk for experiencing a LBI. An example of this could be when an individual is working in a shipping department and attempts to pick up an unexpectedly heavy box that puts a suddenly greater load on the lumbar spine. This is important because previous history of LBP is the single best predictor for experiencing a future LBI or LBP (Cholewicki et al., 2005). It is therefore extremely critical to have precautionary measures in place to avoid a first incident from

occurring due to the high reoccurring rate. A conservative recommendation would be to either lay or stay in a seated position while wearing the vibration belt to decrease any likelihood of a perturbation from occurring.

8.7 Limitations

There are several limitations to be considered for the present study. To begin, all trunk perturbations were considered to be sudden and unexpected. However, it needs to be acknowledged that only the first trunk perturbation is truly unexpected. Milosevic et al. (2015) found that anticipation of direction and timing of a trunk perturbation can increase the reflex response up to 16.8ms. The direction of the perturbation did not change in the present study and was therefore known by the participants. The latencies in the present study were slightly faster compared to previous work using the same perturbation method but there are noted differences between procedures that may also account for this discrepancy (Gregory et al., 2008). Another limitation in the present study is the stabilizing effect of touch during exposure to vibration. Maaswinkel, Veeger, and van Dieën (2014) found that touching an object with the hand provides additional proprioceptive information. Touching an external object when being exposed to lumbar paraspinal muscle vibration has shown to significantly reduce the effects of vibration (Maaswinkel et al., 2014). In the present study participants held a bucket during the sudden perturbation task that could have potentially provided additional feedback and reduced the effects of the vibration belt. Although significant findings were found during the vibration condition the additional feedback provided may have been sufficient to hide any effects post-vibration.

There was also a limitation in regards to the repositioning task selected for this study. All trials had a target position of 45° from the horizontal. Therefore, after performing a total of 6 trials for each condition participant's memory of the position may have become a contributing factor when estimating the target position. This was avoided as much as possible by having the participants alternate between half- and full-flexion trials. It is also noteworthy that when asked about the repositioning task at the end of the study, the majority of participants reported that it was difficult to distinguish if trials were the same target position. Majority of participants also reported that the full-flexion trial was more difficult. Thus, the repositioning task was most likely too difficult and varying to allow for memory to play a significant role.

In regards to data filtering there are some unavoidable limitations to be considered. To begin, it should be recognized that digital filters are limited in their ability to cut-off completely at any chosen cut-off frequency. Most importantly, it needs to be recognized that the vibration EMG data was filtered at a different cut-off frequency to remove noise artifacts. The EMG data collected when the vibration belt was turned on was filtered with a high-pass 100Hz cut-off filter prior to the low pass filter. This filter was used to ensure all mechanical and electrical noise produced from the vibration belt was removed. The frequencies of noise artifacts produced from the vibration belt were mainly around 60Hz that was determined using an FFT. Staudenmann et al. (2007) determined that a high-pass filter with a cut-off frequency of 100Hz could be implemented without removing any significant EMG data representing muscle activity. Therefore, even though a different filter was required to filter the vibration EMG data, the amount of muscle activity found in the EMG should not have been significantly affected.

8.8 Future Research

Based on the findings in the present study several recommendations can be made in terms of the direction for future research. To begin, future research could investigate if indeed the LBP vibration modality belt can cause muscular fatigue and if so, what durations of vibration exposure can induce this fatigue. Additional thoughts may lead to investigating recovery time from vibration induced fatigue as there is some research speculating that LFF can last up to 24 hours (Adamo et al., 2002). Last, future research may also continue to investigate the effects of sitting on the both the sudden trunk perturbation and trunk repositioning task. It would be interesting to explore the effects of sitting for a prolonged period of time and if it has any effect on trunk motor control.

9.0 Conclusion

The current study investigated the effects of a LBP vibration modality belt on trunk motor control. Motor control was assessed using a sudden unexpected trunk perturbation and trunk repositioning task. Changes in trunk postural control were only observed during concurrent vibration as once the vibration was removed no noteworthy differences were found. Concurrent vibration resulted in delayed muscle activation onset latencies as well as potentially elicited the TVR. These findings have important implications as they provide insight into how vibration can compromise trunk motor control. Vibration is a highly excitatory stimulant to muscle spindles, specifically the Ia afferents, and interferes with their ability to function properly. Proper muscle spindle function is essential for providing critical proprioceptive information on body awareness and functions as a protective mechanism against injury. The resulting impaired trunk motor control when wearing a LBP vibration modality belt needs to be considered as it can greatly increase the likelihood of experiencing a LBI. There are a couple recommendations that should be considered when using a LBP vibration modality belt. While wearing the belt you should remain seated or lie down and avoid high-risk situations for experiencing a sudden load. After wearing the belt ample time should be left for recovery to avoid the greater risk of injury associated with trunk muscle fatigue. Overall, wearing a LBP vibration modality belt can compromise trunk postural control and precautionary measures should be implemented to avoid LBIs and LBP.

APPENDIX A

Table 2 Means and p-values for variables of interest for the sudden loading task pre- and post-vibration. A two-way repeated measures ANOVA was used to test for significance. An asterisk represents p<0.05.

Variable	Day	Pre	Post	Condition* p-value	Day* p-value	Condition*Day p-value
LumTrnkFlex	Cont	6.44	6.03	0.003*	0.96	0.04*
	Exp	7.04	5.33			
LumTrnkFlexNorm	Cont	12.23	11.17	0.0084*	0.95	0.11
	Exp	13.15	9.49			
LumTrnkFlexPre	Cont	-0.65	2.72	0.23	0.89	0.09
	Exp	0.58	0.83			
LLES Lat	Cont	77.76	77.15	0.45	0.80	0.30
	Exp	76.88	79.33			
LTES Lat	Cont	71.30	71.60	0.28	0.74	0.27
	Exp	71.06	74.01			
LEO Lat	Cont	96.96	95.96	0.91	0.54	0.48
	Exp	98.26	100.56			
LRA Lat	Cont	103.57	107.58	0.46	0.41	0.90
	Exp	106.84	110.65			
RLES Lat	Cont	76.09	78.62	0.24	0.72	0.07
	Exp	78.94	78.42			
RTES Lat	Cont	72.53	75.32	0.20	0.49	0.61
	Exp	71.20	72.36			
REO Lat	Cont	95.75	103.17	0.26	0.82	0.07
	Exp	98.90	99.5			
RRA Lat	Cont	102.91	104.91	0.17	0.80	0.15
	Exp	112.9	105.44			
LLES Pre	Cont	3.88	3.74	0.07	0.58	0.46
	Exp	3.79	3.41			
LTES Pre	Cont	4.55	4.43	0.55	0.81	0.70
	Exp	4.64	4.63			
LEO Pre	Cont	3.75	4.09	0.96	0.46	0.04*
	Exp	3.70	3.33			
LRA Pre	Cont	5.44	5.07	0.01*	0.83	0.50
	Exp	5.47	5.25			
RLES Pre	Cont	4.24	4.30	0.49	0.87	0.30
	Exp	4.47	4.25			
RTES Pre	Cont	4.44	4.46	0.18	0.33	0.18
	Exp	5.60	5.03			
REO Pre	Cont	4.95	4.87	0.30	0.12	0.52
	Exp	3.96	3.73			
RRA Pre	Cont	5.40	5.27	0.15	0.50	0.37
	Exp	4.74	4.64			

Variable	Day	Pre	Post	Condition* p-value	Day* p-value	Condition*Day p-value
LLES Act	Cont	16.58	15.55	0.0003*	0.58	0.71
	Exp	16.47	14.56			
LTES Act	Cont	31.68	31.02	0.93	0.89	0.55
	Exp	31.28	32.25			
LEO Act	Cont	4.02	8.15	0.50	0.29	0.36
	Exp	4.71	4.12			
LRA Act	Cont	8.45	14.50	0.90	0.44	0.51
	Exp	10.96	6.32			
RLES Act	Cont	16.05	15.36	0.02*	0.96	0.71
	Exp	16.27	15.42			
RTES Act	Cont	27.72	30.51	0.80	0.69	0.25
	Exp	31.69	30.23			
REO Act	Cont	7.64	5.77	0.03*	0.19	0.12
	Exp	6.01	5.35			
RRA Act	Cont	9.87	3.12	0.10	0.61	0.28
	Exp	5.53	4.49			

Table 3 Means and p-values for variables of interest for the trunk repositioning task pre- and post-vibration. A two-way repeated measures ANOVA was used to test for significance. An asterisk represents $p<0.05$.

Variable	Day	Pre	Post	Condition* p-value	Day* p-value	Condition*Day p-value
FullFlexPer	Cont	29.26	24.13	0.30	0.74	0.36
	Exp	26.22	25.06			
FullFlexAb	Cont	6.60	5.63	0.42	0.63	0.39
	Exp	6.66	6.52			
FullFlexRel	Cont	1.52	-0.65	0.055	0.17	0.52
	Exp	-0.92	-2.23			
HalfFlexPer	Cont	10.85	11.08	0.16	0.19	0.16
	Exp	6.91	10.65			
HalfFlexAb	Cont	2.65	2.84	0.26	0.28	0.57
	Exp	1.94	2.49			
HalfFlexRel	Cont	-0.33	0.25	0.53	0.16	0.21
	Exp	-0.21	1.61			

Table 4 Means and p-values for variables of interest for the sudden loading task with vibration on. A two-way repeated measures ANOVA was used to test for significance. An asterisk represents p<0.05.

Variable	Day	Mean	Cont*Exp p-value
LumTrnkFlex	Cont	4.55	0.09
	Exp	4.85	
LumTrnkFlexNorm	Cont	8.82	0.12
	Exp	9.44	
LumTrnkFlexPre	Cont	3.85	0.052
	Exp	2.72	
LLES Lat	Cont	78.27	<.0001*
	Exp	95.07	
LTES Lat	Cont	74.36	0.12
	Exp	78.28	
LEO Lat	Cont	100.23	0.03*
	Exp	113.16	
LRA Lat	Cont	104.02	0.24
	Exp	113.27	
RLES Lat	Cont	79.99	<.0001*
	Exp	98.67	
RTES Lat	Cont	73.35	0.39
	Exp	75.98	
REO Lat	Cont	98.55	0.0002*
	Exp	111.91	
RRA Lat	Cont	106.95	0.09
	Exp	116.53	
LLES Pre	Cont	4.34	<.0001*
	Exp	14.03	
LTES Pre	Cont	4.50	0.01*
	Exp	5.13	
LEO Pre	Cont	3.95	<.0001*
	Exp	8.34	
LRA Pre	Cont	4.96	<.0001*
	Exp	7.87	
RLES Pre	Cont	4.57	<.0001*
	Exp	22.16	
RTES Pre	Cont	4.30	<.0001*
	Exp	6.09	
REO Pre	Cont	4.45	<.0001
	Exp	6.16	
RRA Pre	Cont	5.18	<.0001*
	Exp	6.58	
LLES Act	Cont	14.82	0.0002*
	Exp	11.64	

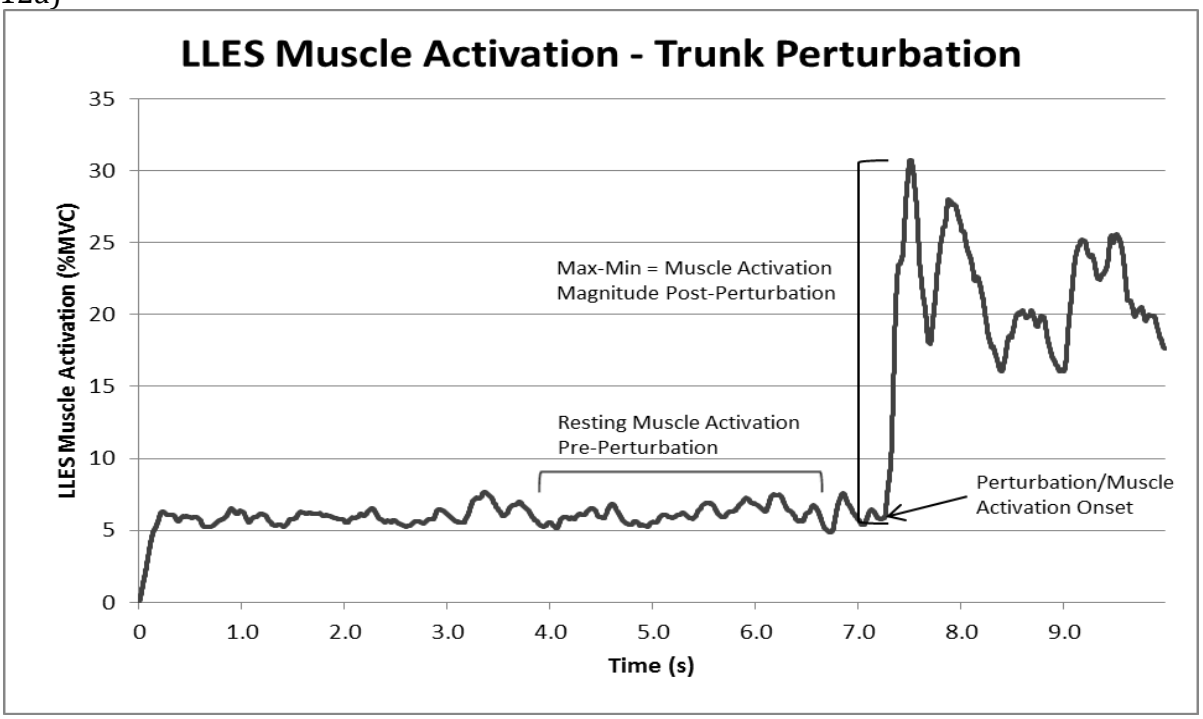
Variable	Day	Mean Value	Cont*Exp p-value
LTES Act	Cont	28.70	0.0008*
	Exp	24.64	
LEO Act	Cont	4.25	0.23
	Exp	5.44	
LRA Act	Cont	3.92	0.02*
	Exp	2.03	
RLES Act	Cont	14.25	0.0003*
	Exp	11.06	
RTES Act	Cont	26.55	0.03*
	Exp	23.89	
REO Act	Cont	4.70	0.23
	Exp	5.54	
RRA Act	Cont	2.79	0.01*
	Exp	1.84	

Table 5 Means and p-values for variables of interest for the trunk repositioning task with vibration on. A two-way repeated measures ANOVA was used to test for significance. An asterisk represents $p<0.05$.

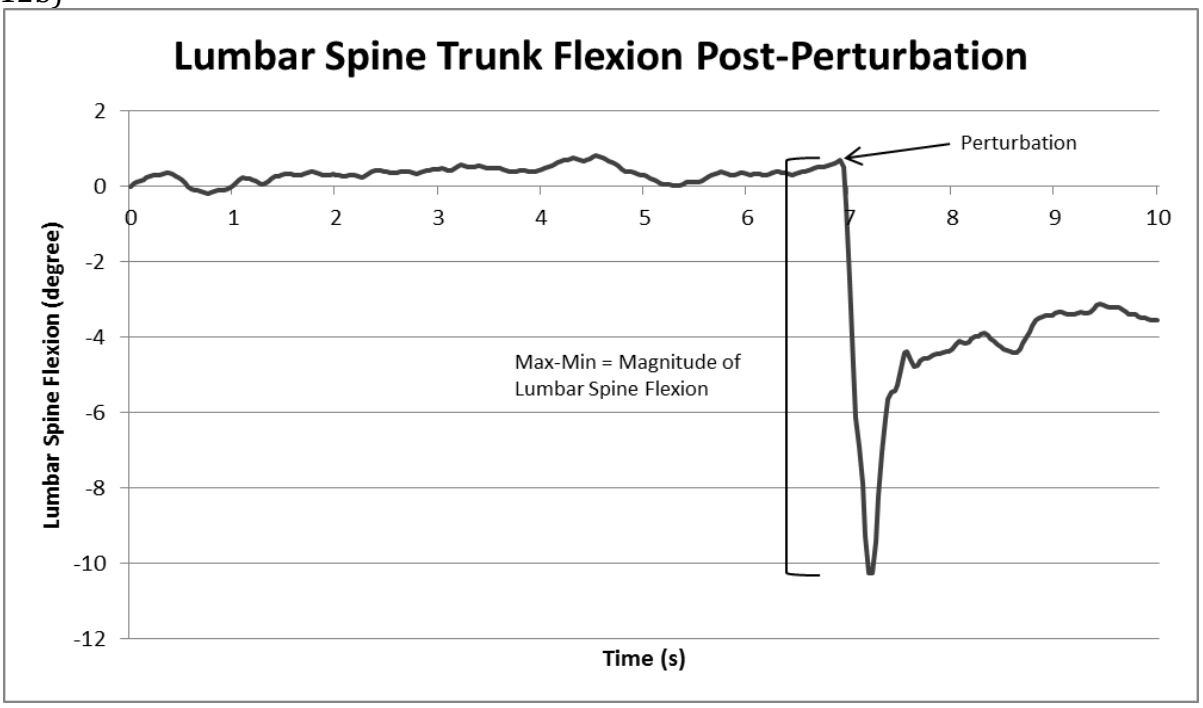
Variable	Day	Mean Value	Cont*Exp p-value
FullFlexPer	Cont	28.24	0.09
	Exp	20.79	
FullFlexAb	Cont	4.86	0.23
	Exp	3.98	
FlexRel	Cont	1.52	0.14
	Exp	0.28	
HalfFlexPer	Cont	13.95	0.80
	Exp	13.28	
HalfFlexAb	Cont	2.25	0.86
	Exp	2.33	
HalfFlexRel	Cont	0.49	0.20
	Exp	-0.27	

APPENDIX B

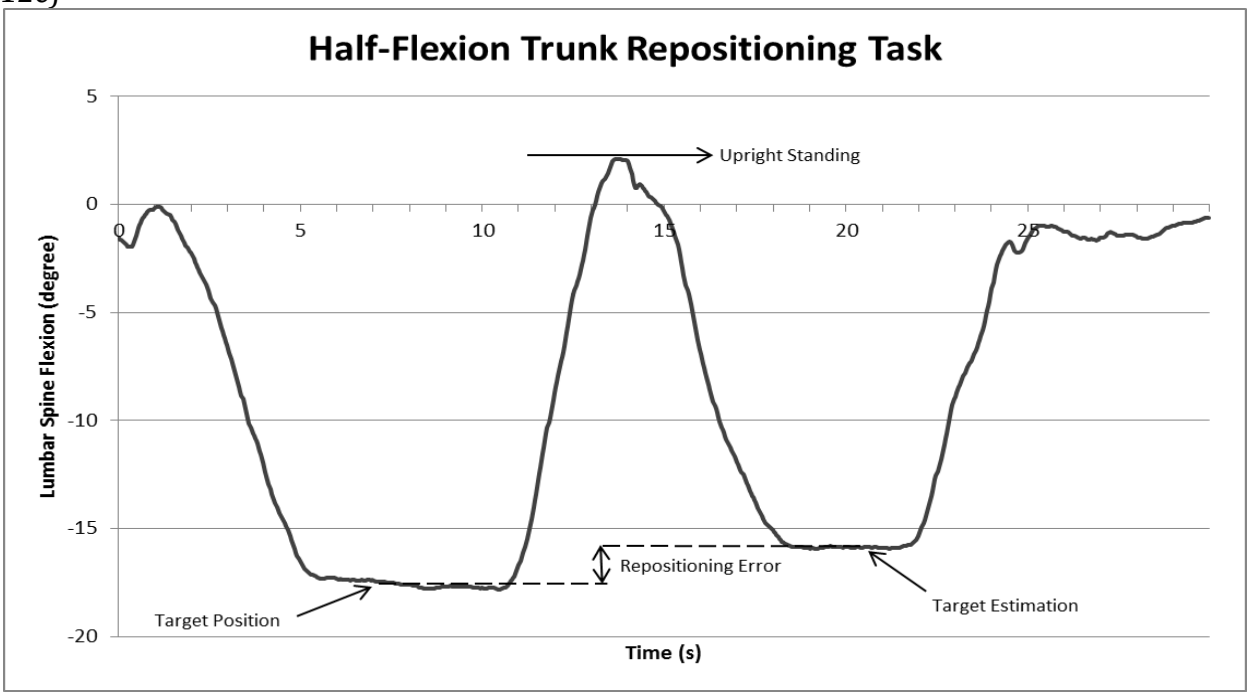
12a)



12b)



12c)



12d)

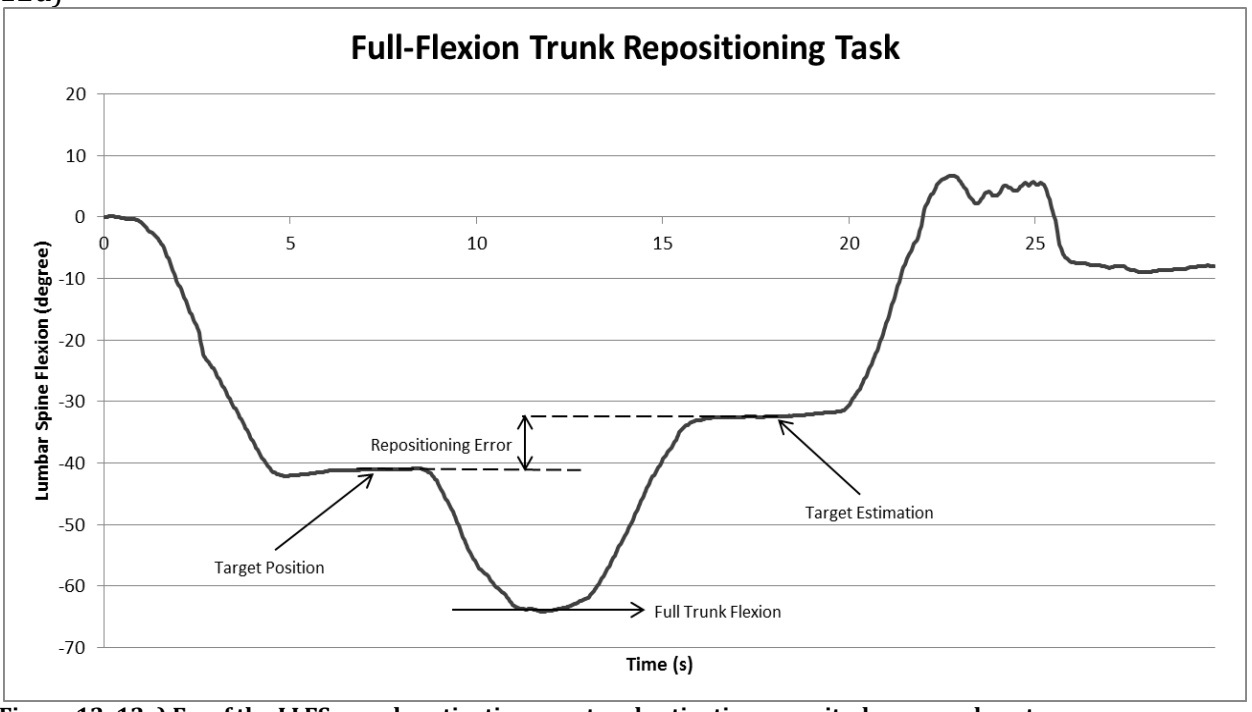
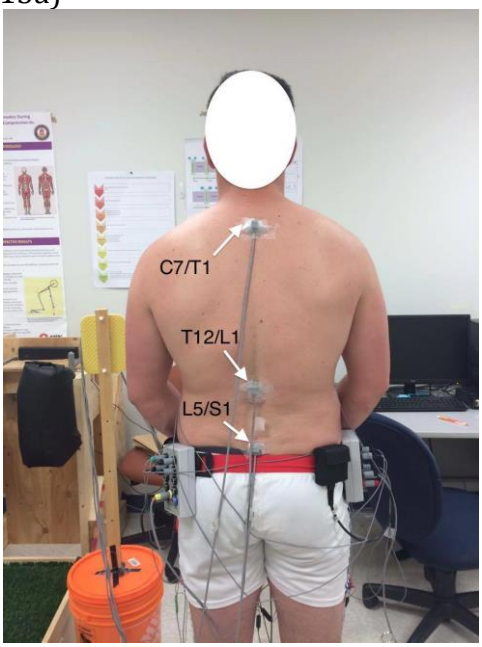


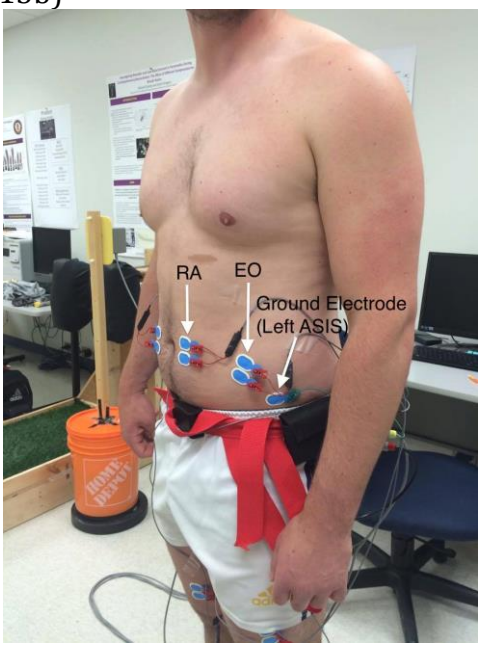
Figure 12: 12a) Ex. of the LLES muscle activation onset and activation magnitude pre- and post-perturbation. 12b) Ex. of lumbar spine trunk flexion post-perturbation showing magnitude of trunk flexion caused from the trunk perturbation. 12c) Ex. of lumbar spine trunk flexion during the half-flexion trunk repositioning task as well as repositioning error. 12d) Ex. of lumbar spine trunk flexion during the full-flexion trunk repositioning task as well as repositioning error.

Appendix C

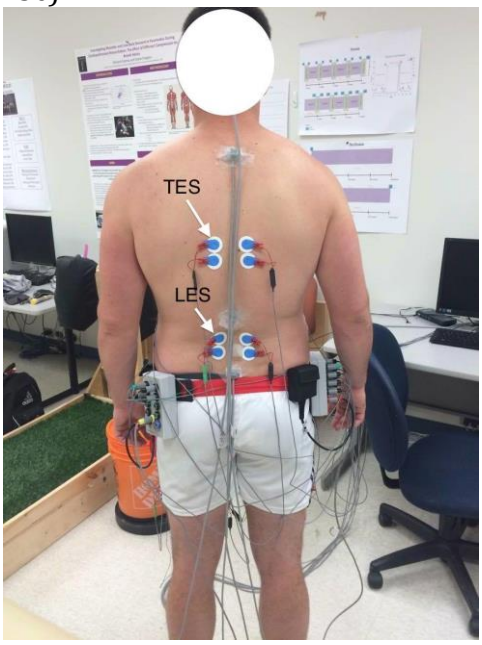
13a)



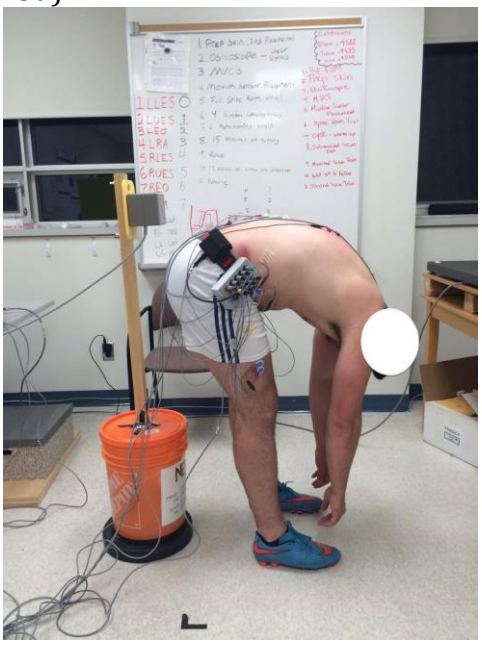
13b)



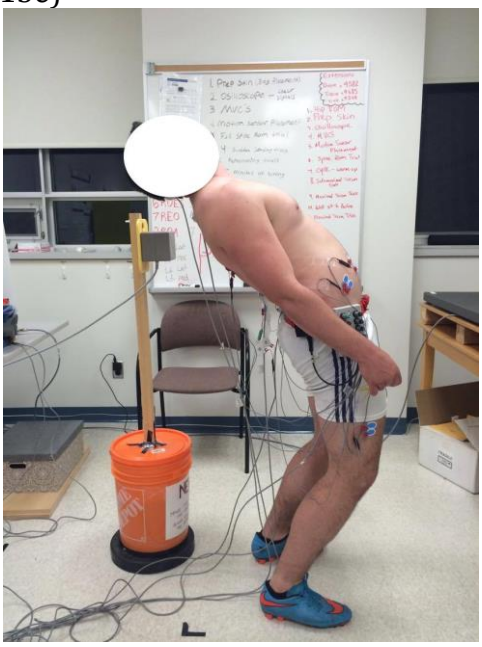
13c)



13d)

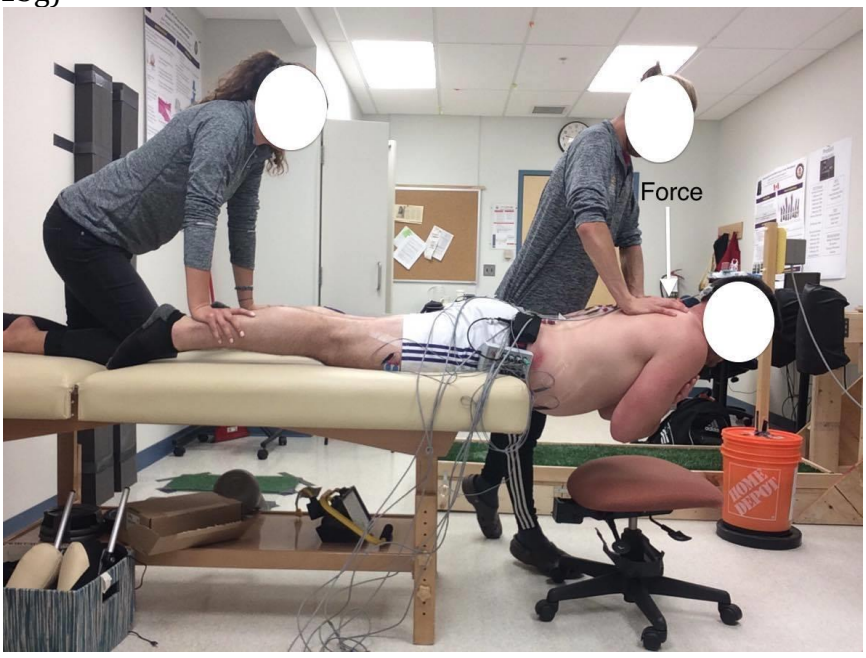


13e)

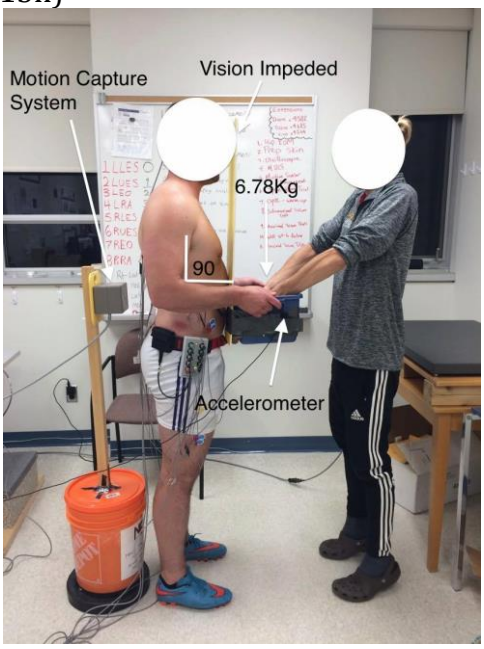


13f)

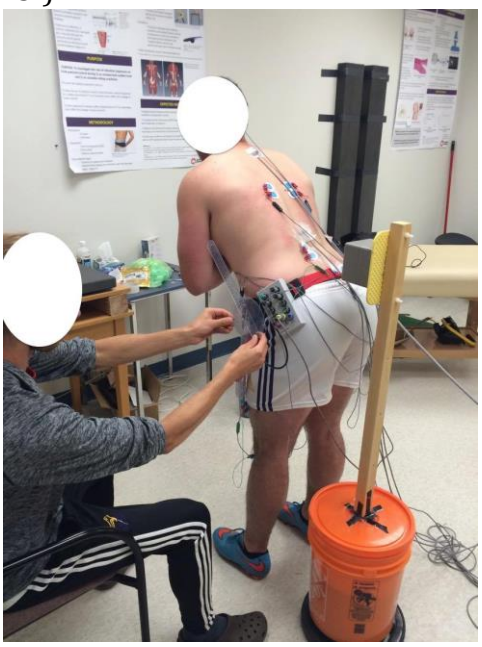
13g)



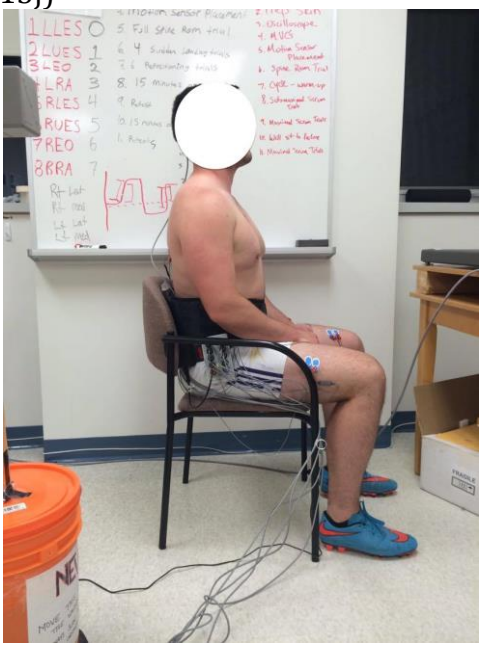
13h)



13i)



13j)



13k)

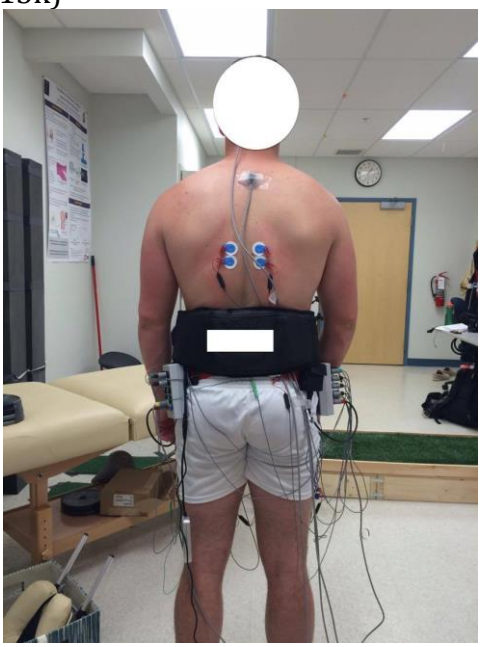


Figure 13: 13a) Participant motion capture setup. 13b) Anterior EMG electrode setup. 13c) Posterior EMG electrode setup. 13d) ROM full flexion. 13e) ROM full extension. 13f) Abdominal MVC. 13g) Back extension MVC. 13h) Sudden unexpected trunk perturbation setup. 13i) Trunk repositioning task. 13j) 15-minute bout of sitting with the LBP vibration modality belt being worn. 13k) Standing while wearing the LBP vibration modality belt.

APPENDIX D

SCREENING QUESTIONNAIRE

VOLUNTEER EXCLUSION CRITERIA Date (MM/DD/YYYY):_____, _____, _____

Name: _____

Address: _____

City, Prov: _____ Postal Code _____

Tel #: (_____)-_____-_____

Age: _____yrs. Height: _____ cm Weight:_____ kg

Gender: M☐ F☐

Do you have any conditions that limit the use of your arms or legs? Y / N

If yes, how much does this condition interfere with your activities?

little or none☐ moderate☐ a great deal☐

Describe:

If you or have or have ever had any balance or musculoskeletal disorders/diseases that would affect your ability to participate in this study you may be excluded. Examples would include: epilepsy, cerebral palsy, multiple sclerosis, parkinson's disease, stroke, visual disorder, or if you are pregnant. Please notify the researcher if you believe you may have a condition that you think may influence your ability to participate.

Have you ever severely injured or had surgery on your: Please check all the applies

a. Head ☐
b. Neck ☐
c. Back ☐
d. Pelvis ☐
e. Ankle, knee, foot ☐

If you checked any of the boxes please describe:

Have you ever experienced low back pain that has lasted more than three consecutive days in the previous year? Y / N

If yes, please describe how and when the injury occurred, if the pain limited everyday activities, level of pain (1-10), and duration before you were able to return to everyday life:

Have you ever broken any bones? Y / N

If yes, which ones? _____

Have you had any recent:

a. Illnesses Y / N
b. Injuries Y / N
c. Operations Y / N

If you answered yes please describe:

Do you have difficulties performing any daily activities? Y / N

If yes, which activities?: _____

Are you currently taking any medications (prescription or over-the-counter), or other drugs?

Medication	Ailment	Frequency of use
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____

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