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Lumbar Posture and Tissue Loading During Short-Term Static Trunk Bending

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in Partial fulfillment of the requirements for the degree of
Master of Science in Industrial Engineering

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Abstract

Lumbar Posture and Tissue Loading During Short-Term Static Trunk Bending

Faisal Alessa

Low back pain (LBP) is among the most prevalent occupational health problems worldwide and is a leading cause of lost work days. Previous studies have suggested that static prolonged trunk bending could generate lumbar muscle fatigue and introduce creep to the lumbar posterior tissues. Such physical changes could lead to alterations to the lumbar active and passive tissue sharing mechanism and also elevate spinal loading, which is highly associated with the risk of LBP. In the past, most occupational ergonomic studies focused on the instantaneous spine biomechanical responses during task performance. A few studies assessed the changes of spine biomechanics due to spinal tissue creep (introduced by prolonged trunk full flexion) and lumbar muscle fatigue (introduced by prolonged or repetitive trunk bending). However, the dynamic changes of lumbar and trunk postures and spinal tissue loadings during the performance of relatively short-term trunk bending tasks are still unclear. Therefore, the purpose of the current study was to investigate the changes of lumbar biomechanics during short-term, sustained trunk bending.

In the present study, fifteen participants performed short-term (40 seconds) static trunk bending tasks in two different trunk postures (30° or 60°) with two different hand load levels (0 or 15lbs). Results of the current study revealed significant reduction of lumbar muscle activities during the course of task performance. This change was coupled with significant increase of lumbar flexion angle and lumbar passive moment. Such increase of lumbar passive tissue loading could help relief/delay lumbar muscle fatigue by compensating the reduced lumber active tissue loading. Findings of this study suggest that, during the performance of sustained trunk bending, there is an internal mechanism to shift loading from lumbar active tissues to passive tissues by increasing the lumbar flexion. This mechanism is beneficial in reducing the amount of lumbar muscle fatigue; however, lumbar passive tissue creep could be generated at a faster rate.

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List of Acronyms

LBP	Low Back Pain
DALYs	Disability Adjusted Life-Years
MSDs	Musculoskeletal Disorders
EMG	Electromyography
FRP	Flexion-Relaxation Phenomenon
ARB	Active Region Boundary
SD	Standard Deviation
C7	The 7th cervical vertebra
T12	The 12th thoracic vertebrae
S1	The 1st sacral vertebrae
L#	The number of lumbar vertebrae
MVC	Maximum Voluntary Contraction
ES	Erector Spinae
MU	Multifidus
RA	Rectus Abdominus
EO	External Oblique
LPM	Lumbar Passive Moment
ANOVA	Analysis of variance

Chapter 1: Introduction

Low back pain (LBP) remains one of the most prevalent occupational health problems worldwide (Deyo et al., 2006). Approximately 80% of U.S. population members are estimated to experience at least one episode of LBP in their lifetimes (Hellman & Imboden, 2009). Although the majority of people recover, approximately 20% of patients with acute LBP experience chronic back problems (Weiner & Nordin, 2010).

Globally, occupational-related LBP has been among the leading causes of lost work days. In the World Health Organization (WHO) 2010 Global Burden of Disease study, LBP was ranked 6th, (rising from 11th in 1990), among top diseases and injuries that cause the largest number of Disability Adjusted Life-Years (DALYs), which is a measure of the overall disease burden, expressed as the number of years lost caused by illness, disability or early death (Global Burden of Disease, 2010). In the United States, the economic burden associated with LBP is extremely large. Several studies have estimated that the direct (e.g. medical) and indirect (e.g. lost time, productivity) cost related to LBP is around 100 billion dollars annually (Luo et al., 2004; Katz, 2006).

The etiology of LBP is multifactorial. Previous studies have suggested that in general LBP is associated with genetic factors (Junqueira et al., 2014), psychosocial factors (Gatchel et al., 1995), individual factors (Richard & Edward, 1989), biomechanical factors (Bernard, 1997; Marras et al., 1995), and other risk factors (Hoogendoorn et al., 2000). Previous effort in studying biomechanical factors mainly focused on finding the association between the magnitude and duration of mechanical loadings on spinal tissues and LBP risks. Evidence provided by in-vitro studies showed that excessive mechanical loading could cause vertebra fracture (Brinckmann et al., 1988) and intervertebral disc rupture (Adams et al., 2000). As indicated by the evidence stated above, having a clear understanding of the spinal tissue loadings during task performance is critical for the prevention of LBP.

The structure of the human lumbar spine is complex. Mainly, the lumbar spine consists of two types of tissues: active tissues (e.g. the contractile component of muscles) and passive tissues (ligaments, fascia discs, bone, and non-contractile component of muscles). During forward trunk bending, a transition of load from lumbar active tissues to passive tissues occurs at deeper trunk flexion postures (Ning et al., 2011; Ning et al., 2012). This load shifting demonstrates the synergy between lumbar active and passive tissues and was termed as flexion relaxation phenomenon (FRP) by Floyd and Silver (1951, 1955). Previous studies showed that the load sharing synergy between lumbar active and passive tissues could be altered by several factors including ligament creep caused by prolonged trunk bending (Shin et al., 2009), the direction and speed of trunk bending (Ning et al., 2011; Sarti et al., 2001), and lumbar muscle fatigue (Descarreaux et al., 2008).

In the past, ergonomic studies have suggested that maintaining flexed trunk posture for a prolonged period of time could elevate the risk of LBP due to increased spinal loading and muscle fatigue (Solomonow et al., 2003). In occupational settings static trunk bending tasks are commonly observed in many industries such as mining (Gallagher 2008), agriculture (Fathallah 2010) and construction (Boschman et al., 2011). Previous studies also found that instead of trunk posture, lumbar posture may be the major factor that influences lumbar active and passive tissue synergy which affects spinal stability and loading (McGill et al., 2000). Previous efforts in studying lumbar postures and tissue loadings have been mainly focusing on dynamic motions (e.g. during lifting and lowering) (Arjmand et al., 2011; Potvin et al 1991). For static postures, most previous industrial ergonomic studies have not considered the evolvement of biomechanical responses during the task performance (Arjmand and Shirazi-Adl, 2005; McGill et al., 2000; Kahrizi et al., 2007). However, during a prolonged posture holding task, the lumbar-pelvic posture as well as trunk muscle activation patterns could alter significantly without affecting the general trunk posture (Shin et al., 2009; McGill and Brown, 1992). Such changes could also alter the synergy between lumbar active and passive tissues and change spinal tissue loadings; which is highly associated with the risk of LBP.

Therefore, the purpose of the current study was to investigate the changes of lumbar posture and the associated lumbar active and passive loadings during static trunk bending tasks. It was hypothesized that when maintaining a short-term bended trunk posture, we will observe reduced lumbar extensor muscle activity and increased lumbar flexion angle. It was also hypothesized that lumbar passive moment will increase to compensate for the reduced lumbar active moment.

Chapter 2: Background

2.1 Trunk flexion as a LBP risk factor

Trunk flexion is commonly involved in occupational tasks performed in industries such as mining (Gallagher 2008), agriculture (Fathallah 2010) and construction (Boschman et al., 2011) (Figure 1). Previous studies have identified both static (e.g. posture holding) and dynamic (e.g. lifting and lowering) trunk flexion as occupational risk factors for the development of LBP (Liira et al., 1996; Marras et al., 1995; Kraus et al., 1997), especially when performing prolonged static trunk flexion and repetitive trunk bending tasks (Marras, 2000; Manchikanti, 2000; BLS, 2009; Muslim et al., 2013; Hoogendoorn et al., 2000).

Figure 1: Workers in different occupational settings perform repeated short-term trunk bending tasks.

As the trunk flexes forward from the upright standing posture, the external loading acting on the spinal (especially the lumbar spine) starts to increase (Figure 2). To counter balance this elevated external loading and control trunk posture, the lumbar extensor muscles (such as erector spinae, multifidus) start to contract and generate active internal force. Due to the relatively small moment arms that lumbar muscles have, these muscle forces are relatively high which result in high loading (compression and shear forces) on the vertebrae and intervertebral discs (Toussaint et al., 1995).

Previous studies have shown that excessive loading on the spinal structure could cause fracture on the vertebral body (Brinckmann et al., 1988) and herniation on the discs (Adams et al., 2000), which further lead to spinal disorder and pain (Marras et al., 2001a). Although occasionally performed trunk flexion with moderate hand load is unlikely to cause immediate damage to the spinal structure, studies have found that prolonged or repetitive trunk flexion could generate micro damage to the spinal structure and eventually lead to LBP over a period of time (e.g. in days, months or years) (Coenen et al., 2012; Brinckmann et al., 1988).

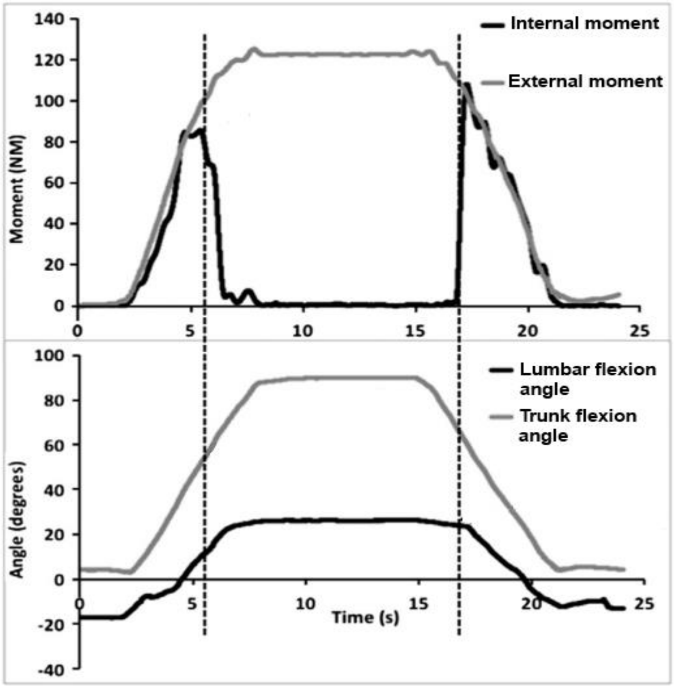

Figure 2: Trunk and lumber flexion angle vs. external and internal moment (adopted from Ning et al., 2012).

The degrees of trunk and lumbar bending are the determining factors of the load sharing mechanism between lumbar active tissues and passive tissues. With the increase of lumbar and trunk flexion, the mechanical loadings on lumbar posterior ligamentous and discs increase (Adams and Dolan, 1996; Arjmand et al., 2011; McGill, 1997; Potvin et al., 1991; Kahrizi et al., 2007). *In vivo* studies have found an exponential increment in the bending moment resisted by lumbar passive tissues (spinal ligaments and discs) when the trunk is flexed more than half of the range between upright standing and full flexion (Adams and Dolan, 1991; Dolan et al., 1994b; Ning et al., 2012; Ning and Nussbaum, 2015). A number of previous studies have shown that the increase of lumbar and trunk flexion significantly increases spinal loading (Ning et al., 2012; Ning and Nussbaum 2015; Arjmand and Shirazi-Adl, 2006; Kahrizi et al., 2007), which was highly associated with the occurrence of LBP (Granata and Marras, 1993; Granata et al., 1997; Marras and Granata, 1995; Marras and Granata, 1997).

2.1.1 Dynamic trunk motion

Trunk dynamic motion (e.g. lifting and lowering) was evidently linked to the occurrence of MSDs (Bernard, 1997; Marras et al., 1995). In the past, ergonomic studies have investigated trunk cyclic movement via both *in vitro* (Yoganandan et al., 1994) and *in vivo* studies (Olson et al., 2004) to understand its effects on the biomechanical response of the spine. Cyclic trunk motion was found to have several effects on the spinal biomechanical response including development of muscle fatigue (Dolan and Adams, 1998), alteration of the lumbar active and passive tissues' recruitment (Olson et al., 2004; Shin and D'Souza, 2010), reduction of spinal stability (Solomonow et al., 2008), and increment of spinal bending moment (Dolan and Adams, 1998), all of which were recognized as risk factors of LBP.

2.1.2 Static trunk motion

Maintaining flexed trunk posture for an extended period of time could elevate the risk of LBP (Solomonow et al., 2003). Several ergonomics studies have examined the mechanical changes caused by prolonged static trunk flexion (Toosizadeh et al., 2012; Shin and Mirka, 2007). During static full trunk flexion, the gravitational force acting on the upper body and head is counterbalanced mainly by moment generated by lumbar passive tissues (Solomonow et al., 2003; McGill & Kippers, 1994). Maintaining this flexed posture for an extended period of time decreases lumbar tissue stiffness and generates creep deformation among lumbar passive tissues (Adams and Dolan, 1996; Burns et al., 1984; Li et al., 1995; Solomonow et al., 2003; Shin and Mirka, 2007). As a result of creep deformation, more laxity will be developed in the lumbar viscoelastic tissues, and the resistance to the sagittal flexion moment will be reduced (Adams and Dolan, 1996; Adams et al., 1987; Olson et al., 2004; Solomonow, 2004). The reduction of lumbar passive tissue stiffness can be compensated by increasing muscle contractions (McCook et al., 2009; Olson et al., 2009). However the increased muscle activation level could accelerate the accumulation of muscle fatigue (Shin et al., 2009; Adams and Dolan, 1995), which could further reduce spinal stability (Solomonow et al., 2000; Granata and Orishimo, 2001). These mechanical changes may lead to an increased risk of LBP especially when prolonged trunk flexion is performed without enough rest (Cholewicki and McGill, 1996; Solomonow, 2004; Solomonow et al., 2003; Toosizadeh et al., 2012) (Figure 3).

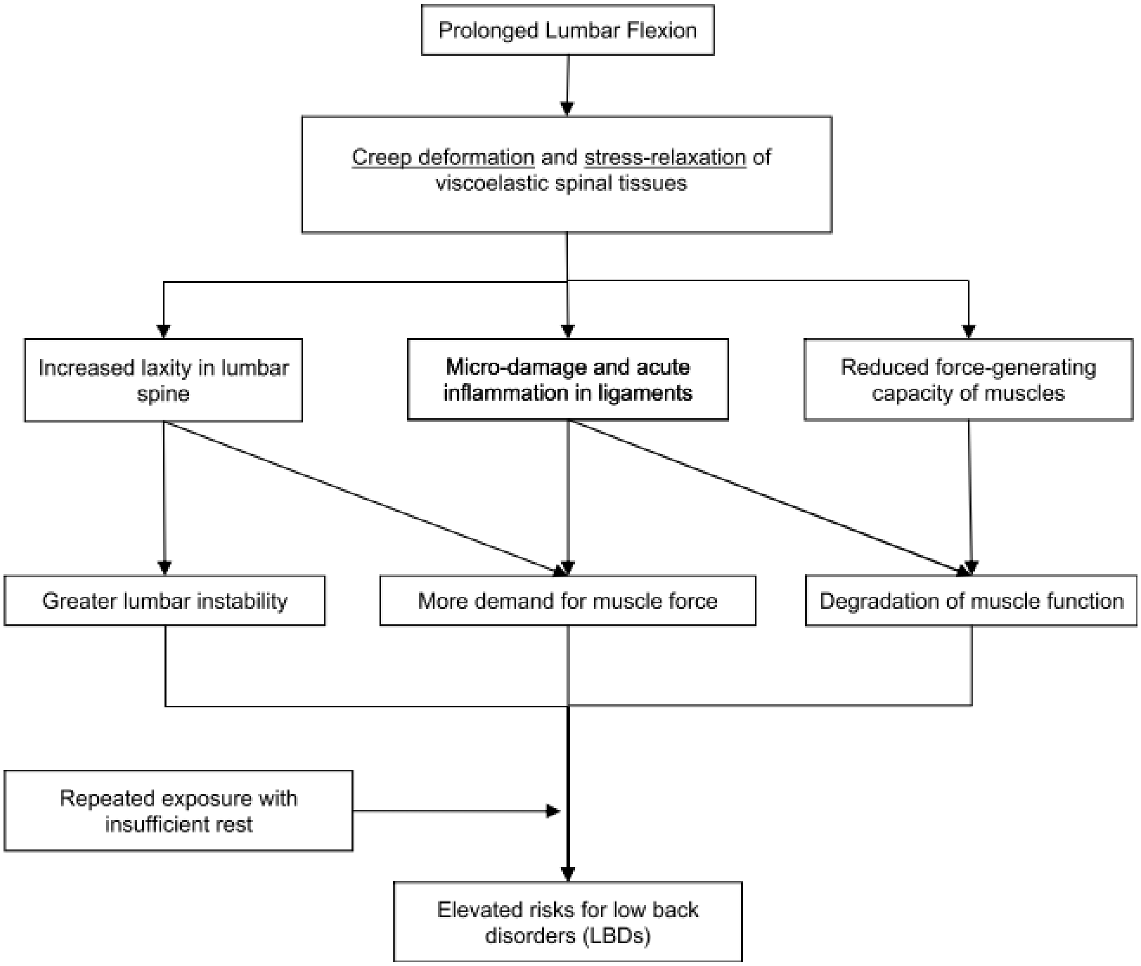

Figure 3: The relationships between prolonged static trunk flexion risk factors (Shin and Mirka, 2007)

2.2 Risk assessment tools

To combat the high prevalence of occupational musculoskeletal disorders (MSDs) (including LBP), three main approaches have been developed and applied: 1) self-assessment, where workers report their own discomfort and injuries and suggest the potential cause of these injuries; 2) professional observation, where an expert observer observes the work on site or from recorded video, then uses a systematic method to classify risk factors; and 3) Direct measurement, where instruments are used directly to evaluate muscle activities joint angles and force output etc. (Li and Buckle, 1999).

2.2.1 Self-assessment

Self-assessment is normally survey-based methods in which workers report their pain, discomfort and injuries that occurred in work places. Sometimes estimations of the causes of these conditions are also included. The large amount of data from workers feedback can help to observe problems and issues that are may not be possible to detect via other assessment tools (Wang et al., 2015; Spielholz et al., 2001).

Previously, several survey-based studies have demonstrated high prevalence of LBP among different industries such as construction and agriculture (Holmstrom et al., 1992; Hildebrandt, 1995; Sturmer et al., 1997; Andersson, 1999; Rosecrance et al., 2006). A survey study of construction workers concluded that prolonged trunk flexion was one of the major risk factors for LBP among construction workers (Goldsheyder et al., 2002). In this study of construction workers, the two categories: "bending or twisting back in awkward way" and "working in the same position for long periods of time" were reported as the most difficult work-related activities that were associated with high prevalence of LBP. Similarly, among farmers, the two activities "work in same position for a long time" and "bend/twist back awkwardly" were reported as the second and third most problematic job factors in contributing to work-related pain and injury (Rosecrance et al., 2006).

2.2.2 Professional observation

Professional observation is a method typically conducted by safety and health professionals with the use of MSDs observational tools to evaluate the health risks among different occupational tasks. Some of the observational tools have been widely used to identify MSDs risk factors such as awkward postures, repetitive motions, and prolonged working hours in occupational settings. Rapid Upper Limb Assessment (RULA) (McAtamney and Corlett,

1993) and Rapid Entire Body Assessment (REBA) (Hignett and McAtamney, 2000) are examples of the assessments tools that were developed to assess the risk of MSDs.

Trunk flexion has been one of the main postures assessed in these observational methods. Postural assessment tools such as REBA and RULA often assign a higher risk score to a task if the task involves trunk flexion greater than 20° from vertical position, which indicates increased risk of developing LBP (Hignett and McAtamney, 2000; McAtamney and Corlett, 1993). The assigned risk score usually is much higher when the trunk flexion angle is greater than 60° which clearly demonstrates the role played by trunk flexion angle as a risk factor of LBP.

2.2.3 Direct measurement

Direct measurement is usually performed by safety and health professionals and researchers in either occupational settings or in a laboratory environment. Typically, measurements such as body dimensions, trunk kinematics, muscle activities, and hand/ground forces are collected using calipers, goniometers, motion sensors, electromyography (EMG) electrodes, force sensors, etc. Direct measurement generally yields highly accurate measurements making results more dependable in comparison to professional observation and self-assessment (Li and Buckle, 1999). However, in many cases, applying direct measurements can be difficult in occupational settings. The direct measurement approach often requires sophisticated instrumentation, which can be expensive and may not be portable. Therefore, direct measurement is more often used in laboratory studies.

In addition to direct measurement, researchers also use a modeling approach to estimate tissue properties and loadings. Such an approach is necessary because of the complexity of the human musculoskeletal system. For instance, to estimate muscle forces and the associated tissue loading, EMG-assisted biomechanical models were developed (Marras and Granata, 1997; Nussbaum and Chaffin 1998). Moreover, to estimate passive tissue loading, several anatomical models have been developed (Arjmand and Shirazi-Adl, 2006; Bean et al. 1988) with the assistance of tissue property information obtained from *in-vitro* studies (Adams and Hutton, 1985; Brinckmann et al., 1988).

2.3 Lumbar tissues load sharing mechanism

2.3.1 Flexion-Relaxation Phenomenon

Flexion-Relaxation Phenomenon (FRP) was first discovered in the early 1950's (Floyd and Silver, 1951). During the past 30 years, FRP has been studied more intensively to investigate the load sharing mechanism between lumbar active and passive tissues (Kippers and Parker, 1984; Ning et al., 2011; Ning et al., 2012). FRP is identified by an observed reduction and eventual silence of the EMG signals of the lumbar extensor muscles during full trunk flexion motion (Figure 4A). During trunk bending, a transition of load from lumbar active muscles (e.g. lumbar extensor muscles) to lumbar passive tissues (ligaments, fascia discs, bone, and non-contractile component of muscles) occurs at deeper trunk flexion postures (Ning et al., 2011; Ning et al., 2012), which demonstrates the synergy between lumbar active muscles and passive tissues. Studies have suggested that this transition of load indicates that the tension generated by passive tissue stretching was adequate to counterbalance the external moment acting on the lumbar spine, therefore allowing lumbar extensor muscles to cease activation (Solomonow et al., 2003; Floyd and Silver, 1951; Allen, 1948).

Previous studies discovered that the lumbar and trunk posture at which the lumbar extensor muscles' FRP occurs could be changed by several factors such as the speed and the direction of trunk motion (Ning et al., 2011; Sarti et al., 2001), the stance width and foot posture (Hu et al., 2014), the rate of lifting (Sarti et al., 2001), lumbar muscle fatigue (Descarreaux et al., 2008) and creep among lumbar ligaments (Shin et al., 2009, Kippers and Parker, 1984; Gupta, 2001). More recently, FRP was found to be absent or altered among LBP patients (Shirado et al., 1995); therefore, FRP observation has potential to be used for the identification and diagnosis of LBP patients (Neblett et al., 2003, 2010; Watson et al., 1997).

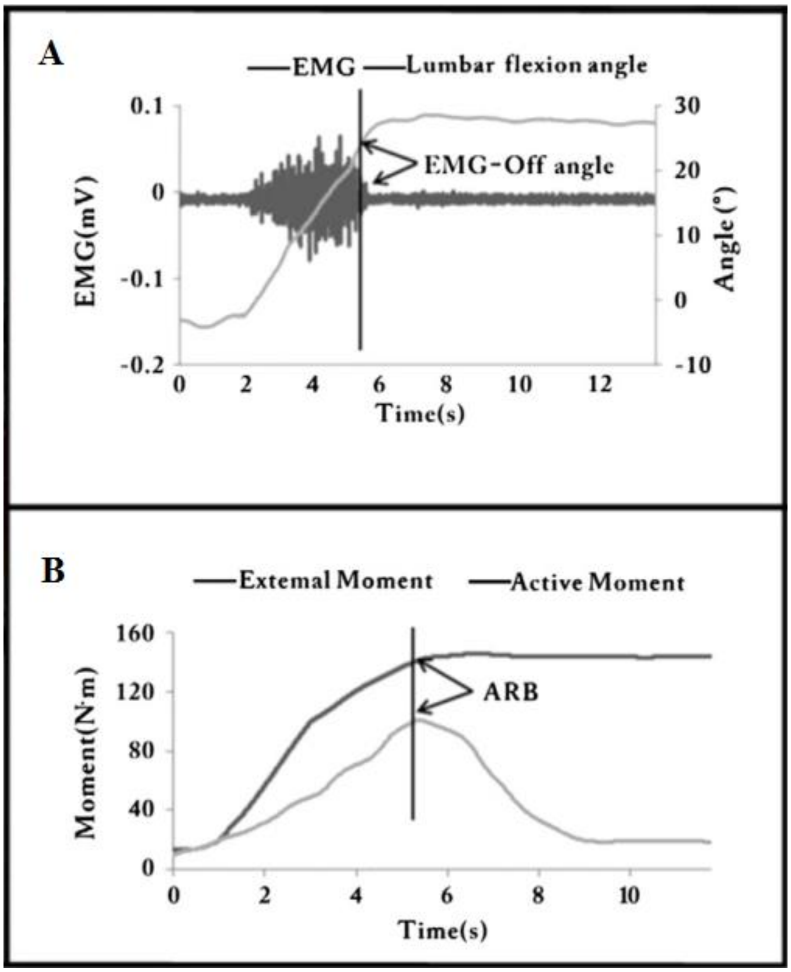

Figure 4: Onset of EMG activities' silence (A), and ARB example (B) (Hu et al., 2014).

2.3.2 Active region boundary (ARB)

As explained earlier, FRP represents the local load transition for each lumbar muscle individually which could identified by myoelectric silence. In contrast, active region boundary (ARB) describes the systematic (global) load shifting from lumbar extensor muscles to lumbar passive tissues (Figure 4B). During trunk flexion, ARB is identified when the internal moment significantly declined compared to the external moment (Ning et al., 2012; Hu et al., 2014). In other words, ARB identifies the lumbar and trunk posture beyond which the internal active moment starts to decrease drastically and the passive lumbar tissues stand to be the primary load bearer.

2.3.3 Lumbar posture and spinal tissue loading

The effect of lumbar posture on lumbar spine loading while lifting has been studied before (van Dieen et al., 1999). Potvin et al. (1991) concluded in their study that the risk of LBP may be influenced more by the change in lumbar posture rather than the choice of stoop or squat techniques. Moreover, previous literature found that instead of trunk posture, lumbar posture may be the major factor that influences lumbar active and passive tissue synergy which affects spinal stability and loading (McGill et al., 2000). In other words, since lumbar passive tissue stress is directly associated with tissue tension or elongation, which is determined by the degree of rotation in lumbar spine (i.e. lumbar flexion), lumbar posture plays a main role in the alteration of the load bearing.

Previous efforts in studying lumbar postures and tissue loadings have been mainly focusing on dynamic motions (e.g. during lifting and lowering). For static postures, most previous studies have considered them as uniform, unchanged tasks. However, during a prolonged posture holding task, the lumbar-pelvic posture as well as trunk muscle activation patterns could alter significantly without affecting the general trunk posture. Such changes could have fundamental effects on the lumbar tissue load sharing synergy, spinal tissue loadings and the associated LBP risks (McGill et al., 2000; Kahrizi et al., 2007; Arjmand and Shirazi-Adl, 2005).

Lumbar posture was found to have a direct impact on the load sharing mechanism between lumbar active muscle and lumbar passive tissue. Previous studies showed conflicting results in terms of which lumbar posture could reduce the risk of back injuries. Thus, more flexed lumbar spine (kyphotic) postures could elevate loadings on lumbar passive tissues which could generate tissue creep and therefore increase the risk of back injury (Figure 5) (McGill, 1997; Arjmand and Shirazi-Adl, 2005). Furthermore, kyphotic lumbar postures could change the orientations of the lumbar extensor muscles, thereby reducing their ability of supporting lumbar shear loadings, which is highly associated with the risk of LBP (McGill et al., 2000). However, more kyphotic lumbar postures continue to be recommended by some researchers as these postures reduce lumbar extensor muscle activities (Gracovetsky et al., 1981, 1985).

More lordotic lumbar postures result in higher lumbar extensor muscle activation levels which provide improved lumbar stability, as the lumbar passive tissues are less effective in protecting the spinal structure (Hart et al., 1986; McGill, 1997, 2000). Recent empirical studies have, however, suggested maintaining a neutral lumbar flexion posture (i.e. posture with moderate flexion) during static weight holding (Adams et al., 1994; Arjmand and Shirazi-Adl, 2005).

In conclusion, the existing literature contains conflicts regarding the influence of lumbar postures on the risk of lower back injuries. A better understanding of how lumbar posture changes during prolonged posture holding and its impact on spinal loading and the associated LBP risks are needed.

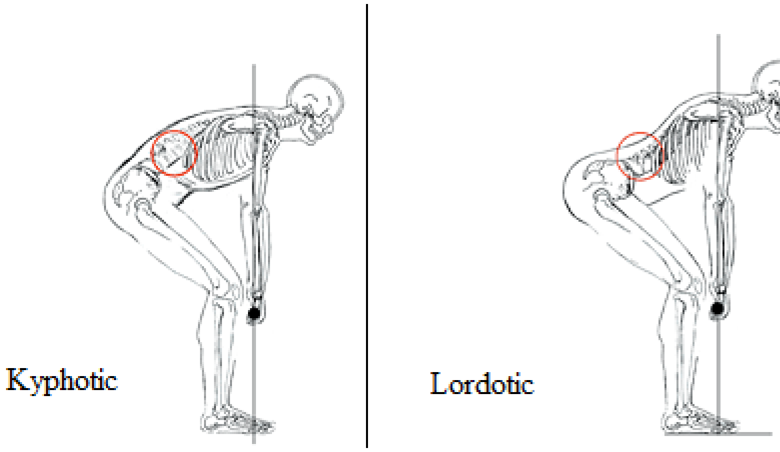

Figure 5: Kyphotic and lordotic lumbar postures.

2.4 Lumbar muscle fatigue

Lumbar muscle fatigue has been clearly classified as a major risk factor for the development of LBP (Luoto et al. 1995; Kankaanpa et al. 1998; Roy et al. 1990). Specifically, lumbar muscles could lose their force generation capacity due to fatigue which consequently reduces their support to the spinal structure (Bigland-Ritchie et al., 1995; Golhoffer et al., 1987; Gardner-Morse et al., 1995). Lumbar muscle fatigue was also known to alter the load synergy between lumbar active muscles and passive tissues (Descarreaux et al., 2008; Olson et al., 2004). When muscle stiffness decreased because of fatigue (Golhoffer et al., 1987), lumbar passive tissues compensate for this reduction to maintain the reduced spinal stability (Solomonow et al., 2000). Reduced spinal stability was recognized as a cause and result of LBP (Mcgill, 2002). Moreover, the change in muscle recruitment could potentially increase spinal loading which was linked to increased risk of LBP (Hu and Ning 2015a; Marras et al., 2005). Lumbar muscle fatigue was also found to have influence on lumbar–pelvic motion rhythm and coordination (Hu and Ning 2015a, 2015b), which may increase spinal loading and lead to elevated risk of LBP.

2.5 Lumbar passive tissue elongation

Prolonged, sustained trunk flexion causes lumber passive tissue elongation and may lead to tissue creep. Previous researchers have investigated tissue behavior through both *in vitro* (Adams and Dolan, 1996) and *in vivo* studies (McGill and Brown, 1992) using both human and animal samples (Solomonow et al., 2003). The elongation of the lumbar passive tissues is mainly affected by the time of exposure to deep trunk flexion postures. The development of creep among lumbar passive tissues can be quantified by assessing the trunk sagittal range of motion. The increase of the maximum trunk flexion angle during full trunk bending suggests the increase of laxity (the development of creep) among lumbar passive tissues (McGill and Brown, 1992; Solomonow et al., 2003; Shin and Mirka, 2007).

Another way to identify lumbar passive tissue elongation is when an increase in lumbar flexion angle occurs at a constant bending moment during static trunk bended posture. Moreover, lumber passive tissue creep can be identified by the observed delay of the onset of EMG activities silence during trunk flexion motions. This increase of FRP onset suggests a reduced stiffness of lumbar passive tissues (Solomonow et al., 2003; Shin et al., 2009).

Bazrgari et al. (2011) investigated the influence of duration and the external load during prolonged trunk flexion, revealing that tissue elongation increased with increasing trunk flexion duration and with added external load. McGill and Brown (1992) also found that females developed more tissue elongation than males after been exposed to the same period of prolonged trunk flexion. Females also have shown more changes in the FRP response than males (Solomonow et al., 2003).

Lumbar passive tissue elongation is linked to the increased laxity among lumbar tissues and the reduced ability to resist external moment in the sagittal plane (Adams and Dolan, 1996; Adams et al., 1987). The lumbar extensor muscles therefore compensate for this reduction (Shin et al., 2009). As discussed above, lumbar passive tissue creep as a result of prolonged trunk flexion is associated with increased risk of LBP (Adams and Dolan, 1996; McGill and Brown, 1992).

2.6 Rationale and hypotheses

Existing literature suggests that trunk flexion is a LBP risk factor, especially when maintaining in the flexed posture for prolonged period of time (Marras, 2000; Manchikanti, 2000; BLS, 2009; Muslim et al., 2013; Hoogendoorn et al., 2000). Previous studies have found that lumbar posture may be the major factor that influences lumbar active and passive tissue synergy, which affects spinal stability and loading (McGill et al., 2000). Also, previous efforts in studying lumbar postures and tissue loadings have been mainly focusing on dynamic motions (e.g. during lifting and lowering). As stated previously, for static postures, most previous studies have considered them as uniform, unchanged tasks. However, during a prolonged posture-holding task, the lumbar-pelvic posture as well as trunk muscle activation patterns could alter significantly without affecting the general trunk posture (Shin et al., 2009; McGill and Brown, 1992), which could have fundamental effects on the lumbar tissue load sharing synergy, spinal tissue loadings and the associated LBP risks.

Most previous findings in the literature regarding the effects of static trunk bending were obtained after exposing participants to prolonged (over 10 minutes) static full trunk flexion. The main purpose of these studies was either to investigate the development of creep after performing prolonged deep trunk flexion (McGill and Brown, 1992; Solomonow et al., 2003; Shin and Mirka, 2007) or to evaluate lumbar biomechanics after the development of lumbar passive creep (Toosizadeh et al., 2012; Solomonow et al., 2003). Other studies considered lumber posture during static trunk flexion tasks to be uniform; thus, these studies assessed the effect of lumber posture on lumber biomechanics instantaneously (Arjmand and Shirazi-Adl, 2005; McGill et al., 2000; Kahrizi et al., 2007). However, the underlying mechanism of lumbar biomechanics during static prolonged trunk flexion remains unclear. The importance of understanding lumbar biomechanical behavior during prolonged trunk flexion comes from the fact that lumbar angle is found to have a major role in the synergy between lumbar active and passive tissues (Arjmand and Shirazi-Adl, 2005; McGill et al., 2000; Kahrizi et al., 2007).

Therefore, the purpose of the current study was to investigate the changes of lumbar posture and the associated lumbar active and passive loadings during short-term sustained bended trunk posture. It was hypothesized that when maintaining short-term bended trunk posture, we will observe increased lumbar flexion angle, reduced lumbar extensor muscle activities, and increased lumbar passive moment to compensate for the reduced lumbar active moment.

Chapter 3: Method

3.1 Participants

Fifteen male participants from the student population of West Virginia University participated in the current study (see Appendix A for the recruitment letter). Their average body weight, height and age were 168.8 (SD 25.7) lb., 68.4 (SD 3.5) inches, and 24.9 (SD 4) years, respectively. All participants reported no current or history of low back injuries or pain. Prior to the data collection, participants signed informed consent forms. The experimental design and procedures of this study were approved by the West Virginia University Institutional Review Board (see Appendix B).

3.2 Equipment

Muscle activities (EMG) were recorded via eight bi-polar surface EMG electrodes (Bagnoli, Delsys, Boston, MA, USA), placed over the skin of both sides of L3 and L4 paraspinals (4cm and 2cm away from the mid-line of spine respectively), rectus abdominus (1 cm above and 2 cm away from the umbilicus) and external oblique (15 cm away from the umbilicus) (Figure 6, Figure 9). A magnetic field-based motion tracking system was used to collect lumbar and trunk kinematics (Figure 7). Three motion sensors were placed over the skin of C7, T12, and S1 vertebrae using double-sided tape (Ning et al., 2011) (Figure 8). Finally, a custom-made reference frame was used for participants to reach and maintain the designated TRUNK ANGLE (Figure 9).

3.2.1 Sampled muscles

Biomechanical studies of the lower back region generally involve sampling activities of the major muscle of the lumbar torso. This includes left and right sides of erector spinae (ES), multifidus (MU), rectus abdominus (RA), and external oblique (EO) (Marras and Mirka, 1992; Arjmand and Shirazi-Adl, 2005; Ning et al., 2011). Extension moments are mainly generated by ES and MU while RA and EO are responsible for generating flexion moments. Studies that involve investigating lumbar posture changes also require sampling extension muscles and flexion muscles, due to co-contraction phenomenon (Granata et al., 2005). Co-contraction phenomenon is the simultaneous contraction of agonist and antagonist muscles around a joint to generate movement or hold a static posture. Moreover, EMG-assisted models use EMG signals from both lumbar paraspinal muscles and abdominal muscles to estimate internal active and passive moments (Marras and Granata, 1997).

Figure 6: Surface electromyography (EMG) data collection system (Model: Bagnoli, Delsys Inc, Boston, MA, USA) (left) and bi-polar surface electrodes (right).

Figure 7: Magnetic field-based motion tracking system (Model: Motion Star, Ascension Technology Corporation, Burlington, VT, USA).

Figure 8: motion tracking sensors

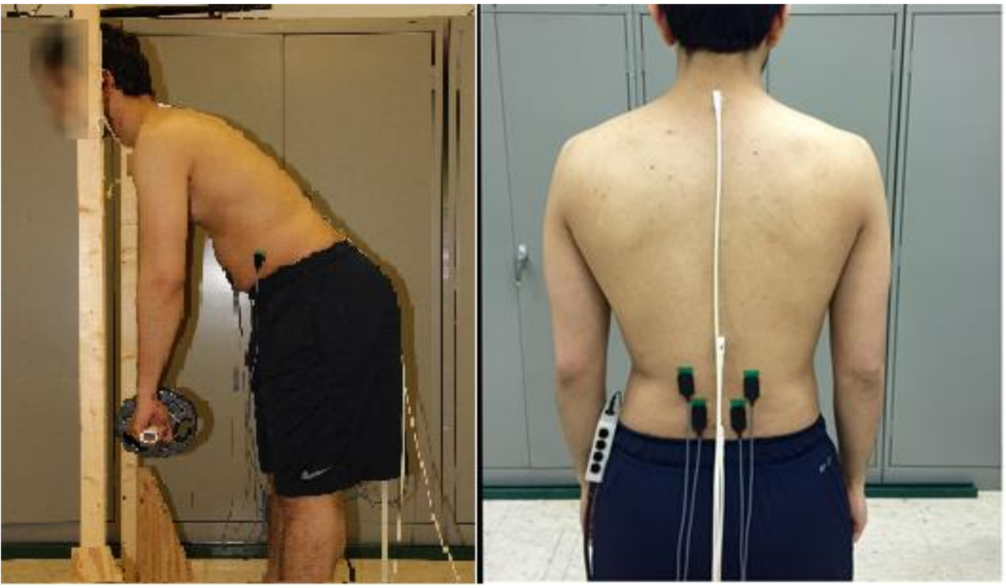

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Figure 9: Demonstration of experiment setup and the trunk angle reference apparatus.

3.3 Experimental design

3.3.1 Independent variables

The independent variables of the current study were trunk flexion angle (TRUNK ANGLE), external load (WEIGHT), and duration of posture holding (DURATION).

TRUNK ANGLE was defined as the angle between the vertical line and the line between the C7 and the S1 motion sensors, natural upright posture generates a ~0 value (Ning et al., 2011) (Figure 10). Two levels were considered: 30° and 60°. These two levels were examined as they represent the mid-range of trunk flexion prior to the drastic load shifting from active to passive lumbar tissue which is reported to occur near 65° of trunk flexion (Arjmand and Shirazi-Adl, 2005). This mid-range of trunk flexion is also more realistic in several occupational settings.

The independent variable WEIGHT has two levels: 0 and 15lb. In each trial, participants were required to perform a specific trunk posture with or without external load for 40 seconds; the two levels of DURATION were defined as the beginning five seconds of the task performance and the ending five seconds of the task performance. The duration of 40 seconds and the external load of 15lb were set according to the pilot study as tasks could be performed without generating muscle fatigue. The load was made of disc weights and secured to a polyvinyl chloride (PVC), which also were used as handles. The combination of two levels of TRUNK ANGLE and two levels of WEIGHT generated four different conditions. In order to avoid the influence of lumbar muscle fatigue, participants performed two repetitions of each condition, generating a total of 8 trials.

3.3.2 Dependent variables

Dependent variables of this study include: lumbar flexion angle (LUMBAR ANGLE), lumbar passive moment (LPM), normalized EMG signals from Erector Spinae (ES), Multifidus (MU), Rectus Abdominus (RA), and External Oblique (EO).

LUMBAR ANGLE was defined as the difference between the pitch angles of the T12 and S1 motion sensors in the sagittal plane (Ning et al., 2011) (Figure 10). Each dependent variable has two sets of values; averages of the beginning five seconds and averages of the ending five seconds. Procedures of estimating LPM is explained in the data processing section.

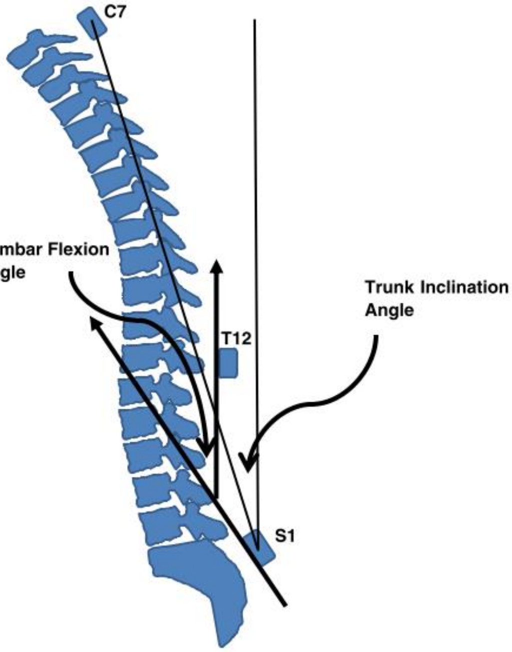


Figure 10: Definition of trunk and lumbar flexion angles (Ning et al., 2011).

3.4 Experimental procedure

Upon the arrival of participants, the procedures of the experiment were explained to participants in detail and informed consents were obtained (see Appendix C). Next, basic anthropometric data including age, body weight, height, trunk depth, width and length were measured. Participants were then given a ~10 minutes training session in order to become familiar with the tasks to be performed and to warm-up their back muscles.

At the beginning of data collection, surface EMG electrodes were first fitted to the above explained sites, and participants were required to perform two repetitions of isometric maximum trunk flexion/extension exertions at a ~20^{o} trunk flexion posture against a static resistance provided by a dynamometer (Humac Norm, CSMi, MA, USA). The maximum EMG values recorded while performing these maximum voluntary contraction (MVC) exertions were used later for EMG normalization. When completing MVC exertions, motion sensors were attached to the sites explained above and participants were asked to perform three full flexion trials, which would be used later to estimate lumbar passive moment. Participants were asked to perform a smooth forward trunk flexion (from upright posture to full flexion) during 7 seconds while maintaining a straight knee and down arms (Ning and Nussbaum, 2015). After that, participants were directed to stand in front of the reference frame to perform the designated tasks. In each trial, participants were required to maintain the designated TRUNK ANGLE (30^o or 60^o) for 40 seconds with or without holding a 15lb load in hand.

Since the main purpose of this study was to investigate how lumbar posture behaves during the sustained short-term bended trunk posture, participants were not given any instructions in what lumbar posture they should perform. The trunk angle, lumbar angle and muscular EMG were measured during the entire 40 seconds of task performance. The presentation of the eight trials was randomized and five minutes of rest was provided between trials in order to avoid the development of muscle fatigue.

To further test the development of lumbar muscle fatigue, two fatigue measurement trials were performed before and immediately after data collection in order to understand if significant lumbar muscle fatigue was generated. The fatigue measurement task required participants to hold a 20lb box in a ~45^o trunk flexion posture for 6 seconds (Hu and Ning 2015). Participants that demonstrated clear lumbar muscle fatigue during the data collection were excluded from the dataset.

3.5 Data processing

EMG signals were first transferred into frequency domain and then filtered with a low-pass frequency of 500 Hz, a high-pass frequency of 10 Hz, and a notch filter of 60 Hz and its aliases up to 500 Hz. The EMG data were then transferred back to time domain and fully rectified and smoothed. Muscle EMG signals were normalized to their maximum EMG values obtained from the MVC trials and presented as a percentage of their maximum. Muscle fatigue development was characterized by the reduction of EMG median frequency.

The method of calculating the median frequencies of the EMG data from the measurement tasks is described in the previous literature (Deluca, 1997). The three dimensional coordinates of the three motion sensors were used to calculate trunk and lumbar flexion angles. TRUNK ANGLE was calculated as the angle formed by the vertical line and the line between the C7 and the S1 motion sensors, natural upright posture generates a ~0 value (Ning et al., 2011) (Figure 10). LUMBAR ANGLE was calculated as the difference between the pitch angles of the T12 and S1 motion sensors in the sagittal plane (Ning et al., 2011) (Figure 10). In order to investigate the effect of the independent variable DURATION on the dependent variables, averages of the beginning five seconds and the ending five seconds of the static tasks performance were calculated for all dependent variables.

3.5.1 Lumbar passive moment (LPM) estimation

Lumbar posture is the major determining factor for lumbar passive tissue loading. As lumbar angle increases, the lumbar posterior passive tissues elongate, resulting in higher stress among these tissues. This relationship between the increase of lumbar passive moment and lumbar flexion angle follows a two-stage non-linear pattern (Ning et al., 2012; Ning and Nussbaum, 2015). A recent study modeled the magnitude of lumbar passive moment as a function of lumbar flexion angle during trunk flexion motions (Ning and Nussbaum, 2015). The authors also concluded that the speed of the bending motion does not have a significant influence on the total lumbar passive moment; thus, in the current study, the LPM during static trunk bending posture was estimated using Eq(1).

$$LPM(a) = \sigma_i \times \left(\frac{e^{\beta_i \times (a-c)} - 1}{e^{\beta_i} - 1} \right) \tag{1}$$

LPM: Lumbar Passive Moment.

a: Lumbar angle.

c: Initial lumbar angle in the upright standing posture (participant-specific constant).

σ_i and $\beta_{i:}$ Model parameters for subset *i*, used to control the shape of the profile.

Subset 1: from the upright standing posture to the ARB.

Subset 2: from the ARB to the full trunk flexion posture.

Parameters of the model (i.e. σ_i and β_i) were estimated for each subject from the full trunk flexion trials using a custom computer program. The least squares fitting technique were used and coefficients of determination (R^2) were calculated to ensure the best-fit for each subset (Figure 11) (Ning and Nussbaum, 2015) (Appendix A).

For each full trunk flexion trial, lumbar passive moment was estimated as the different between external moment and internal active moment. External moment at the L5/S1 joint during the full trunk flexion was calculated as a function of upper body mass, center of mass, trunk flexion angle, and instantaneous acceleration (Mirka et al., 1998; Ning and Nussbaum, 2015). Internal active moment was estimated using a previously published EMG-assisted model (Marras and Granata, 1997; Ning et al., 2012). This biomechanical model uses normalized EMG signals from ES, MU, RA, and EO to estimate the instantaneous muscle forces and moment about L5/S1 joint with the consideration of the force–length and force–velocity relationships (Davis et al., 1998; Marras and Granata, 1997). The moment arms of trunk muscles (to the center of the L5/S1 joint) and cross-sectional areas were estimated using regression equations established from the literature (Jorgensen et al., 2001; Marras et al., 2001).

After the profile of lumbar passive moment during trunk flexion trials was obtained, the dataset was then divided into two subsets at ARB and modeled separately. Parameters such as, σ and β were estimated for each subset in each trial. After that, mean values of σ_i and β_i were obtained for each subject. Finally, LPM at the beginning and ending of the short-term trunk bending tasks were estimated using Eq(1).

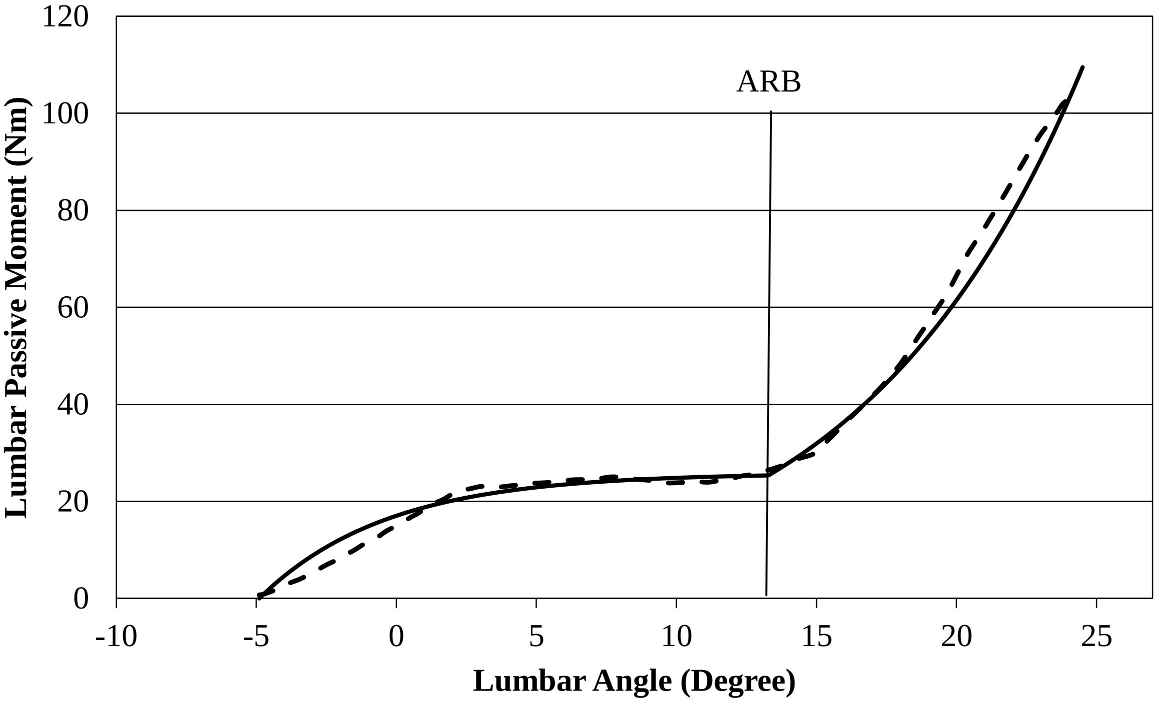


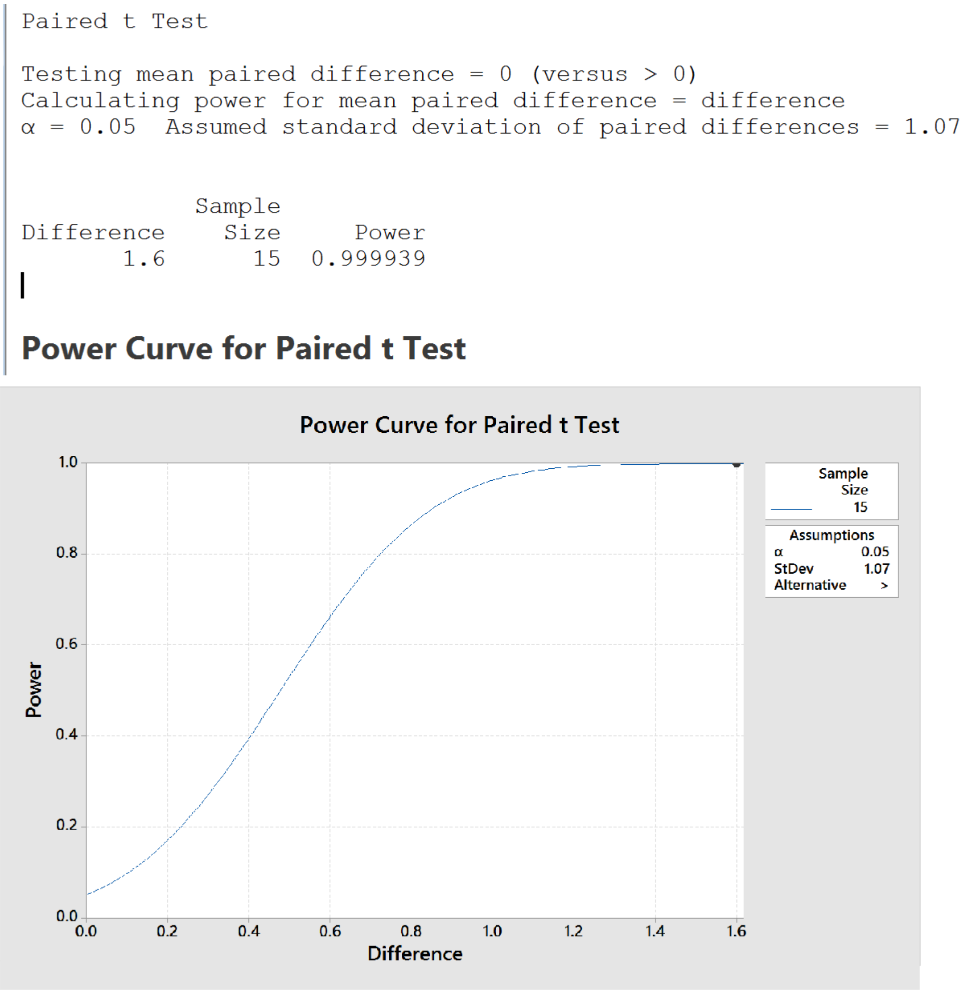
Figure 11: A sample of the modeled relationship between lumbar passive moment and lumbar flexion angle. The dashed line represent the estimated lumbar passive moment from the full trunk flexion trial. The solid line represent the modeled LPM using Eq(1).

3.6 Statistical analysis

Statistical analysis of the current study was conducted in three steps. First, the control of TRUNK ANGLE conditions and lumbar muscle fatigue was evaluated. Second, the student's t-test (paired t-test) was performed to assess the effect of DURATION on all dependent variables (see Appendix D for the normality test). Thus dependent variables obtained in the beginning of each trial were compared to the ending of the same trial. Finally, two-way ANOVA was performed to analyze the influence of the independent variables TRUNK ANGLE and WEIGHT on the changes of dependent variables from the beginning to the end of the static trunk bending task. A criteria p-value of 0.05 was used for all statistical analyses. All the statistical analysis was performed using Minitab 17 statistical analysis software (Minitab Inc., PA, USA).

3.7 Power analysis

Power analysis calculation were done on the difference observed on the dependent variable Lumbar angle due to its importance and role in the current study. Since the population mean and standard deviation for the change in lumbar angle during static posture are not available, sample mean and sample standard deviation were used to calculate the power of the statistical analysis. The mean change in lumber angle which was observed in 15 participants (i.e. sample size) was 1.6^{o} and the standard deviation was 1.07. Thus, power of the statistical analysis was 0.99. The following graph (Figure 12) shows the ROC curve and the output of power analysis in Minitab.



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Paired t Test

Testing mean paired difference = 0 (versus > 0)
Calculating power for mean paired difference = difference
α = 0.05  Assumed standard deviation of paired differences = 1.07


            Sample
Difference    Size     Power
       1.6      15  0.999939
```

Power Curve for Paired t Test

Figure 12: ROC curve and the output of power analysis in Minitab

Chapter 4: Results

4.1 The control of trunk angle and lumbar muscle fatigue

Results of our statistical analyses showed that for both 30° and 60° TRUNK ANGLE conditions the actual trunk angle remained unchanged from the beginning to ending of the 40 seconds of posture holding (Figure 13). Therefore, the magnitude of external moment was constant during the static posture holding trials. In addition, no significant reduction of lumbar muscle EMG median frequency was observed on any lumbar muscles (Figure 14), meaning that no significant muscle fatigue was generated during the data collection.

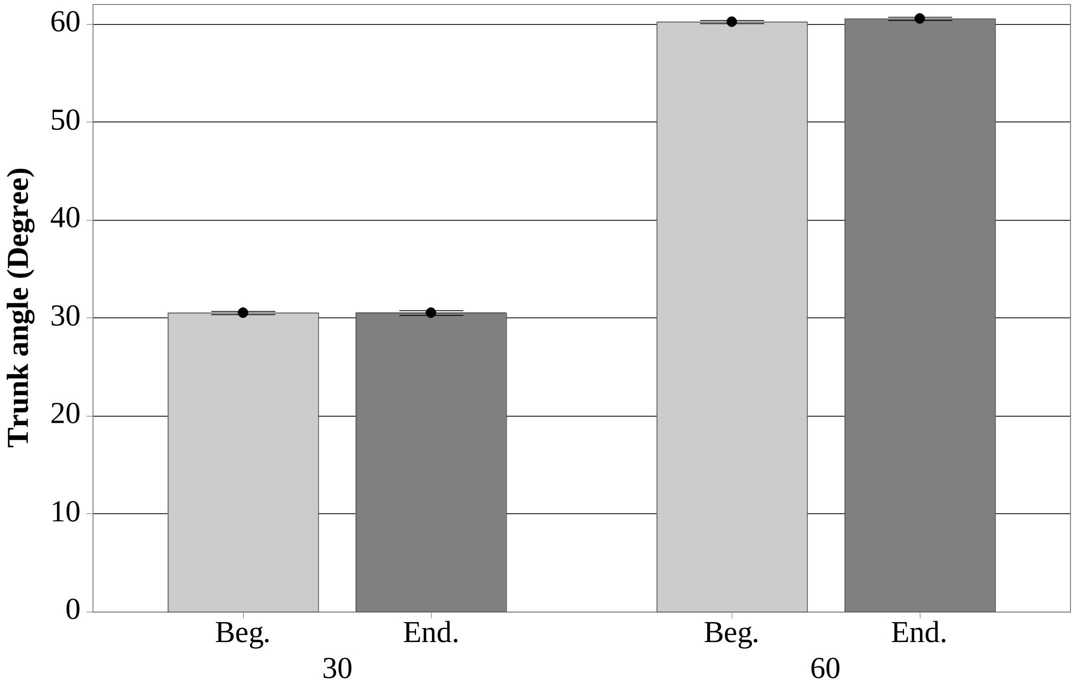

Figure 13: Beginning and ending of TRUNK ANGLE posture at 30° and 60° levels.

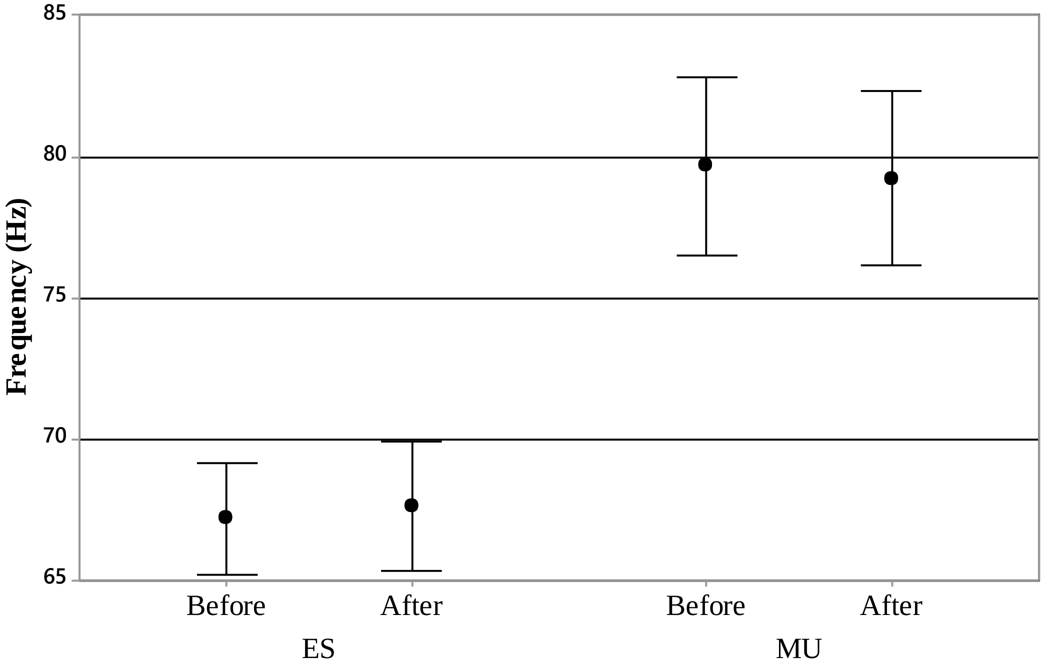

Figure 14: Median frequency from the fatigue measurement trials for the back muscles (ES and MU) before and after the task performance. Star indicates significant change. Bars indicate the corresponding standard error.

4.2 The effects of DURATION

Statistical analysis of the independent variable DURATION is the most important in the current study because such analysis can reveal the underlying mechanism of LUMBAR ANGLE and lumbar active and passive muscle synergy during the static posture holding.

To investigate how maintaining short-term static trunk flexion could affect the dependent variables, the effect of the independent variable DURATION on all dependent variables was investigated using paired t-test for each level of TRUNK ANGLE and WEIGHT. Figure 15 displays how lumbar angle changed during the short-term static postures from beginning to ending of the static posture holding. LUMBAR ANGLE was significantly increased at the ending of the static postures in all conditions except the condition of 30^o trunk angle with external weight. Lumbar angle slightly increased in the 30^o trunk angle with external weight condition; however, this increment was not statistically significant. In other words, when participants maintained trunk flexion posture for 40s LUMBAR ANGLE increased significantly at the end of the posture holding.

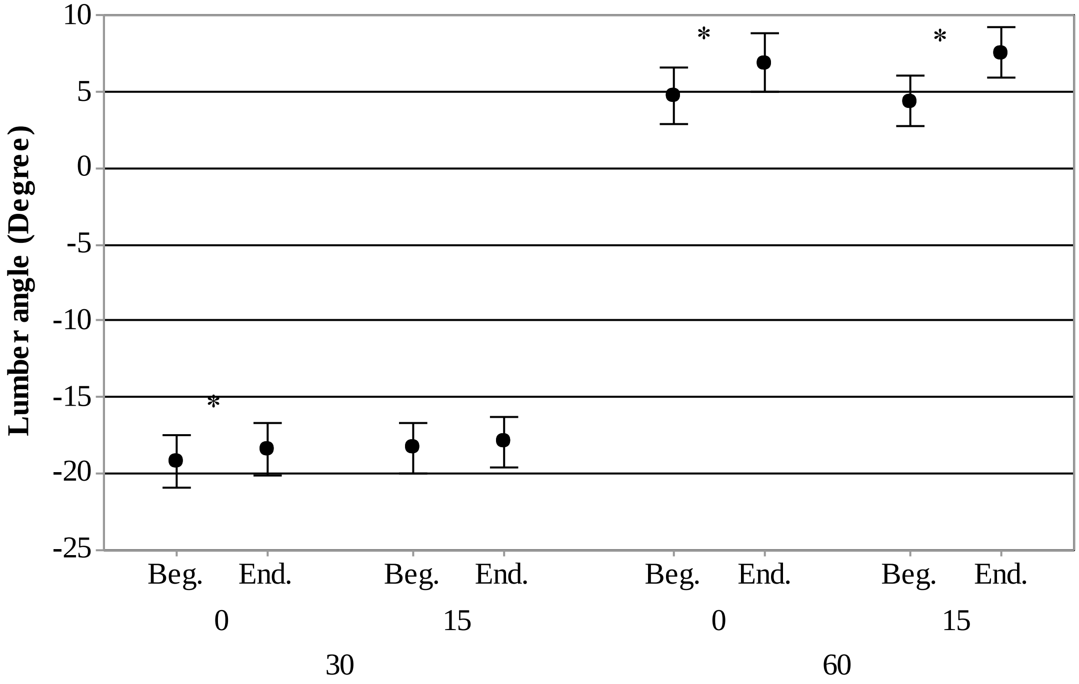

Figure 15: Beginning and ending of LUMBAR ANGLE during the deferent conditions of TRUNK ANGLE (i.e. 30^o and 60^o) and WEIGHT (i.e. 0 and 15lb). Star indicates significant change. Bars indicate the corresponding standard error.

Together with the increase of LUMBAR ANGLE, significant reduction of muscle activities (normalized EMG) were observed from ES and MU in all TRUNK ANGLE and WEIGHT conditions but the condition of 30^o trunk angle without external weight for ES (Figures 16, 17). RA and EO at the 30^o condition reduced slightly but significantly at both conditions of WEIGHT; while at the 60^o condition the effect of DURATION was not significant on RA and EO (Figures 18, 19). Finally, LPM increased significantly after maintaining short-time static bended trunk postures in all conditions except when maintaining

30^o trunk angle with external weight; yet LPM increased slightly, but not with a statistically significant result in this condition (Figure 20). All these results about the effect of DURATION support our initial hypothesis.

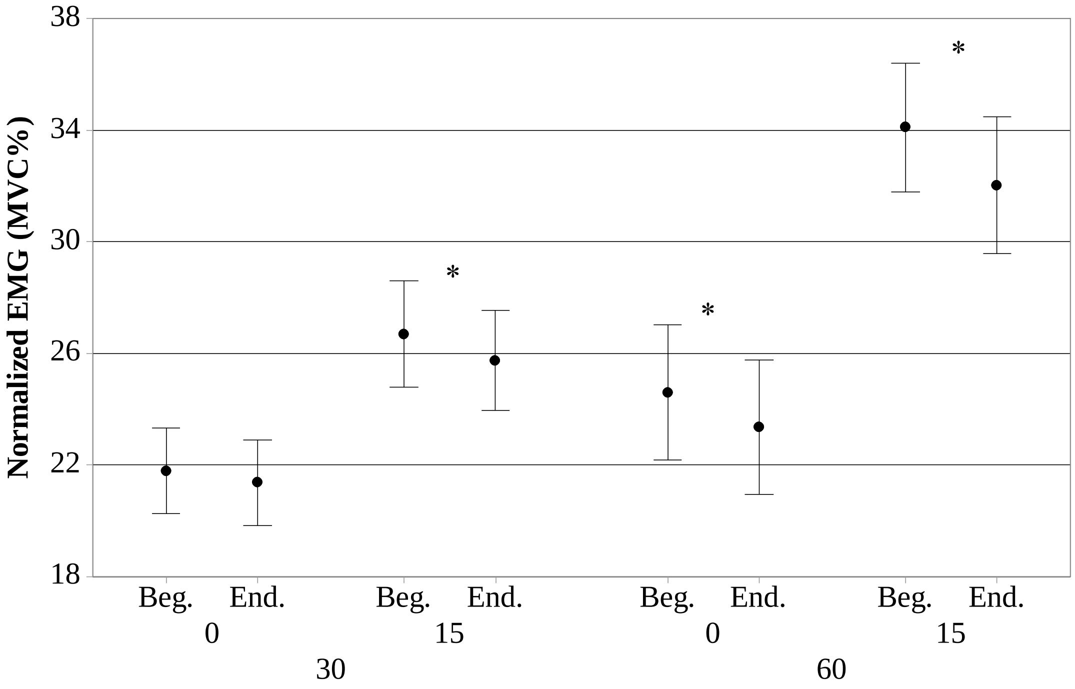

Figure 16: Beginning and ending of normalized EMG signals for ES during the deferent conditions of TRUNK ANGLE (i.e. 30^o and 60^o) and WEIGHT (i.e. 0 and 15lb). Star indicates significant change. Bars indicate the corresponding standard error.

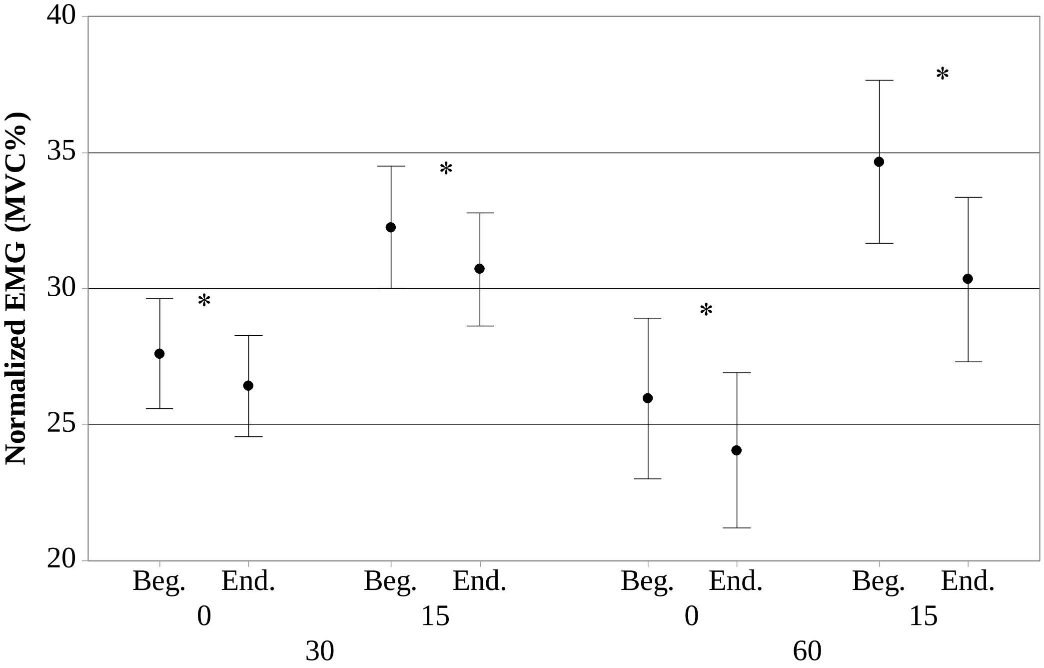

Figure 17: Beginning and ending of normalized EMG signals for MU during the deferent conditions of TRUNK ANGLE (i.e. 30° and 60°) and WEIGHT (i.e. 0 and 15lb). Star indicates significant change. Bars indicate the corresponding standard error.

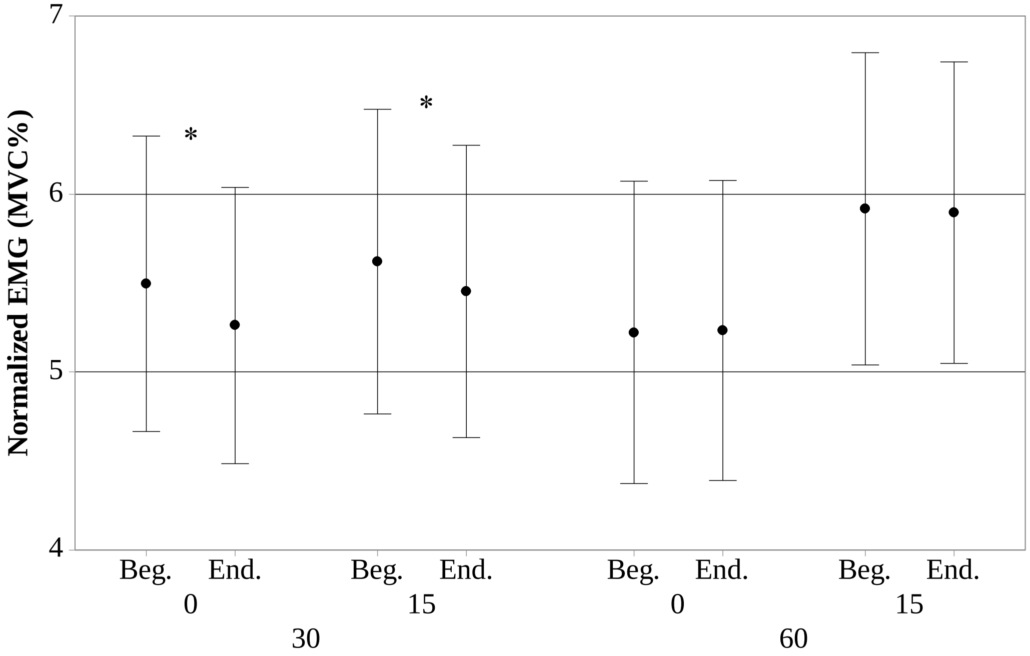

Figure 18: Beginning and ending of normalized EMG signals for RA during the deferent conditions of TRUNK ANGLE (i.e. 30° and 60°) and WEIGHT (i.e. 0 and 15lb). Star indicates significant change. Bars indicate the corresponding standard error.

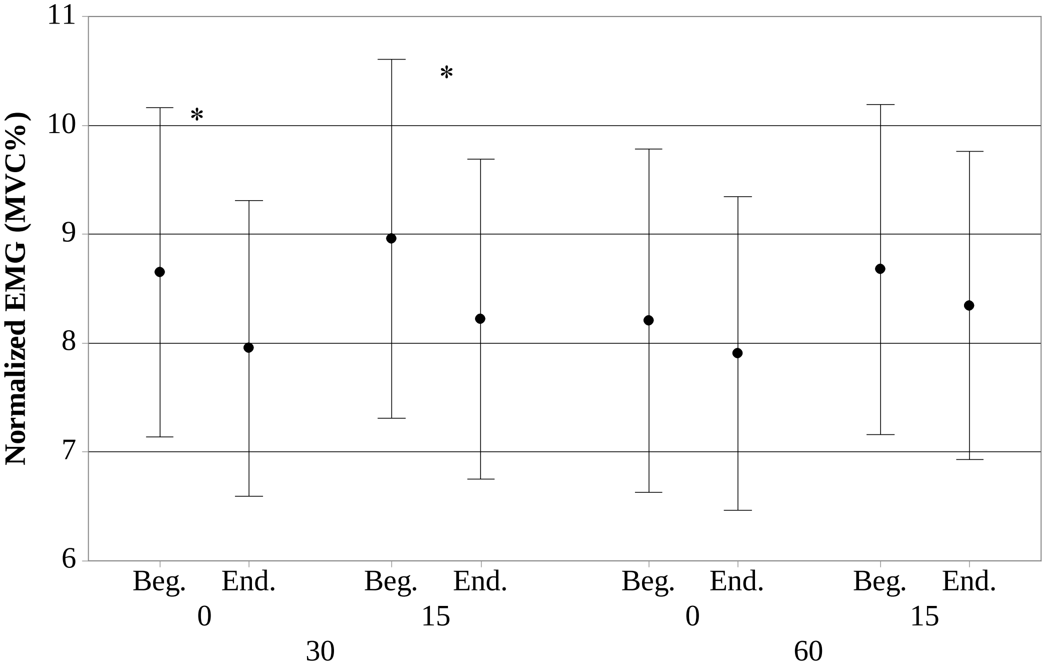

Figure 19: Beginning and ending of normalized EMG signals for EO during the deferent conditions of TRUNK ANGLE (i.e. 30° and 60°) and WEIGHT (i.e. 0 and 15lb). Star indicates significant change. Bars indicate the corresponding standard error.

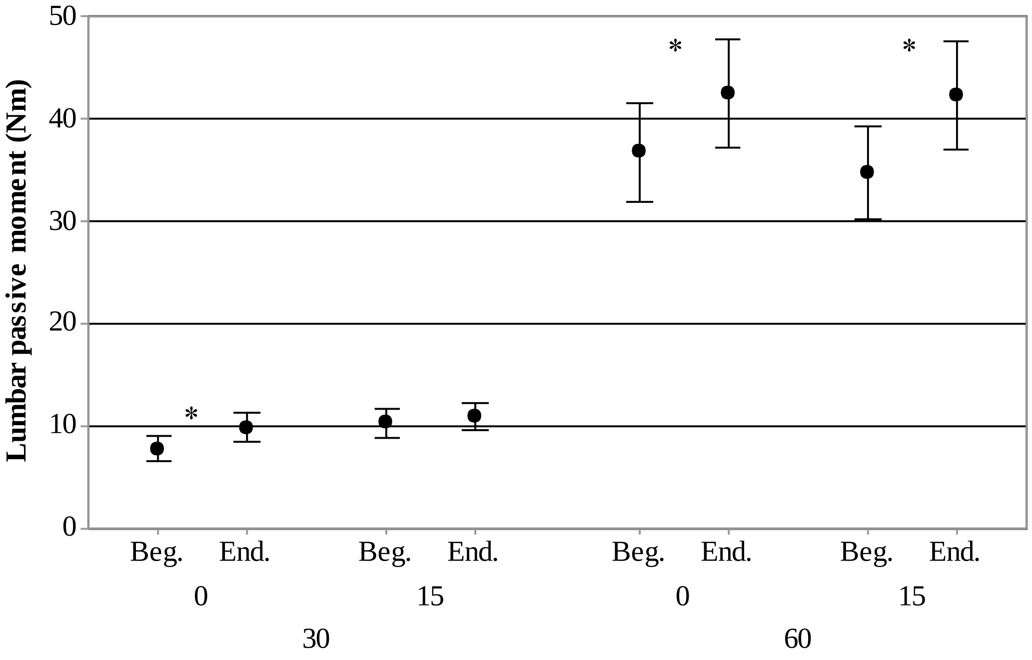

Figure 20: Beginning and ending of lumbar Passive moment (LPM) at diffract conditions of TRUNK ANGLE (i.e. 30° and 60°) and WEIGHT (i.e. 0 and 15lb). Star indicates significant change. Bars indicate the corresponding standard error.

4.3 The effects of TRUNK ANGLE and WEIGHT

Further statistical analysis was performed to look at whether changing between different conditions of TRUNK ANGLE and WEIGHT could have a significant effect on the amount of change at the ending of the short-term static postures. This analysis was done with respect to the difference between beginning and ending of all dependent variables. In other words, data obtained from the ending of the sustained short-term trunk bending were substituted from that obtained from the beginning of the short-term static bending. Univariate ANOVA analysis showed that the independent variable TRUNK ANGLE significantly affected the amount of change on all dependent variables except ES muscle. The effect of the independent variable WEIGHT and the interaction effect between TRUNK ANGLE and WEIGHT were not significant (Table1).

Table 1: Results of univariate ANOVA analysis for the effect of TRUNK ANGLE and WEIGHT on the amount of change. Bolded values indicate significant affect by independent variable.

Independent Variables	Dependent variables					
	LUMBAR ANGLE	ES	MU	RA	EO	LPM
TRUNK ANGLE	**$P < 0.001$**	$P = 0.104$	**$P = 0.012$**	**$P = 0.009$**	**$P = 0.043$**	**$P = 0.001$**
WEIGHT	$P = 0.388$	$P = 0.214$	$P = 0.071$	$P = 0.689$	$P = 0.857$	$P = 0.896$
TRUNK ANGLE *WEIGHT	$P = 0.051$	$P = 0.961$	$P = 0.259$	$P = 0.648$	$P = 0.978$	$P = 0.332$

Table 2 illustrates the significant effect of TRUNK ANGLE by displaying the mean values of change at the ending of the static postures. Conditions of TRUNK ANGLE were tested using paired t-test. Changing TRUNK ANGLE from 30^o to 60^o significantly caused more change at LUMBAR ANGLE, MU and LPM. While a similar trend was also observed for the ES muscles, such an effect was not statistically significant. The change at RA and EO muscles was also significant, but in an opposite pattern. Increasing TRUNK ANGLE caused less change at the ending of the static postures.

Table 2: Mean values for the amount of change at the end of performing the static postures for dependent variables at deferent conditions of TRUNK ANGLE.

TRUNK ANGLE	Dependent variables					
	LUMBAR ANGLE (º)	ES (%MVC)	MU (%MVC)	RA (%MVC)	EO (%MVC)	LPM (Nm)
30º	0.6	-0.7	-1.5	-0.2	-0.7	1.4
60º	2.7	-1.7	-3.2	0	-0.4	6.7

Chapter 5: Discussion and conclusions

The goal of the current study was to investigate the changes of lumbar biomechanics during short-term sustained trunk bending. During the experiment, participants stayed in 30^o or 60^o of flexed trunk posture with or without an external load for 40 seconds. Since observing changes on the lumbar posture was one of the main purposes of this study, no instructions were given to participants regarding what specific lumbar posture to obtain. Results showed that trunk angle and lumbar muscle fatigue was successfully controlled; thus, external moment was constant during the static posture holding, and the effects of lumbar muscle fatigue on trunk biomechanics were eliminated.

Change in both lumbar posture and muscle activities were observed (this change was significant in most conditions) during the course of the 40 seconds static trunk bending. Specifically, these results indicate that lumbar muscle activity significantly decreased, while short-term bended trunk posture was maintained. This reduction of lumbar muscle activity was coupled with significant increment of lumbar passive moment, which indicates the load shifting from lumbar active to passive tissue. This was also shown by the observed significant increment of lumbar flexion angle.

When maintaining static trunk flexion postures, the external moment about the L5/S1 joint (mainly determined by upper body weight and external load) is counterbalanced by forces generated by both lumbar active and passive tissues. Given that trunk posture is fixed (i.e. constant external moment) and muscle fatigue is controlled, the synergy between active and passive tissue to resist the external moment around L5/S1 joint is mainly governed by lumbar posture (Arjmand and Shirazi-Adl, 2005). As lumbar angle increases (i.e. flexed posture), lumbar passive tissues elongate and generate higher passive force. Consequently, less lumbar active muscle forces are needed to resist external moment. This phenomenon was confirmed by the observed reduced lumbar active muscle activity. Findings of the current study illustrate the main role of lumbar posture on the synergy between lumbar active and passive tissue and spinal loadings; findings which concur with the existing literature (Potvin et al. 1991; McGill, 1997; Arjmand and Shirazi-Adl, 2005).

A possible explanation of the observed reduction in lumbar extensor muscle activation during the static posture holding is that this is possibly an internal motor mechanism to help reduce the accumulation of lumbar muscle fatigue by allocating loadings to the passive tissues. Our results show that participants tended to adopt more flexed postures toward the ending of the static posture holding, which transferred more loadings to lumbar passive tissues. Such a mechanism is beneficial in protecting lumbar muscles, which in turn will allow longer duration of task performance. However, the increased lumbar passive tissue loading could lead to the development of lumbar passive tissue creep (Solomonow et al., 2003; Shin and Mirka, 2007).

In the past, creep induced by prolonged static exposure was only reported and investigated after maintaining deep full trunk flexion for a long period of time. McGill and Brown (1992), for example, reported that after 20 minutes of static trunk full flexion, lumbar flexion angle increased (i.e. creep) by an average of 5.5°. Another study observed an average increase in the lumbar flexion angle by ~ 4° after performing 10 minutes of full trunk flexion (Shin and Mirka, 2007). Creep among lumbar passive tissues is typically caused by maintaining fully flexed lumbar posture for an extended period of time. The magnitude of lumbar passive moment during such trunk full flexion was reported to be around 120 Nm (Ning et al., 2012; Ning and Nussbaum, 2015). In the current study, lumbar passive moment at trunk mid-range flexion (e.g. 60°) reached around 42 Nm at the ending of the static posture holding (Figure 20). Hence, findings of the present study suggest that mid-range static trunk flexion postures (e.g. 30° and 60°) are generally safe but could potentially generate passive tissue creep only when performed repeatedly over a long period of time.

As discussed in the background section, creep deformation increases the amount of laxity among lumbar passive tissues, causing these tissues to be stretched more in order to maintain the same force output. This reduction of lumbar tissue stiffness may further compromise the stability of lumbar structure and its ability to overcome external loading (Adams et al., 1987; Olson et al., 2004; Solomonow, 2004). With the development of lumbar passive tissue creep, larger active muscle forces are needed to compensate the reduced internal moment (McCook et al., 2009; Olson et al., 2009), which could accelerate the accumulation of muscle fatigue (Shin et al., 2009; Adams and Dolan, 1995). As a result, the overall spinal stability could be further reduced, which elevates the risk of LBP (Solomonow et al., 2000; Granata and Orishimo, 2001; Cholewicki and McGill, 1996; Solomonow, 2004).

Results shown in table 2 indicate that when more flexed trunk posture was maintained (i.e. 60°), the amount of change in the lumbar angle, extensor muscles (i.e. ES and MU), and LPM induced by the sustained short-term trunk bended postures increased. The mean increase in lumbar angle at the ending of the posture holding was 0.6° and 2.7° at 30° and 60° trunk angle flexion, respectively. When lumbar spine is flexed more (i.e. increased lumbar angle), lumbar passive tissue is stretched more which means increased lumbar passive force output. This relationship between lumbar flexion angle and passive force was illustrated in the present work by the increased amount of LPM at the ending of the 60° trunk posture, as compared to 30° posture. This relationship was explained in the literature to follow a well-defined non-linear pattern of lumbar passive moment increase (Ning et al., 2012; Ning and Nussbaum, 2015).

Results of the present work showed that holding an external load during the sustained short-term trunk bended postures did not affect the change in lumbar posture and LPM significantly (Table 1). A potential explanation could be the relatively light external load used in this study (i.e. 15lb) and the short time of exposure. Heavier hand load and longer posture holding duration could possibly introduce more changes to the lumbar biomechanics.

Findings of the present study demonstrate that in real occupational settings, when workers are required to sustain short-term bended trunk posture (e.g. harvesting, masonry, assembly line, etc.), the internal loading will be gradually shifted from lumbar active tissues to passive tissues over time. One previous study reported decreased L5/S1 joint compression and shear forces when the lumbar spine is flexed (Arjmand and Shirazi-Adl, 2005). In such a scenario, lumbar passive tissues serve as the main load bearer in counterbalancing the external moment. However, as discussed earlier, increased passive load could eventually accumulate creep. Thus, it could be prudent to advise those whose jobs involve repetitive short-term bended trunk postures to take breaks in between to avoid accumulation of lumbar passive creep. Also, it is suggested to train workers in such occupations to perform static trunk bindings with slightly flexed lumbar posture in order to avoid/delay muscle fatigue development. This suggestion is based on the findings of previous studies that during static bending postures muscle fatigue development is much faster than the development of creep deformation (McGill and Brown, 1992; Shin et al., 2009).

The current study has some limitations that need to be noted. To avoid the possibility of unwanted lumbar muscle fatigue, relatively short duration of static trunk posture holding tasks were performed. Future studies should investigate the changes of lumbar postures and trunk muscle activities when holding static posture for longer periods of time. In addition, the magnitude of the external load used in the current study was relatively low. Thus, no significant effect of the external load was observed. Finally, only male participants were recruited in the present work. Previous studies reported that females may have slightly different lumbar tissue structure and soft tissue viscoelastic properties (McGill and Brown, 1992; Norton et al., 2004).

In conclusion, the purpose of the current study was to investigate lumbar biomechanics during sustained short-term trunk bending tasks. During the performance of these tasks, although the general trunk positions remain unchanged, the underlying mechanism of controlling the equilibrium between external and internal moment was found to undergo several changes. The main finding of the present work is the observed load shifting from lumbar active to lumbar passive tissues during the static posture holding. Specifically, at the ending of the static posture holding, lumbar active muscle activities decreased, and this reduction was compensated by increased passive tissue force output induced by the increased lumbar flexion angle. This effect was also shown by the increased lumbar passive moment at the ending of the static posture holding. While such a mechanism could prevent or reduce lumbar muscle fatigue, it may simultaneously accelerate the development of creep among lumber passive tissues, which may lead to long term spinal disorders.

5.1 Future direction

The current study mainly focused on the changes of lumbar biomechanics during static short-term bended trunk posture. It was suggested that when workers in occupational setting perform such postures, more flexed lumbar posture is recommended in order to delay lumbar muscle fatigue. However, in some situations workers perform longer duration (i.e. prolonged) or more repetitions of static trunk bending which could result in more changes in lumbar biomechanics. Future studies should investigate changes in lumbar biomechanics during prolonged and repeated static postures. Results obtained from the current study showed that during the sort-term static trunk bending only small portion of internal lumbar active loading was transferred into passive loading, meaning that muscle fatigue development would still occur at some point. Moreover, studying prolonged or repeated static trunk bending tasks could be beneficial in investigating the possibility of lumbar creep deformation occurrence as a result of the load shifting from lumbar active to passive component. Also, if prolonged static postures could result in more load shifting as compared to short-term static postures, it is important to investigate whether the increased lumbar passive loading could elevate the risk of injury or not.

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Appendixes

Appendix A: Recruitment letter

Dear [Mr. LAST NAME],

I am writing to tell you about a study that being conducted at the ergonomics lab at West Virginia University (WVU) by Dr. Xiaopeng Ning (Principal Investigator) and Faisal Alessa (Co-Investigator). The title of this study is "Lumbar Posture and Tissue Loading during short-term Static Trunk Bending". The purpose of this research is to investigate the changes of lumbar biomechanics during static trunk bending tasks. Generally, the study involves maintaining two levels of forward trunk flexion (30 and 60 degree) for 40 seconds with and without holding external weight of 15lb. the total number of trials is 8. It also involves 4 trials to measure the maximal voluntary contraction and two trials of holding 20 lb. for 6 seconds. The study last for around 90 minutes.

You may be eligible for participating in this study if you have no current or history of low back pain.

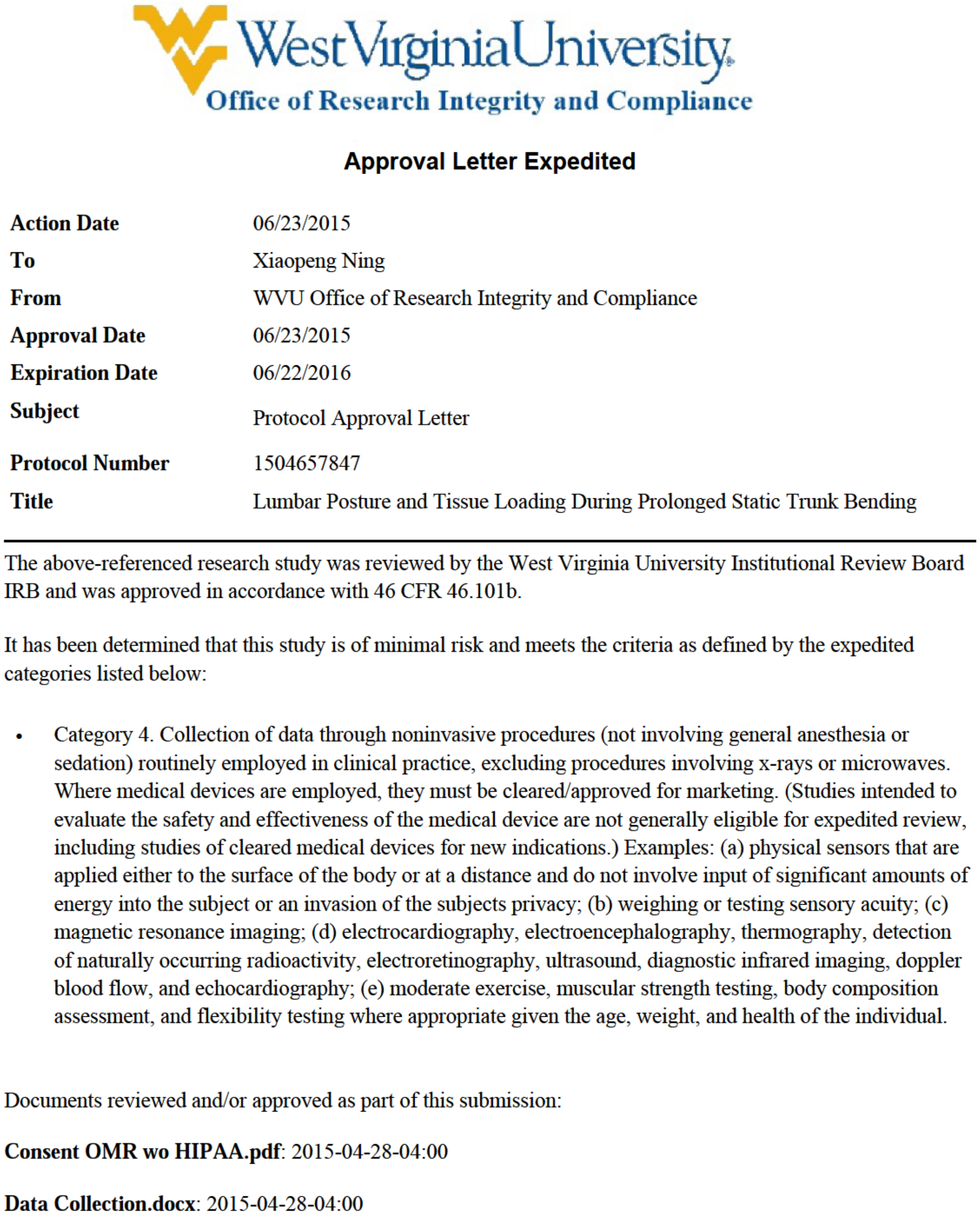
It is important to know that this letter is not to tell you to join this study. It is your decision. Your participation is voluntary. Whether or not you participate in this study will have no effect on your grades or your standing at WVU.

If you are interested in participating in this study, please respond to this email to provide you with all the information about this study. You do not have to respond if you are not interested in this study. If you do not respond, no one will contact you.

Thank you for your time and consideration. We look forward to hearing from you.

Sincerely,

Appendix B: IRB approval letter



West Virginia University
Office of Research Integrity and Compliance

Approval Letter Expedited

Action Date	06/23/2015
To	Xiaopeng Ning
From	WVU Office of Research Integrity and Compliance
Approval Date	06/23/2015
Expiration Date	06/22/2016
Subject	Protocol Approval Letter
Protocol Number	1504657847
Title	Lumbar Posture and Tissue Loading During Prolonged Static Trunk Bending

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The above-referenced research study was reviewed by the West Virginia University Institutional Review Board IRB and was approved in accordance with 46 CFR 46.101b.

It has been determined that this study is of minimal risk and meets the criteria as defined by the expedited categories listed below:

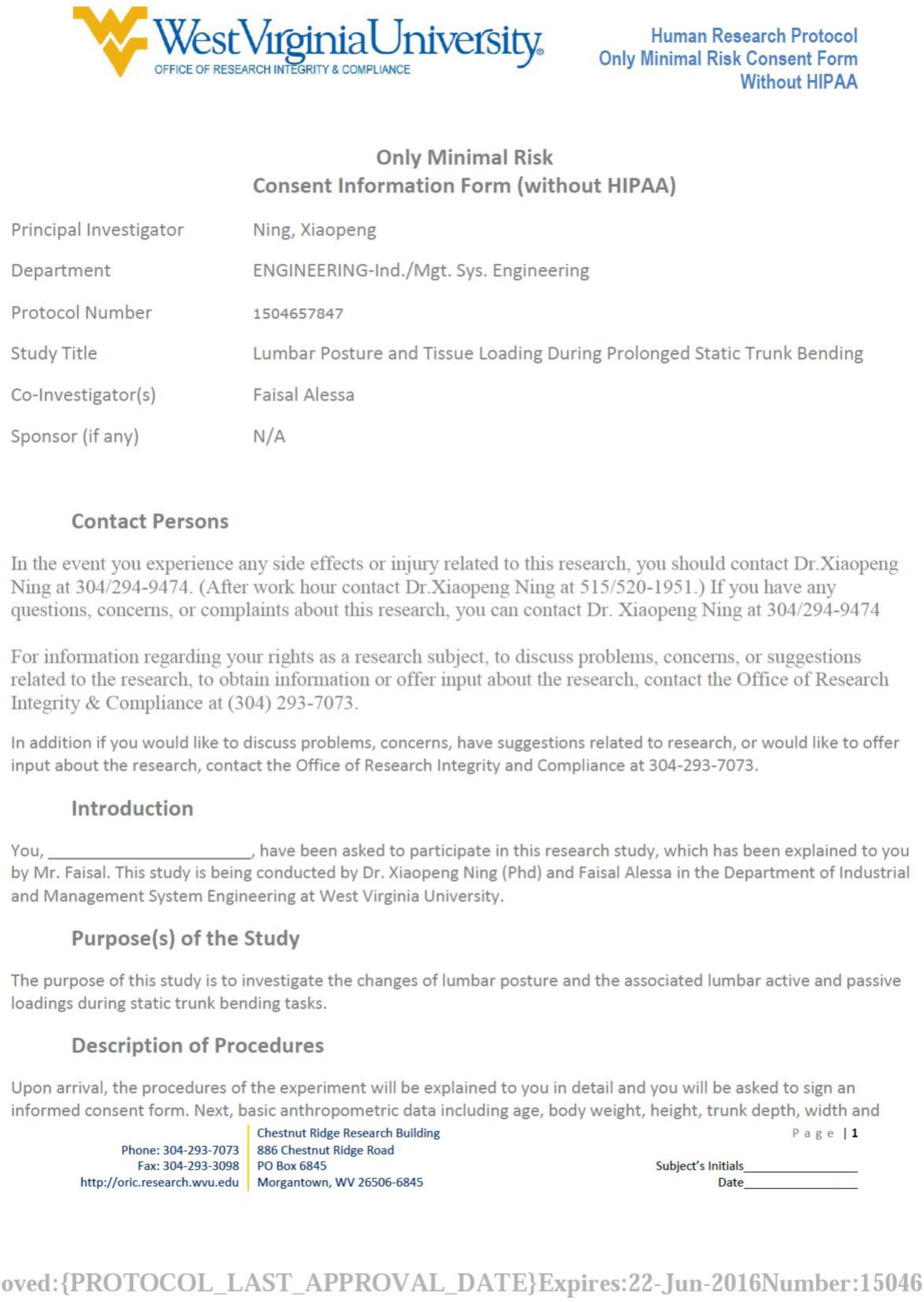
- Category 4. Collection of data through noninvasive procedures (not involving general anesthesia or sedation) routinely employed in clinical practice, excluding procedures involving x-rays or microwaves. Where medical devices are employed, they must be cleared/approved for marketing. (Studies intended to evaluate the safety and effectiveness of the medical device are not generally eligible for expedited review, including studies of cleared medical devices for new indications.) Examples: (a) physical sensors that are applied either to the surface of the body or at a distance and do not involve input of significant amounts of energy into the subject or an invasion of the subjects privacy; (b) weighing or testing sensory acuity; (c) magnetic resonance imaging; (d) electrocardiography, electroencephalography, thermography, detection of naturally occurring radioactivity, electroretinography, ultrasound, diagnostic infrared imaging, doppler blood flow, and echocardiography; (e) moderate exercise, muscular strength testing, body composition assessment, and flexibility testing where appropriate given the age, weight, and health of the individual.

Documents reviewed and/or approved as part of this submission:

Consent OMR wo HIPAA.pdf: 2015-04-28-04:00

Data Collection.docx: 2015-04-28-04:00

Appendix C: Consent form



West Virginia University
OFFICE OF RESEARCH INTEGRITY & COMPLIANCE

Human Research Protocol
Only Minimal Risk Consent Form
Without HIPAA

Only Minimal Risk
Consent Information Form (without HIPAA)

Principal Investigator	Ning, Xiaopeng
Department	ENGINEERING-Ind./Mgt. Sys. Engineering
Protocol Number	1504657847
Study Title	Lumbar Posture and Tissue Loading During Prolonged Static Trunk Bending
Co-Investigator(s)	Faisal Alessa
Sponsor (if any)	N/A

Contact Persons

In the event you experience any side effects or injury related to this research, you should contact Dr.Xiaopeng Ning at 304/294-9474. (After work hour contact Dr.Xiaopeng Ning at 515/520-1951.) If you have any questions, concerns, or complaints about this research, you can contact Dr. Xiaopeng Ning at 304/294-9474

For information regarding your rights as a research subject, to discuss problems, concerns, or suggestions related to the research, to obtain information or offer input about the research, contact the Office of Research Integrity & Compliance at (304) 293-7073.

In addition if you would like to discuss problems, concerns, have suggestions related to research, or would like to offer input about the research, contact the Office of Research Integrity and Compliance at 304-293-7073.

Introduction

You, _______________________, have been asked to participate in this research study, which has been explained to you by Mr. Faisal. This study is being conducted by Dr. Xiaopeng Ning (Phd) and Faisal Alessa in the Department of Industrial and Management System Engineering at West Virginia University.

Purpose(s) of the Study

The purpose of this study is to investigate the changes of lumbar posture and the associated lumbar active and passive loadings during static trunk bending tasks.

Description of Procedures

Upon arrival, the procedures of the experiment will be explained to you in detail and you will be asked to sign an informed consent form. Next, basic anthropometric data including age, body weight, height, trunk depth, width and length will be measured. You will be then given a ~10 minutes training session in order to become familiar with the tasks to be performed and warm-up your back muscles. You will then be fitted with a set of sensors designed to capture muscle activation levels (EMG) and 3D positions and angles (Motion sensors). EMG sensors will be placed over the following muscles (right and left): erector spinae, lumbar multifidus and abdominal muscle. Motion sensors will be placed over the following location: neck C7 level, thoracic spine T12 level and lumbar spine L5 level. You will then stand on HUMAC NORM with your trunk, pelvis points and lower extremities secured and perform two trials of maximum lumbar extension and two trials of maximum lumbar flexion against a stationary resistance in a 20 degree lumbar forward flexion posture. Each maximum voluntary contraction trial will be five seconds long and a one minute rest period will be provided between exertions in order to reduce the chance of fatigue and injury. Up until then, the set up procedure finishes. You will then move to the testing area and perform designated tasks. you will perform 8 repetitions of prolonged trunk flexion for 40 seconds. Four of these repetitions will include holding a 15lbs. weight. You will also be asked to perform two more trials right before and after the data collection in order to understand if clear lumbar muscle fatigue was generated. The fatigue measurement task requires you to hold a 20lbs box in a ~45 degree trunk flexion posture for 6 seconds. This study will take approximately 90 minutes.

Discomforts

There is a minimal risk for low back muscle strain and fatigue while performing the maximum exertions. Therefore, you will be required to complete a warm up before these tasks and sufficient rest between trials.

Alternatives

You do not have to participate in this study.

Benefits

You may not receive any direct benefit from this study. The knowledge gained from this study may eventually benefit others.

Financial Considerations

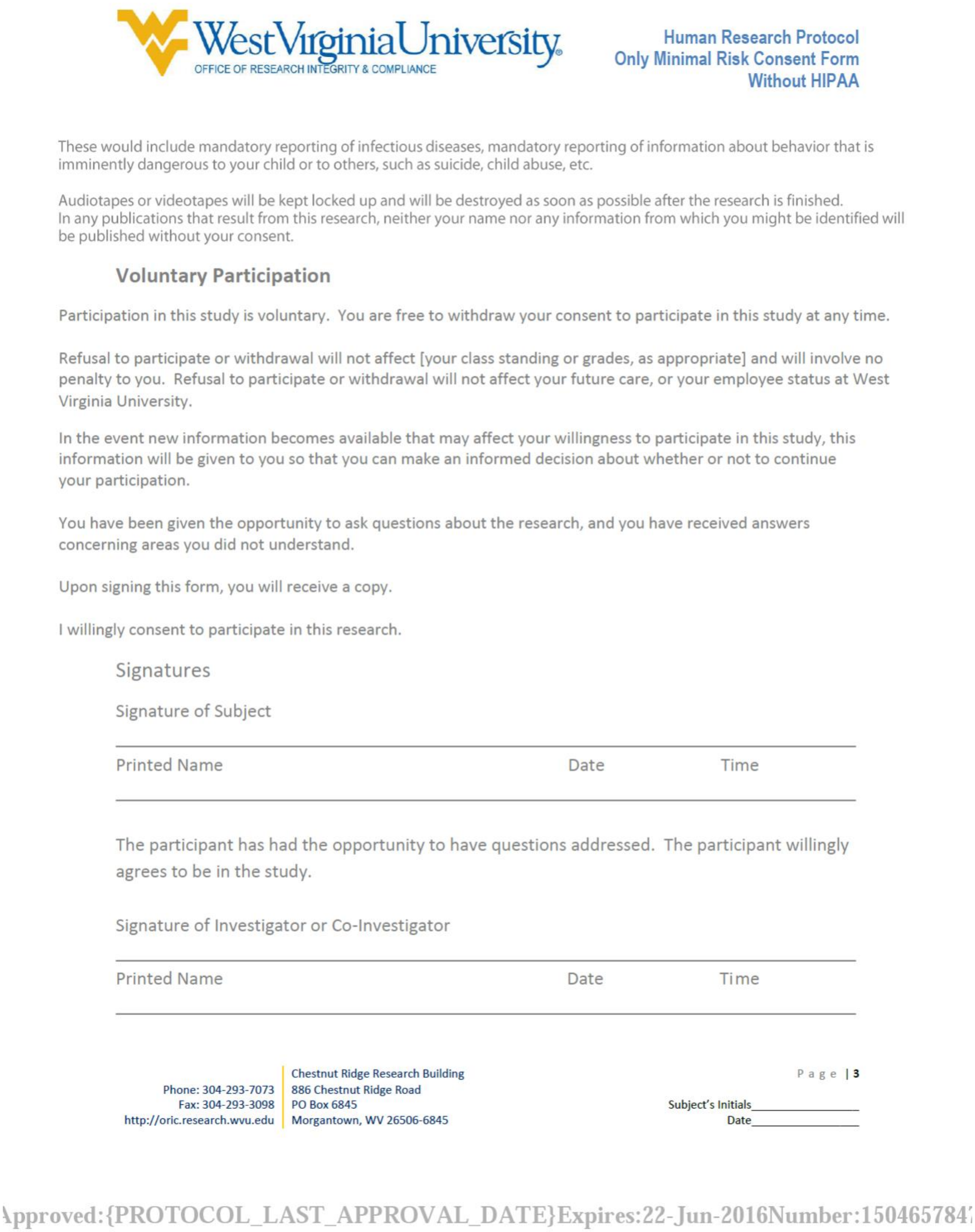
You will not receive any compensation for participation in the study and will not incur any costs related to the study. It is very important for you to understand that neither the investigator nor WVU or it associated affiliates has the funds set aside to pay for the cost work wages or any care or treatment that might be necessary because you get hurt or sick taking part in this study. Any injuries that may result from this study would not be eligible for workers' Compensation as this is not a job related injury. Understand that any treatments necessary will be billed to the participant or to your personal health insurance, and you may wish to consult your insurance provider before participating in this study.

Confidentiality

Any information about you that is obtained as a result of your participation in this research will be kept as confidential as legally possible. Your research records and test results, just like hospital records, may be subpoenaed by court order or may be inspected by the study sponsor or federal regulatory authorities (including the FDA if applicable) without your additional consent.

In addition, there are certain instances where the researcher is legally required to give information to the appropriate authorities.

Subject's Initials________________
Date________________



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Human Research Protocol
Only Minimal Risk Consent Form
Without HIPAA

These would include mandatory reporting of infectious diseases, mandatory reporting of information about behavior that is imminently dangerous to your child or to others, such as suicide, child abuse, etc.

Audiotapes or videotapes will be kept locked up and will be destroyed as soon as possible after the research is finished.
In any publications that result from this research, neither your name nor any information from which you might be identified will be published without your consent.

Voluntary Participation

Participation in this study is voluntary. You are free to withdraw your consent to participate in this study at any time.

Refusal to participate or withdrawal will not affect [your class standing or grades, as appropriate] and will involve no penalty to you. Refusal to participate or withdrawal will not affect your future care, or your employee status at West Virginia University.

In the event new information becomes available that may affect your willingness to participate in this study, this information will be given to you so that you can make an informed decision about whether or not to continue your participation.

You have been given the opportunity to ask questions about the research, and you have received answers concerning areas you did not understand.

Upon signing this form, you will receive a copy.

I willingly consent to participate in this research.

Signatures

Signature of Subject

Printed Name Date Time

The participant has had the opportunity to have questions addressed. The participant willingly agrees to be in the study.

Signature of Investigator or Co-Investigator

Printed Name Date Time

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Subject's Initials________________
Date________________

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Appendix D: Statistical analysis

i. Normality test:

The normality assumption of the difference between beginning and ending of dependent variables was checked using Kolmogorov-Smirnov test as follow:

Hypothesis:

H_0: The data follow a normal distribution.
H_a: The data do not follow a normal distribution.
$\alpha = 0.05$

Kolmogorov-Smirnov test was performed using Minitab and the following graphs show the probability plots for data of important dependent variables. As can be seen in the following figures, p-values are greater than 0.05 which means that the data follow normal distribution.

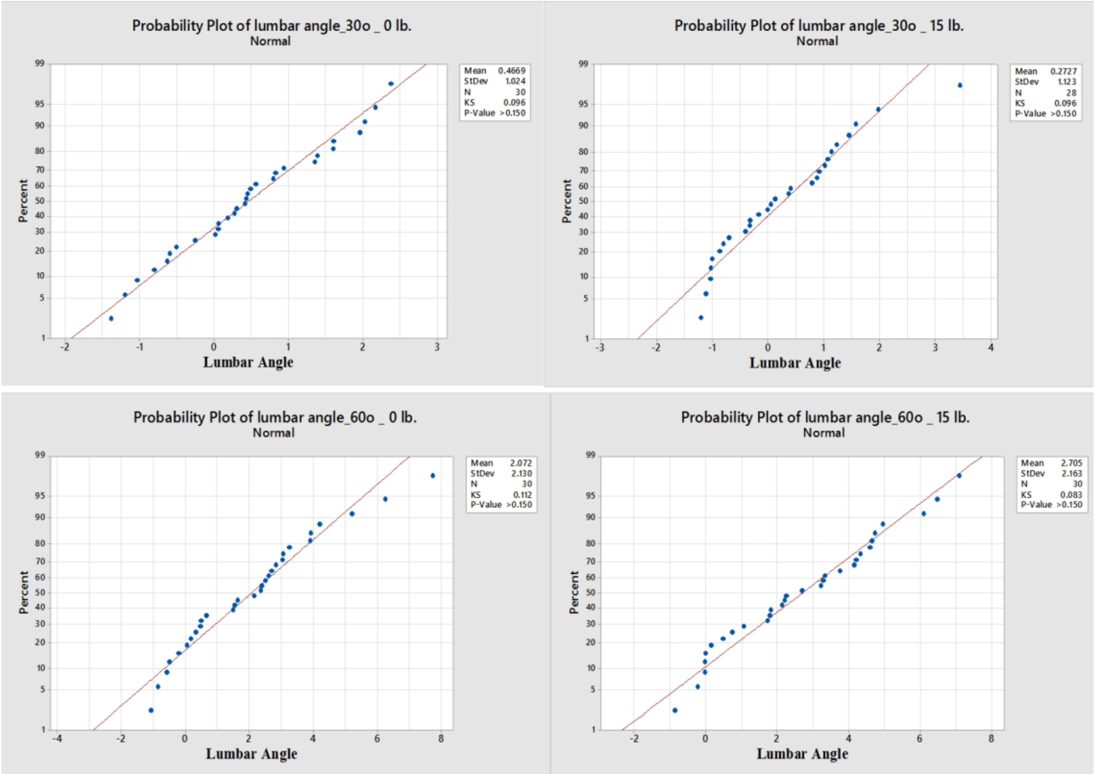

Figure (a): Normality test for the difference between beginning and ending lumbar angle.

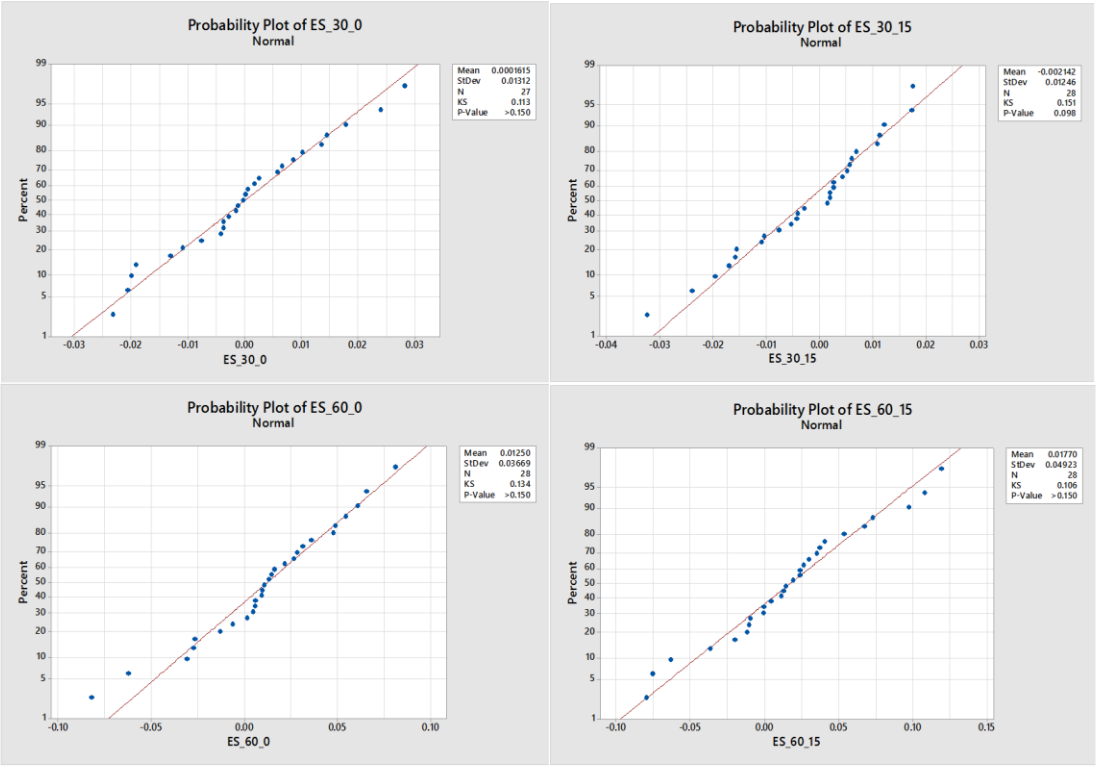

Figure (b): Normality test for the difference between beginning and ending ES activities.

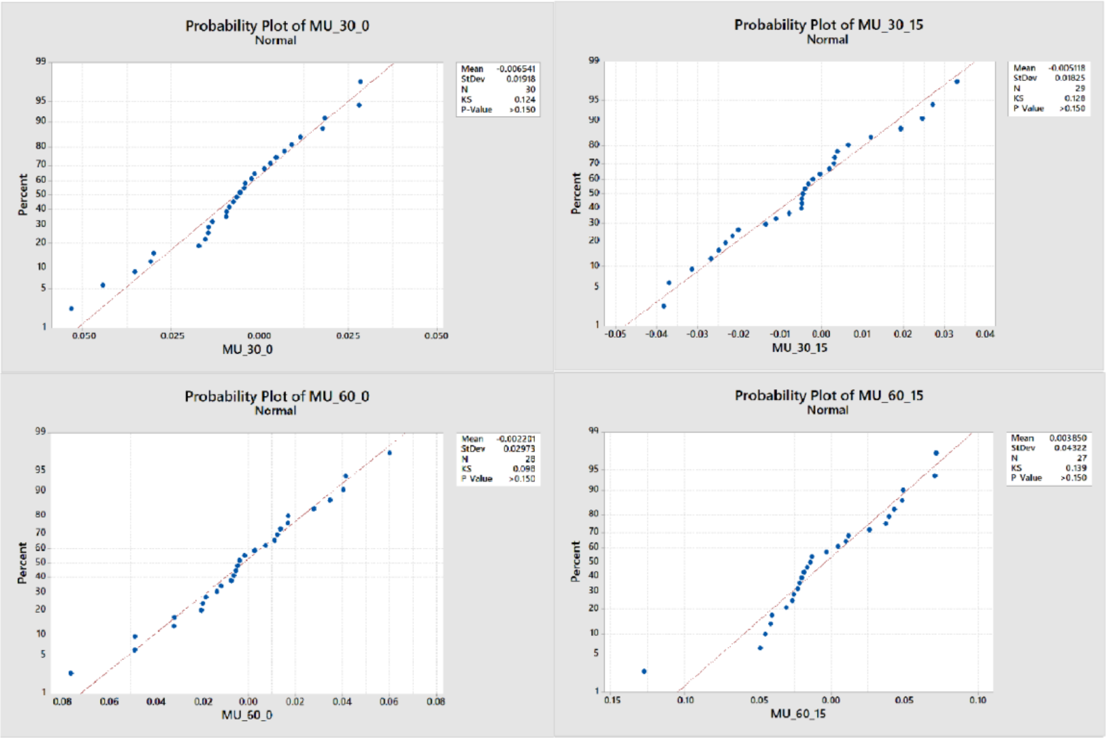

Figure (b): Normality test for the difference between beginning and ending MU activities.

ii. LPM model parameters:

Mean (SD) values of the parameters used in the LPM model:

Subset	σ	β	R^2
1	5.43 (3.07)	-0.26 (0.15)	0.67 (0.17)
2	0.25 (0.21)	0.117 (0.032)	0.96 (0.02)

Appendix E: Processed data

The following data represent the change observed at the ending of the posture holding (Ending – Beginning)

subject	Trunk angle	Weight	Lumber angle	ES (MVC%)	MU (MVC%)	RA (MVC%)	EO (MVC%)	LPM (Nm.)
1	30	0	0.45	-0.76	-1.45	-0.07	-0.09	2.73
			0.83	-0.02	-0.41	-0.10	-0.18	4.57
		15	-1.02	-0.42	-2.49	-0.18	-0.25	-7.04
			-1.00	-1.08	-0.31	-0.10	-0.19	-6.44
	60	0	0.49	0.60	-1.82	-0.03	-0.11	0.02
			0.19	1.08	-0.37	0.00	-0.09	0.01
		15	2.14	-0.01	-2.28	-0.09	0.04	0.08
			2.27	1.46	-3.04	-0.02	0.04	0.14
2	30	0	1.65	0.28	-0.67	0.01	-0.24	0.00
			1.97	-1.05	-2.43	-0.37	-0.79	0.01
		15	2.36	-1.16	-1.01	-0.28	-0.68	0.08
			2.04	0.22	-1.54	-0.12	0.18	1.89
	60	0	3.46	-10.85	-10.17	-0.23	-0.52	52.75
			2.09	-7.26	-2.65	-0.16	0.33	27.35
		15	1.99	-7.04	-4.60	-0.01	0.10	15.71
			4.01	-12.99	-12.68	-0.14	-0.21	51.58
3	30	0	0.80	-0.27	-1.71	-0.23	0.05	5.23
			-1.19	1.46	-1.33	0.01	0.00	-4.62
		15	-1.59	-1.95	-2.33	-0.43	-0.12	-0.34
			1.99	0.15	-3.69	-0.10	-0.15	6.23
	60	0	2.62	0.94	-3.16	-0.05	-0.27	8.54
			3.07	1.47	-4.84	-0.08	-0.05	0.00

		15	1.75	1.15	-4.01	-0.14	-0.45	0.00
			2.21	3.53	-2.56	-0.39	-0.11	9.70
4	30	0	0.31	-0.11	0.71	-0.21	-0.48	
			0.44	1.03	1.78	-0.27	-0.48	
		15	0.92	1.14	2.71	-0.18	-0.73	
			1.03	-0.28	-1.10	-0.33	-0.76	
	60	0	1.50	-6.20	0.72	-0.04	-0.26	10.75
			0.50	-0.61	-0.54	-0.23	-0.17	5.62
		15	0.16	-1.98	1.17	-0.08	0.11	2.45
			1.08	-6.31	-1.85	0.00	-0.66	9.40
5	30	0	0.42	-1.33	-0.61	-0.13	0.63	1.18
			-0.25	1.03	-0.58	-0.10	0.57	-0.73
		15	0.41	-0.21	-1.33	0.41	0.42	0.91
			0.05	-2.11	-3.23	-0.12	-0.18	0.20
	60	0	2.16	0.46	-0.71	0.95	3.89	6.85
			2.70	2.45	-3.28	-0.15	0.32	11.34
		15	3.30	2.86	-1.64	0.75	4.77	15.15
			4.61	2.96	-3.03	-0.11	1.54	1.52
6	30	0	-1.09	-9.46	2.66	1.58	-7.14	3.83
			1.39	0.58	-0.85	0.17	-0.29	1.56
		15	0.28	0.06	-1.53	-0.12	-0.37	0.60
			0.80	1.75	0.20	0.03	-0.22	0.99
	60	0	-0.70	0.61	-0.03	0.12	-0.37	-0.76
			3.26	0.49	-1.95	0.05	-0.25	0.00
		15	2.41	1.64	1.23	0.14	-0.27	0.00
			7.11	-0.04	-4.82	0.18	-0.17	10.42
7	30	0	2.38	-0.37	-4.42	0.19	-1.67	9.60
			2.03	0.67	1.85	0.45	-0.24	0.00
		15	1.14	-3.23	-3.83	0.25	-1.48	2.88
			0.13	-1.70	-2.68	0.32	-0.76	0.21
	60	0	2.37	-3.06	-7.56	0.31	-0.88	3.65
			3.06	2.19	-0.74	0.34	-0.70	4.67
		15	2.71	-7.51	-15.34	-0.65	-3.10	3.42
			4.16	1.95	-1.30	0.23	-1.77	5.95
8	30	0	0.50	-2.31	-3.07	-0.17	-0.84	1.94
			1.36	0.02	-0.93	-0.18	-1.30	7.75
		15	1.46	-0.53	0.31	-0.10	-0.97	9.98
			-0.01	1.75	-0.44	-0.10	-0.45	0.00
	60	0	6.27	-8.18	1.36	0.78	-0.30	30.91
			1.56	-2.64	-0.16	0.38	-0.28	0.00
		15	3.76	-19.88	-20.04	1.49	-1.51	28.05
			4.34	2.40	0.98	1.71	0.08	19.82
9	30	0	0.07	-2.05	-0.55	-0.15	-0.51	0.53

			0.02	-1.91	-0.73	-0.18	-0.59	0.00
		15	-1.10	-1.03	-0.39	-0.17	-0.76	-0.63
			-0.40	-2.39	-0.78	-0.22	-0.59	-0.63
	60	0	1.66	-2.70	-0.45	-0.18	-0.35	12.26
								-14.66
		15	0.75	-1.02	-0.32	-0.03	-0.68	5.97
			1.80	-3.65	-1.41	-0.16	-0.70	16.45
10	30	0	2.17	-1.19	-0.13	-0.29	-0.34	6.20
			1.96	-0.49	-0.22	-0.04	-0.44	5.84
		15	1.08	-0.40	-0.47	0.13	-0.23	2.41
			3.45	-0.96	-0.47	0.11	-0.48	7.74
	60	0	7.75	0.63	-0.62	-0.01	-0.05	0.68
			5.23	0.18	-1.17	0.21	-0.34	0.57
		15	4.75	-1.30	-2.01	0.36	-0.37	0.37
			6.49	2.67	-2.14	0.00	-0.33	0.59
11	30	0	0.49	-0.91	-1.03	-0.04	-0.30	0.25
			-0.27	-1.37	-0.11	-0.20	-0.41	-1.08
		15	-0.27	-1.03	-1.82	-0.11	-0.33	-1.58
			-0.65	-0.16	-0.78	-0.30	-0.39	-3.94
	60	0	0.37	-0.52	-0.89	0.12	-0.31	2.64
			0.49	-0.20	-0.28	-0.08	-0.19	4.53
		15	2.10	-9.27	-17.28	-0.05	-0.07	14.06
			1.97	-2.09	-2.69	0.00	-0.14	11.82
12	30	0	0.19	-0.11	-1.38	-0.31	-4.63	1.68
			0.78	0.11	-1.34	-1.05	-2.30	1.88
		15	1.10	-2.05	-0.46	-0.45	-5.79	1.58
			0.24	-1.81	-1.57	-0.17	-2.56	0.79
	60	0	0.39	-0.83	-3.18	0.13	-4.61	0.00
			0.64	-0.98	-2.71	-0.60	-2.20	0.00
		15	0.98	-2.25	-3.24	-1.19	-2.54	0.00
			0.29	-3.60	-2.61	-1.25	-2.60	0.00
13	30	0	0.94	0.50	-0.88	-0.61	0.19	2.69
			2.77	0.18	-11.54	-0.53	-0.08	1.13
		15	-1.21	0.38	-4.96	-0.40	0.21	-1.31
			-0.60	0.21	-8.42	-0.34	-0.43	-0.83
	60	0	1.78	0.11	-3.68	-0.39	0.43	0.00
								0.00
		15	4.47	3.95	-6.14	-0.56	0.14	0.03
			6.13	3.27	-8.89	-0.21	0.35	0.02
14	30	0	0.36	-2.11	-0.46	-1.79	-1.79	1.32
			0.00	-4.69	-2.03	-0.62	-1.30	0.00
		15	-0.24	-4.96	-2.09	-1.47	-1.28	0.00
			0.66	-4.27	-0.35	-0.19	-1.38	2.10

	60	0	0.72	-0.73	-1.80	-0.18	-1.39	0.28
			-0.33	-1.37	-3.31	-0.12	-1.77	-3.68
		15	3.40	-3.50	-1.32	-0.35	-0.73	3.71
			1.80	-7.55	-1.76	-0.77	-1.16	0.15
15	30	0	1.64	1.76	-0.20	0.06	-1.21	7.65
			0.58	0.99	0.42	-0.17	-1.58	0.00
		15	1.96	0.19	-1.79	-0.23	-0.88	1.65
			0.94	-2.96	-0.91	-0.25	-0.58	1.21
	60	0	2.90	-2.62	-4.30	-0.40	1.71	0.01
			1.77	-0.92	-0.61	-0.12	-0.41	8.28
		15	4.56	-0.19	-1.23	0.05	0.14	0.00
			5.70	0.43	0.58	0.22	0.16	0.01