

COMPARISON OF THORACIC AND LUBMAR SPINE ANGLES AND TRANSIENT PAIN
DEVELOPMENT BETWEEN STANDING AND SUPINE NEUTRAL AXIAL TWISTED
POSITIONS

AARON SIU

A THESIS SUBMITTED TO
THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

GRADUATE PROGRAM IN KINESIOLOGY AND HEALTH SCIENCE
YORK UNIVERSITY
TORONTO, ONTARIO

July 2017

© Aaron Siu, 2017

Abstract

Suspected mechanisms by which axial twist contributes to low back pain have recently been investigated using MRI. However, the impact of the supine orientation required in horizontal MRI, and prevalence of prohibitive transient pain development from the non-neutral positions during scanning have not been quantified. Therefore, the goal of this study was to quantify spine kinematics in neutral and axial twist postures between standing and supine positions, and to quantify and characterize transient pain development during a prolonged supine axial twist protocol.

Kinematics, muscle activation, self-reported pain data were collected from 20 university aged male during trials of standing and supine in neutral and axially twisted postures and prolonged supine axial twist trial. Heeding a recommended 15min limit to minimize transient pain development, attention should be paid to lumbar lordosis and axial twist in supine neutral and lumbar lateral bend in supine axial twist.

Dedication

To the brightest and loving memories of Andrew Siu and Florence Lee.

Always loved, forever missed, and never forgotten.

Acknowledgements

First and foremost, I'd like to thank my advisor Dr. Drake for giving me the opportunity to explore the field of biomechanics and research. Regardless of the time of day or how busy your schedule was, you never hesitated to lend a helping hand. The constant support all the while pushing my boundaries past comfort made it possible for learning and growth both personally and academically.

To my thesis committee members Dr. Kuk and Dr. Egdell, I thank them for investing their valuable time and effort, bringing their expertise and refining my work in creative, efficient, and detailed manners.

To my better half and biggest supporter Joey, thank you from all the spontaneous late night food deliveries, lending an ear, or just being there to give me a hug- I couldn't have done it without you and I'm excited for the journey that lies ahead of us.

Susari, where do I start, I'm so glad to have started and now successfully finished this chapter of our lives together. Through the good, the bad, and ugly- we've had too many memorable moments that Pepper and I will cherish forever. Thanks for always making me laugh and supporting me whenever I was falling short. We promised at our undergraduate convocation to help each other through this challenging degree, look we did it!

Alison and Brian, I constantly admire your achievements and success. Thank you for being great role models, seeing potential in me, and playing instrumental roles in my own achievements and successes.

Although I did not get the opportunity to directly work with either of you, Corinne and Brendan you have both moulded much of my early years volunteering at the Drake lab. Thank

you for helping me make important decisions which resonated throughout the success of my academic journey.

Claudia, Steve, Matt, and Graham I can't thank you enough for all your collective and sincere efforts. Each one of you took me under your wing and taught me invaluable lessons, it was evident how much you cared and wanted me to see me succeed.

Jamie and Mario, thank you for your committed hard work. Despite the numerous late nights, early morning collections, or tight deadlines that needed quick turnarounds, you two were always more than willing to help. I've enjoyed our (unfortunate) short time working together however I strongly believe success is just around the corner for the both of you!

Vince, Jeev, and Dimitri thanks for making many late nights at the office a joy to work. Though we are from different labs, you've always treated me as one of your own and it's been a pleasure exchanging ideas and supporting one another. I will truly miss our delicious food outings and the many laughs and stories we've shared! Special thanks to Vince and Cameron for their tireless help throughout my piloting process.

Jeffrey, though you've moved on to much bigger and better things, finally after 7 years I conclude my time at York where we first met. So much has changed, yet our brotherhood unwavered. Thank you for your enthusiasm and support despite traveling all over the world!

Lastly, and most importantly, My Pillars: Susan, Andrea, and Alison. You are the foundation of who I am today and everything I have achieved. Thank you for looking after me, supporting me every step along the way, and the never-ending unconditional love you show me. The three of you inspire me to become a better person with hopes that one day, I may be as generous, intelligent, and strong as of you are.

Table of Contents

Abstract	ii
Dedication	iii
Acknowledgements.....	iv
Table of Contents.....	vi
List of Tables	viii
List of Figures	ix
Glossary	xii
1. Global Introduction	1
1.1. Research Questions	3
1.2. Hypotheses	3
2. Literature Review	5
2.1. MRI Patient Positioning: Supine and Standing in Neutral	5
2.2. Axial Twist	6
2.2.1. Risk Factor for LBP and Injury.....	7
2.2.2. Kinematics of Axial Twist.....	7
2.2.3. Considerations of Axial Twist for MRI	8
2.3. Transient Pain Development	10
3. Introduction	13
4. Methodology	15
4.1. Participants	15
4.2. Instrumentation.....	15
4.2.1. Kinematics	15
4.2.2. EMG	24
4.3. Procedures	27
4.4. Data Processing	31
4.4.1. Kinematics	31
4.4.2. EMG	32
4.4.3. Self-Reported Pain VAS Score-Transient Pain Development.....	32
4.5. Data Analysis	33
5. Results.....	35
5.1. Participant Characteristics	35
5.2. Standing and Supine: Neutral and Axial Twist	35
5.2.1. Standing vs Supine: Neutral.....	35
5.2.2. Standing vs Supine: Axial Twist.....	38
5.3. PSAT-Prolonged Supine Axial Twist	41
5.3.1. Evaluating Transient Pain Development during PSAT	41
5.3.2. Evaluating Kinematics during PSAT.....	44
5.3.3. Evaluating Electromyography during PSAT	48
5.4. Summary of Key Points.....	51
6. Discussion.....	52
6.1. Comparison Between Standing and Supine.....	53
6.1.1. Comparison Between Standing and Supine: Neutral	53
6.1.2. Comparison Between Standing and Supine: Axial Twist	55
6.2. PSAT- Prolonged Supine Axial Twist.....	56

6.2.1.	Evaluating Transient Pain Development and PSAT	56
6.2.2.	Characterizing Transient Pain Development during PSAT: Kinematics and EMG	57
6.3.	Limitations	59
7.	General Thesis Overview	60
7.1.	Revisiting Hypothesis.....	60
8.	Conclusion	62
9.	References	63
Appendix A: Exit Survey		72

List of Tables

- Table 5.1:** Summary of anthropometric data and statistics by pain group. Main effect of pain group was not found to be significantly different, $p>0.071$.
- Table 5.2:** For mean joint angles of both spine regions and all directions there was a significant main effect of position found ($p<0.008$) in both the thoracic and lumbar spine (as indicated in bold and with an asterisk).
- Table 5.3:** Summary of statistical analysis results for the magnitude of mean joint angles of all spine regions and directions. Main effect was direction and found to be significantly different ($p<0.026$) in off-axes lateral bend and flexion-extension for the lumbar spine indicated in bold and with an asterisk.
- Table 5.4:** Summary of statistical analysis results for mean joint angles of all spine regions and directions. Main effect was position and found to be significantly different ($p<0.001$) indicated in bold and with an asterisk.
- Table 5.5:** Summary of statistical analysis results for kinematic relative joint angles of all spine regions and directions. Main effects were pain and time while interaction effect was pain x time. Effects was not found to be significantly different, $p>0.111$.
- Table 5.6:** Summary of statistical analysis results for EMG (%Max) of all 8 muscle bilaterally. Main effects were pain and time while interaction effect was pain x time. Effects was not found to be significantly different ($p<0.107$).

List of Figures

- Figure 2.1:** Sample of self-reported pain (VAS) scoring sheet with 100mm straight line with “No pain” and “Worst pain imaginable” anchors. Participants mark across the 100mm line with a pen how much LBP they currently experience.
- Figure 4.1:** 3DInvestigator™ position sensor mounted horizontally and vertically.
- Figure 4.2:** Configurations of active markers into two types of rigid bodies: **A-** individual infrared emitting active markers, **B-** three active markers and a NDI Smart Marker Rigid Bodies™ plate assembled into a rigid body with Velcro straps to secure to limbs, **C-** *anterior view* of five active markers and a custom 3D printed mount assembled into a rigid body to position along the trunk. **D-** *lateral view*.
- Figure 4.3:** Custom constructed mounts used to optimize visibility of rigid bodies inside the motion capture space: **A-** Posterior view extension fin constructed for T₁₂ rigid body (15cm extension protruded through the table during supine to allow visibility and tracking from beneath the table). **B-** Superior view of 45° wedge constructed for sternum rigid body (used to increase visibility and tracking between standing and supine positions). Red “X” indicates where the rigid body was attached via epoxy or double sided tape.
- Figure 4.4.A:** Set up of motion tracking rigid bodies in the posterior view. Three active marker rigid bodies were taped and strapped bilaterally to the upper arms and thighs. Five active marker custom printed rigid bodies were taped to the right iliac crest and T₁₂ (mounted to custom extension fin).
- Figure 4.4.B:** Set up of motion tracking rigid bodies in the anterior view. Five active marker custom printed rigid bodies with 45° wedge taped to the manubrium.
- Figure 4.5:** Posterior view showing anatomical bony landmarks used for digitization to corresponding rigid bodies to define and track each segment.
- Figure 4.6:** Digitization probe shown with four integrated infrared emitting diodes, pointing tip, and a scale of the predefined known 3D spatial location used to associate bony landmarks to rigid bodies.
- Figure 4.7:** Anterior view showing anatomical bony landmarks used for digitization to the corresponding rigid body to define and track the thoracic segment.
- Figure 4.8:** Anterior view showing anatomical bony landmarks used for digitization to the corresponding rigid body to define and track the thoracic segment.
- Figure 4.9:** *Left:* Posterior view showing bilateral electrode placement locations. (Actual electrode placement for Gluteus Medius was directly on the skin under the garment.) *Right:* Anterior view showing bilateral electrode placement locations.

Figure 4.10: Schematic map of order of procedures in protocol.

Figure 4.11: **A-** *Coronal* view of PSAT position with straps across the shoulders and waist, hands across the abdomen while pelvis and legs are twisted to the left by a ratcheting strap. **B-Sagittal** view. After extensive pilot work and consultation from a MRI technician, this position and arrangement was chosen on the basis of maximum comfort to the participant where they did not have to actively hold the posture.

Figure 5.1: Mean relative joint angles (SD) of the lumbar spine between standing neutral and supine neutral. Significant effect of position in all three axes where supine neutral exhibited greater axial twist to the left, lateral bend to the left, and less extension. Asterisk indicates significant post-hoc comparisons, $p<0.005$.

Figure 5.2: Magnitude of mean relative joint angles (SD) of the lumbar spine between standing axial twist to the right and left directions. Significant effect of direction on the off-axes (x-lateral bend, z-flexion-extension) where standing axial twist to the right exhibited more lateral bend and flexion/extension than standing axial twist to the left. No effect of direction on primary axis (y-axial twist). Asterisk indicates significant post-hoc comparisons, $p<0.026$.

Figure 5.3: Mean relative joint angles (SD) of the lumbar spine between standing axial twist and supine axial twist. Significant effect of position on off-axis (x-lateral bend) where supine axial twist exhibited greater lateral bend to the left compared to standing axial twist. No effect of position on primary axis (y-axial twist) or off-axis (flexion/extension). Positive numbers indicate direction to left while negative numbers indicate direction to the right. Asterisk indicates significant post-hoc comparisons, $p<0.001$.

Figure 5.4: Mean of max self-reported pain scores (from initial baseline) for both PD and NPD's collapsed over the 45-minute PSAT trial with SD bars showing that PDs reported significantly greater max self-reported pain than NPDs. Asterisk indicates significant post-hoc comparisons, $p<0.001$.

Figure 5.5: Mean (SD) self-reported pain score (from initial baseline) for both PD and NPD's at 5-minute epochs over the 45-minute PSAT trial. Sample size count is indicated at each 5-minute interval. Green horizontal line represents the 10mm self-reported pain cut-off indicative of minimum clinically relevant pain while the red horizontal line represents the 20mm self-reported pain cutoff indicative of clinical pain. Asterisk indicates significant post-hoc comparisons, $p<0.05$. Significant interaction between pain groups and time from $t=25$ mins to $t=45$ mins, ($p<0.001$).

- Figure 5.6:** Mean (SD) relative joint angle for lumbar spine in axial twist (y axis) across nine 5min epochs with no significant effect of pain group, time, or interaction between pain and time, $p>0.121$.
- Figure 5.7:** Mean (SD) relative joint angle for thoracic spine in axial twist (y axis) across nine 5min epochs with no significant effect of pain group, time, or interaction between pain and time, $p>0.317$.
- Figure 5.8:** Mean (SD) relative joint angle for lumbar spine in lateral bend (x axis) across nine 5min epochs with no significant effect of pain group, time, or interaction between pain and time, $p>0.904$.
- Figure 5.9:** Mean (SD) relative joint angle for thoracic spine in lateral bend (x axis) across nine 5min epochs with no significant effect of pain group, time, or interaction between pain and time, $p>0.467$.
- Figure 5.10:** Mean (SD) relative joint angle for lumbar spine in flexion-extension (z axis) across nine 5min epochs with no significant effect of pain group, time, or interaction between pain and time, $p>0.111$.
- Figure 5.11:** Mean (SD) relative joint angle for thoracic spine in flexion-extension (z axis) across nine 5min epochs with no significant effect of pain group, time, or interaction between pain and time, $p>0.183$.
- Figure 5.12:** Example of mean (SD) activation expressed as %MVC for the LEO muscle across nine 5min epochs with no significant effect of pain group, time, or interaction between pain and time, $p>0.831$.
- Figure 5.13:** Example of mean (SD) activation expressed as %MVC for the RL₃ muscle across nine 5min epochs with no significant effect of pain group, time, or interaction between pain and time, $p>0.477$.

Glossary

ASIS: Anterior superior iliac spine

EMG: Electromyography

EO: External oblique muscle

FRP: Flexion-relaxation phenomenon

GM: Gluteus medius muscle

IO: Internal oblique muscle

IREDD: Infrared emitting diode

LBP: Low back pain

LD: Latissimus dorsi muscle

LES: Lumbar erector spinae muscle

LTES: Lower-thoracic erector spinae muscle

MRI: Magnetic resonance imaging

MVC: Maximum voluntary contraction

NPD: Non-transient pain developer

PD: Transient Pain developer

PSAT: Prolonged supine axial twist

PSIS: Posterior superior iliac spine

RA: Rectus abdominis muscle

ROM: Range of motion

UTES: Upper-thoracic erector spinae muscle

VAS: Visual analogue scale

1. Global Introduction

According to The Global Burden of Disease Study 2010 (Hoy et al., 2014), low back pain (LBP) caused more disability than any other condition worldwide. Non-neutral spinal postures, specifically axial twist, have been repeatedly identified as a risk factor for LBP and injury (Frymoyer et al., 1983; Marras et al., 1993; Troup et al., 1981). Currently, research on the impact of axial twist on the spine at a structural level is sparse and our understanding limited. More attention is required on utilizing *in vivo* approaches to elucidate function, ideally with the gold standard of magnetic resonance imaging (MRI). A recent MRI study highlighted the complexity of the relationship among *in vivo* spine passive structures (including the vertebrae, nerve roots, and intervertebral foramina), from analysing the changes observed during axial twist that were not clear in neutral positions (Mayberry & Drake, 2017). However, this study used a horizontal MRI scanner, and so the applicability of the observations to typical activities done in the vertical trunk position is not known especially in the off-axes (unintended motion in lateral bend and flexion-extension axes during axial twist). Due to the prevalence and higher strength (required for structure resolution) of conventional horizontal MRI scanners, it is necessary to compare the angles of the spine between MRI supine and a functional standing position. This comparison can be achieved by quantifying 3D kinematic differences in all three axes (primary axial twist and off-axis) between supine and standing which can be applicable in two manners. Firstly, to clarify the applicability of results from supine MRI and secondly, to serve as a guideline to improve the current applicability of a supine position by highlighting spine areas and axes that may require external adjustments (i.e. wedging) in future work.

To accurately capture spinal units of the lumbar spine amid axial twist using horizontal MRI, participants are required to be exposed to an axial twisted position in supine for a

prolonged duration. Typical scanning durations with sufficient resolution to capture the structures of the entire lumbar spine was reported as at least 20mins (Mayberry & Drake, 2017). Given this, and considering that previous prolonged exposures with protocols such as 2-hour standing and sitting, have induced the development of clinically relevant levels of transient LBP in previously asymptomatic participants, subsequent concerns of transient pain development are important to address for using MRI to investigate axial twist (Nelson-Wong & Callaghan, 2010; 2014; Nairn et al., 2013; Schinkel-Ivy et al., 2013). Therefore the evaluation of transient LBP development is warranted for a prolonged supine axial twist (PSAT) with applications specific to outlining optimal MRI protocol durations whereby risks to participants are minimized. Further, prolonged exposures have demonstrated clinical relevance (of inducing transient LBP in previously asymptomatic participants) by successfully identifying those that developed transient LBP as individuals at greater risk of developing a low back injury in the future (Nelson-Wong & Callaghan, 2010; 2014; Nairn et al., 2013; Schinkel-Ivy et al., 2013). One small study (n=5) by Mayberry (2016) indicated that clinically relevant levels of transient LBP developed during a prolonged supine axial twist position in the participants with the least axial twist range of motion (ROM). However due to limited sample size, whether transient LBP development in a PSAT position relates to clinical neuromuscular measures predictive for increased risks of LBP requires preliminary investigation. Therefore, the objectives of this thesis were to evaluate the kinematic differences (angles) between standing and supine positions with neutral and axial twist spine postures, evaluate transient pain development over a PSAT protocol, and evaluate if PSAT is associated with other biomechanical based measures as a preliminary step for future work to indicate risks of LBP and injury from transient pain development during PSAT.

1.1 Research Questions

The purpose of this thesis was to explore implications of a supine axial twist position: as a surrogate for standing trunk posture in future MRI studies and with potential clinical importance as a clinical screening test (pain development from prolonged exposure), and lastly to improve the understanding of lumbar spine mechanics. Four questions drove this research:

1. How different is the position of the thoracic and lumbar spine between standing and supine in neutral?
2. How different is the ROM of the thoracic and lumbar spine between standing and supine in axial twist?
3. After what duration and what proportion of participants will develop clinically relevant levels of low back pain?
4. Is the development of transient pain in PSAT associated with changes in other biomechanical measures?

1.2 Hypotheses

1. The angles of the thoracic and lumbar spine measured using three orthogonal axes (Y, axial twist; X, lateral bend; Z, flexion-extension) between standing and supine in neutral will be significantly different in at least one axis.
2. The ROM of the thoracic and lumbar spine measured using three orthogonal axes (Y, axial twist; X, lateral bend; Z, flexion-extension) between standing and supine during axial twist will be comparable in the primary axial twist axis and significantly different in at least one off-axis (lateral bend and/or flexion-extension).

3. After 30mins of PSAT, at least 40% of participants will report clinically relevant levels of low back pain (>10mm on the pain visual analogue scale (VAS)).
4. During PSAT, participants who indicate greater than 10mm VAS scores (self-reported pain) will have:
 - a. Significant differences in primary axis or off-axis angles over the duration of PSAT.
 - b. Significant differences in mean EMG of trunk musculature over the duration of PSAT.

2. Literature Review

2.1 MRI Patient Positioning: Standing and Supine in Neutral

Magnetic resonance imaging (MRI) is commonly used to visualize spinal structures and obtain diagnostic parameters necessary for clinical and surgical interventions (Andreasen et al., 2007). The most common configuration of MRI is a horizontal bore where individuals lay horizontally in supine. However, it is unclear how structures of the spine change between a supine position and a more functional standing position. Subsequently, literature has begun to quantify kinematic differences (angles) between a supine position and standing position as it is pertinent when interpreting and applying data from conventional MRI (Mauch et al., 2010).

More recently, a study by Benditz et al. (2017) compared flexion-extension angles in the lumbar spine between standing radiographs and supine 1.5T MRI using 63 asymptomatic participants. A comparison of lumbar angles between the two positions was small (2.9°) but significantly different, where the unsupported supine position exhibited more flexion (a less lordotic or flatter lumbar) than standing (Benditz et al., 2017). Similar results have been reported on 24 asymptomatic male participants (Judith et al., 2009) and on 16 symptomatic participants for spinal stenosis (Madsen et al., 2008) who compared standing radiographs and supine MRI. One study has assessed both positions with an 0.25T vertical MRI on 35 asymptomatic university athletes, and found a significant decrease (6.3°) of lumbar flexion from standing to supine (Mauch et al., 2010). The literature has primarily focused on the lumbar spine region with respect to flexion-extension, and largely depicts more flexion (less lordosis or a flatter lumbar) in supine relative to standing. Overall, these changes were considered small and, subsequently, the two positions concluded as comparable or excellent for depicting internal structures (Benditz et al., 2017; Judith et al., 2009; Madsen et al., 2008; Mauch et al., 2010).

Compared to the abundant literature regard flexion-extension in the lumbar spine, literature comparing the two positions focusing the thoracic region and other axis like axial twist and lateral bend are much scarcer. Wood et al. (1996) used 50 clinically symptomatic participants for mechanical LBP and 50 asymptomatic participants, aged 19-88yrs, to examine both lower thoracic (T₁₀-L₁) and lumbar (L₁-S₁). They reported that the thoracic spine results mirror the lumbar spine, however there was no effect of pain, and a significant decrease in lower thoracic flexion when in supine (less kyphosis or flatter lower thoracic back). Using 20 symptomatic participants for idiopathic scoliosis, Lee et al. (2013) compared standing radiographs and supine MRI and reported similar results in the lateral plane with an acceptable range of error ($\pm 5^\circ$). The collective contribution of these studies to understanding angular differences between neutral standing and supine positions demonstrate the flattening of the thoracic and lumbar spine when supine. Despite this, further research is needed to establish potential kinematic differences (angles) in other axes such as axial twist and lateral bend.

2.2 Axial Twist

The relevance of axial twist will be reviewed in this section, including how axial twist relates to LBP and injury, what is currently known about the angles of axial twist, and finally some key methodological considerations to investigating axial twist with a horizontal MRI. It is important to note that the term kinematics encompasses linear and angular displacement, velocity, and acceleration descriptions of human motion. This thesis focused on the angular kinematic data, and used the terms angles, angular, kinematic, and kinematics to describe the position and ROM of the participants' spine segments.

2.2.1 Risk factor for LBP and Injury

The etiology of injury and LBP is unclear and subsequently often difficult to precisely diagnose (Deyo & Weinstein, 2001). Literature suggests that issues can originate from many structures of the spine, including vertebral bodies, intervening intervertebral disc, facet joints, and the surrounding soft tissues such as ligaments, muscles, and nerves (Deyo & Weinstein, 2001). For example, *in vitro* research has highlighted the risk of damage to the intervertebral disc when axial twist is a component of the loading exposure (Drake et al., 2005; Farfan et al., 1973). More recently, *in vitro* work by Drake et al. (2008) has identified greater injury implications when loading exposures were repetitive, off-axis movements, and axially twisted. Building on these works, Drake & Callaghan (2009) *in vivo* highlighted axial twist as a key modulator to intervertebral disc damage during loading in combined postures as well as being a viable pain generating pathway (Drake & Callaghan, 2009). Furthermore, preliminary work by Mayberry (2016) with a limited sample size, reported the development of clinically relevant levels of LBP during a prolonged axial twist. Therefore, collectively these studies support the workplace epidemiological data by Marras et al. (1993) that axial twist is a risk factor for LBP and injury.

2.2.2 Kinematics of Axial Twist

ROM is a preliminary but necessary step to understanding axial twist and associated mechanics. Standing axial twist ROM of the lumbar spine has been investigated by a number of studies. Data from foundational *in vitro* (Yamamoto et al., 1989) and *in vivo* (Fujii et al., 2007; Haughton et al., 2002; Ochia et al., 2006; 2007; Pearcy, 1985; Pearcy & Tibrewal, 1984; White & Panjabi, 1978) studies reported mean lumbar axial twist ROM values from 6° to 12° with an exception of one study at 23.9°. Due to methodological differences used to attain and normalize

the axial twist ROM between each study, the reported mean lumbar axial twist ROM values also differed between studies. In order to structurally understand *in vivo* axial twist and potential sources of associated pain and injury, the gold standard of MRI is crucial but predominantly requires individuals to be positioned supine. However, few studies have examined supine axial twist ROM of the lumbar spine. In supine, Haughton et al. (2002) reported lumbar axial twist ROM of 5.32° and Fujii et al. (2007) reported 7.7°. Ochia et al. (2006) measured standing axial twist ROM and reported comparable results to previous *in vivo* supine studies without directly collecting data on supine. Only one source, sample size (n=5), has directly compared both positions (Mayberry, 2016). However, these results were limited to a mean trunk axial twist ROM angle and small all-male sample set. While previous literature has reported that axial twist ROM was not found to be statistically different between sexes (Dvorak et al., 1995; Troke et al., 2001; Troke et al., 2005), data from females should be obtained for investigation whenever possible. Limited attention has been given to compare both supine axial twist ROM of the lumbar and thoracic spine with a standing position, but a direct comparison is necessary to understand how meaningful findings in supine are to the customary standing position.

2.2.3 Considerations for Axial Twist in MRI

Conventional horizontal MRI is generally accepted as the gold standard method for investigating and imaging potential pain generating pathways for four reasons. Firstly, MRI utilizes a non-ionizing radiation (the radiation used in MRI has insufficient energy to ionize or cause damage to biological matter) (Formica & Silvestri, 2004). Secondly, MRI captures an *in vivo* state of internal spinal structures which is ideal for representation and quantification compared to *in vitro* states or inferred internal structural behaviours from externally recorded

kinematics. Third, compared to other medical imaging techniques, such as X-Ray, MRI has superior resolution capabilities across a range of spinal structures. Lastly, the prevalence of horizontal MRI is more accessible than compared to upright MRI (only two upright systems in Canada; both are in British Columbia). It should also be noted that the resolution of upright MRIs are much weaker than horizontal MRIs thus implicating the quality of images from upright MRIs.

Despite these benefits of MRI, there are outstanding obstacles when considering investigating axial twist via MRI. For example, using a Siemens 3T Magnetom Tim Trio MR scanner, a typical scanning procedure to capture the structure of several lumbar spine segments in an axial twist position takes approximately 20mins (Mayberry & Drake, 2017): including localizer and imaging scans. Briefly, the procedures used by Mayberry & Drake (2017) initiated with localizing scans to verify anatomical accuracy, followed by a series of 2T-weighted scans of spinal segments: T₁₁-L₁, L₁-L₃, and L₃-L₅ (Mayberry & Drake, 2017). It is important to consider, that participant positioning and rescanning of any unclear images would further extend the 20min duration of prolonged axial twist as movement may blur scanned images. Therefore, it is critical for participants to remain as still as possible for the duration of the MRI protocol to minimize any relative error in the series of spine segment scans.

In the study by Mayberry (2016), 60% of participants (three of five) developed clinically relevant levels of LBP after 30mins of a prolonged supine axially twist, despite being supported and not having to actively maintain the position. While this finding was not expected, it is not surprising as previous research involving prolonged exposures (prolonged sitting and prolonged standing) have also been associated with the development of clinically relevant levels of self-reported LBP (Nairn et al., 2013; Nelson-Wong & Callaghan, 2010; Nelson-Wong & Callaghan,

2014; Schinkel-Ivy et al., 2013b). Nelson-Wong & Callaghan (2014) linked the development of transient LBP in prolonged standing to be predictive in previously asymptomatic individuals for future clinical LBP development. Further, studies have examined these pain developer groups (PD) with non-pain developer groups (NPD) and characterized specific associated muscle activation patterns in standing (Nelson-Wong & Callaghan, 2010; 2014) and in sitting (Nairn et al., 2013; Schinkel-Ivy et al., 2013b). Other than Mayberry (2016), only Shan et al. (2013) investigated prolonged axial twist and LBP development. Clinically relevant increases in LBP were reported by Shan et al. (2013), however this study was limited to a seated position and with only flexion-relaxation phenomenon (FRP) to characterize PD group. Overall, the required MRI protocols can involve relatively lengthy scanning procedures in a given position, and transient pain development is important to both participant well-being as well as potential for clinical relevance as a predictive tool. Therefore, it is important to investigate pain development in the PSAT position and characterize biomechanical measures of transient pain developers.

2.3 Transient Pain Development

The perception of transient pain can be assessed with a VAS that is anchored at one end with “no pain” and the other end with “worse pain imaginable” (Figure 2.1). Typically in biomechanics, the VAS used is a 100mm long straight line where participants mark with a pen how much LBP they feel they are currently experiencing. The VAS has been found to be valid compared to other pain measures and exhibited robust test-retest validity for self-reported discomfort (Revill, 1976; Summers, 2001). In an acute patient population (n=156), Kelly (1998) reported that a 9mm change from baseline represented the minimum clinically relevant difference in pain scores, and found no effect of sex, cause and location of pain, and age. The

VAS is a clinical tool that has been repeatedly used in prolonged exposure studies investigating LBP development to distinguish between PD and NPD. Nelson-Wong et al. (2008) determined that for an unaffected population, versus the patient population used by Kelly (1998), a 10mm change from baseline in pain scores represented the minimum clinically relevant difference and indicated the participant was a transient PD. That is to say, on a 100mm VAS scale any change in score less than 10mm was interpreted as “no pain” and the person a NPD. In addition to this, a review of clinical VAS cutoffs by Sokka (2005) with symptomatic patients for inflammatory and degenerative disease and a study by Sorensen et al. (2016) investigating transient LBP development during a prolonged standing protocol in 57 asymptomatic participants have recommended a change of 20mm as an important cutoff to represent the upper limit of “relatively normal” or accepted as status of clinical pain. Therefore, the minimum change of 10mm in VAS score represented the minimal clinically relevant level of pain and change of up to 20mm or more from baseline on a 100mm VAS scale was interpreted as a clinical level of pain.

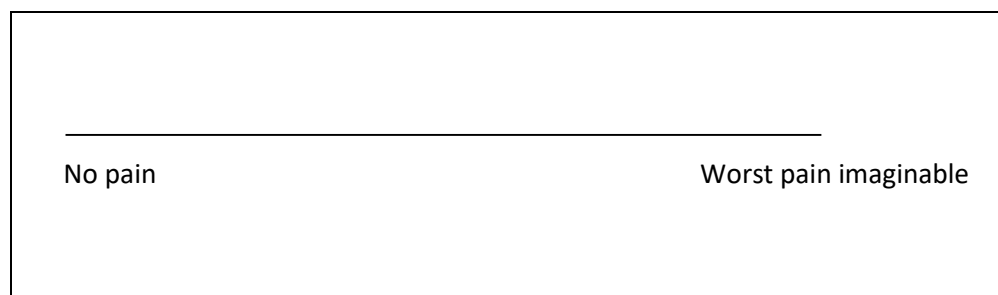


Figure 2.1: Sample of self-reported pain (VAS) scoring sheet with 100mm straight line with “No pain” and “Worst pain imaginable” anchors. Participants mark across the 100mm line with a pen how much LBP they currently experience.

Low back pain could be generated from any structure associated with pain receptors such as but not exclusive to posterior annular fibers, interspinous ligaments, paravertebral musculature

(Wyke, 1970). Previous studies that investigated pain development during prolonged sedentary exposures (sitting and standing works described and referenced in *Section 2.2.3*), have demonstrated that quantifying differences in biomechanical characteristics between PD and NPD responses are important. Typically, a clinical tool (perceived pain rating) is used to identify PD and NPD and use biomechanical measures (kinematics and electromyography) to show differences and patterns between PD and NPD.

3. Introduction

LBP is a global issue where approximately 80% of individuals will suffer from this condition at least once in their lives (Friedly et al., 2010). Axial twist has been repeatedly identified as a risk factor for low back injury and pain in industrial epidemiological studies (Kelsey et al., 1984; Marras et al., 1993). Furthermore, multi-axis movements and loading involving axial twist can yield even more severe risks of injury (Drake et al., 2005). More recent *in vitro* work has been done to show that when the spine is axially twisted from a neutral position there could be deviations in the relationships of various structures and vertebrae of the spine (Drake et al., 2008; Mayberry & Drake, 2017). However, the source and structural understanding of LBP is often undetermined due to the complexity of structures surrounding lumbar vertebrae and intervertebral discs (muscle, ligament, and nervous tissues) (Aoki et al. 2012). Subsequently, there is a need for *in vivo* investigations of axial twist via MRI to study the behaviour of the various structures of the lumbar spine. Limited studies have begun to address certain considerations unique to the implementation of MRI methodology, specifically the requirement that individuals in supine remain as still as possible to ensure clear images. Additionally, only one study gave evidence for comparable axial twist ROM between standing and supine positions despite a limited all-male sex sample size (n=5) (Mayberry, 2016). In addition to comparing axial twist ROM between standing and supine positions, acquiring MRI of the spine during axial twist exposes participants to an axially twisted position in supine for a prolonged duration. Previous literature involving sedentary prolonged exposures has shown to induce transient pain development in previously unaffected individuals. Consequently, the notion of pain development needs to be investigated for a PSAT position. Works from Shan et al. (2013) and Mayberry (2016) both provide preliminary evidence for transient pain development during prolonged axial

twist exposure. Subsequently, the goal of this thesis is threefold. First, to investigate kinematic differences between standing and supine, and between standing axial twist and PSAT (for future MRI methodology). Second, to evaluate any transient pain development during PSAT, and finally to test the sensitivity of pain development of the PSAT position to other biomechanical measures (for identifying individuals at an increased risk of injury).

4. Methodology

To compare standing and supine positions and investigate transient pain development for this thesis, kinematics, muscle activation, and self-reported pain score (VAS) data were collected through a combination of standing and supine in neutral and axial twisted postural trials as well as a 45min supine axial twisted exposure. Based on self-reported pain scores, participants were assigned to pain/no pain groups (PD, NPD), and dependent measures were compared between pain groups and standing and supine positions. York University's Office of Research Ethics has approved all protocols and consent forms relating to this study (Certificate #e2014-325; expiry 28 November 2016).

4.1 Participants

Twenty right-handed males were recruited from the York University undergraduate and graduate student population to participate in the study. Mean (SD) age, body mass, and height were 23.0yrs (4.0), 76.6kg (11.6), and 1.73m (0.08) respectively. Inclusion criteria were that participants were asymptomatic for neck, trunk, and pelvis pain for at least 12 months prior to collection, meaning they had not sought medical treatment or taken two consecutive days off school or work due to neck, trunk, or pelvis pain during that time period. Each participant provided written informed consent prior to beginning the study.

4.2 Instrumentation

4.2.1 Kinematics

Kinematic data were collected at 64 Hz using an active marker optoelectronic three-dimensional (3D) motion capture system (Northern Digital Inc., Waterloo, Canada) that

consisted of: five 3DInvestigator™ position sensors (Figure 4.1), NDI First Principles™ motion capture software (V1.2.4), and Smart Markers that emit infrared light (Figure 4.2.A). Briefly, a series of individual infrared emitting active markers were assembled into units called rigid bodies (Figure 4.2). Each rigid body provided 3D spatial location and orientation data when the respective infrared was detected by any two of the five position sensors. Two separate variations of rigid bodies were designed to track the trunk and limbs respectively (Figure 4.2.B, C). Tracking was performed bilaterally for each of the upper arms and thighs, three active markers were affixed with double sided tape to a NDI Smart Marker Rigid Bodies™ plate (Figure 4.2.B; Northern Digital Inc., Waterloo, Canada) and positioned bilaterally over the approximate midpoint of the upper arms and thighs. The trunk was subdivided into thoracic and lumbar segments respectively using three rigid bodies each consisting of five active markers affixed to a custom 3D printed mount (Figure 4.2.C) with additional mounting fins or wedges where necessary (Figure 4.3). Placed over the manubrium, the thoracic rigid body was mounted on a 45° angle about the Y-axis (Figure 4.4.B, Figure 4.3.B), the T₁₂ rigid body was attached to the end of a custom extension fin and positioned over the spinous process of T₁₂ (Figure 4.4.A, Figure 4.3.A), the lumbar rigid body was positioned over the right iliac crest (Figure 4.4.A). Custom mounts were incorporated with the thoracic and T₁₂ rigid body for the ultimate purpose of maximizing rigid body 3D visibility and tracking between standing and supine positions (i.e. tracking from beneath the table during supine laying).



Figure 4.1: 3DInvestigator™ position sensor mounted horizontally and vertically.

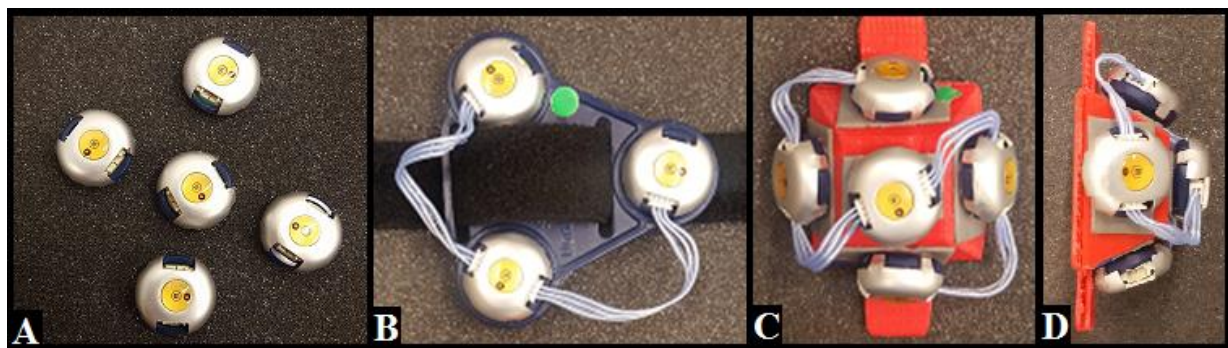


Figure 4.2: Configurations of active markers into two types of rigid bodies: **A-** individual infrared emitting active markers, **B-** three active markers and a NDI Smart Marker Rigid Bodies™ plate assembled into a rigid body with Velcro straps to secure to limbs, **C-** *anterior* view of five active markers and a custom 3D printed mount assembled into a rigid body to position along the trunk. **D-** *lateral* view.

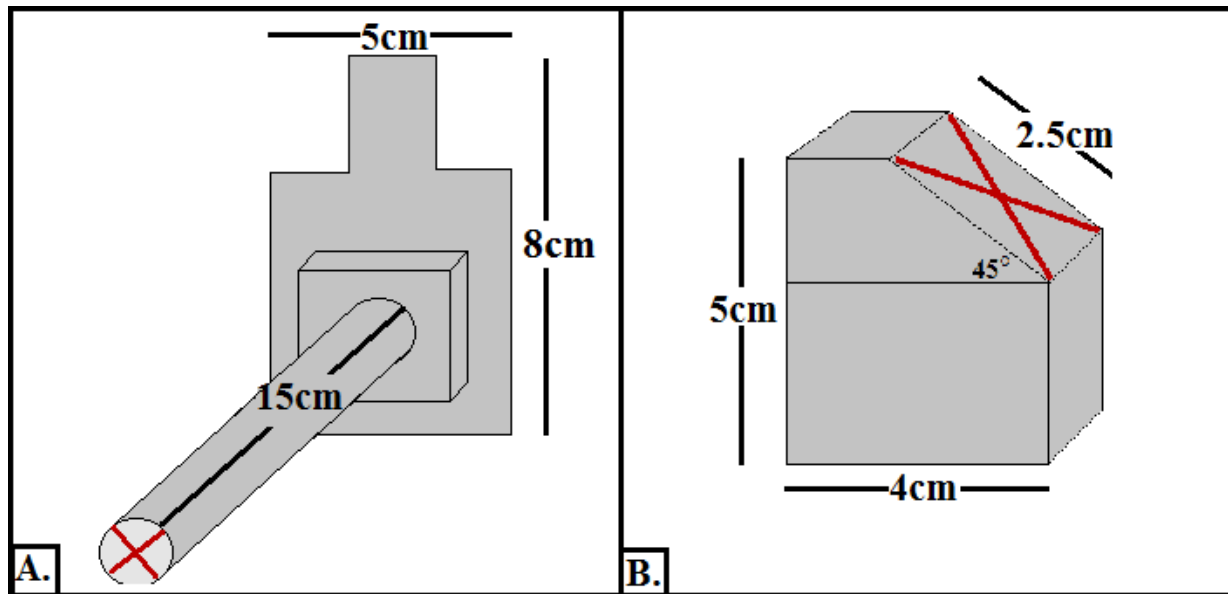


Figure 4.3: Custom constructed mounts used to optimize visibility of rigid bodies inside the motion capture space: **A-** Posterior view extension fin constructed for T₁₂ rigid body (15cm extension protruded through the table during supine to allow visibility and tracking from beneath the table). **B-** Superior view of 45° wedge constructed for sternum rigid body (used to increase visibility and tracking between standing and supine positions). Red “X” indicates where the rigid body was attached via epoxy or double sided tape.

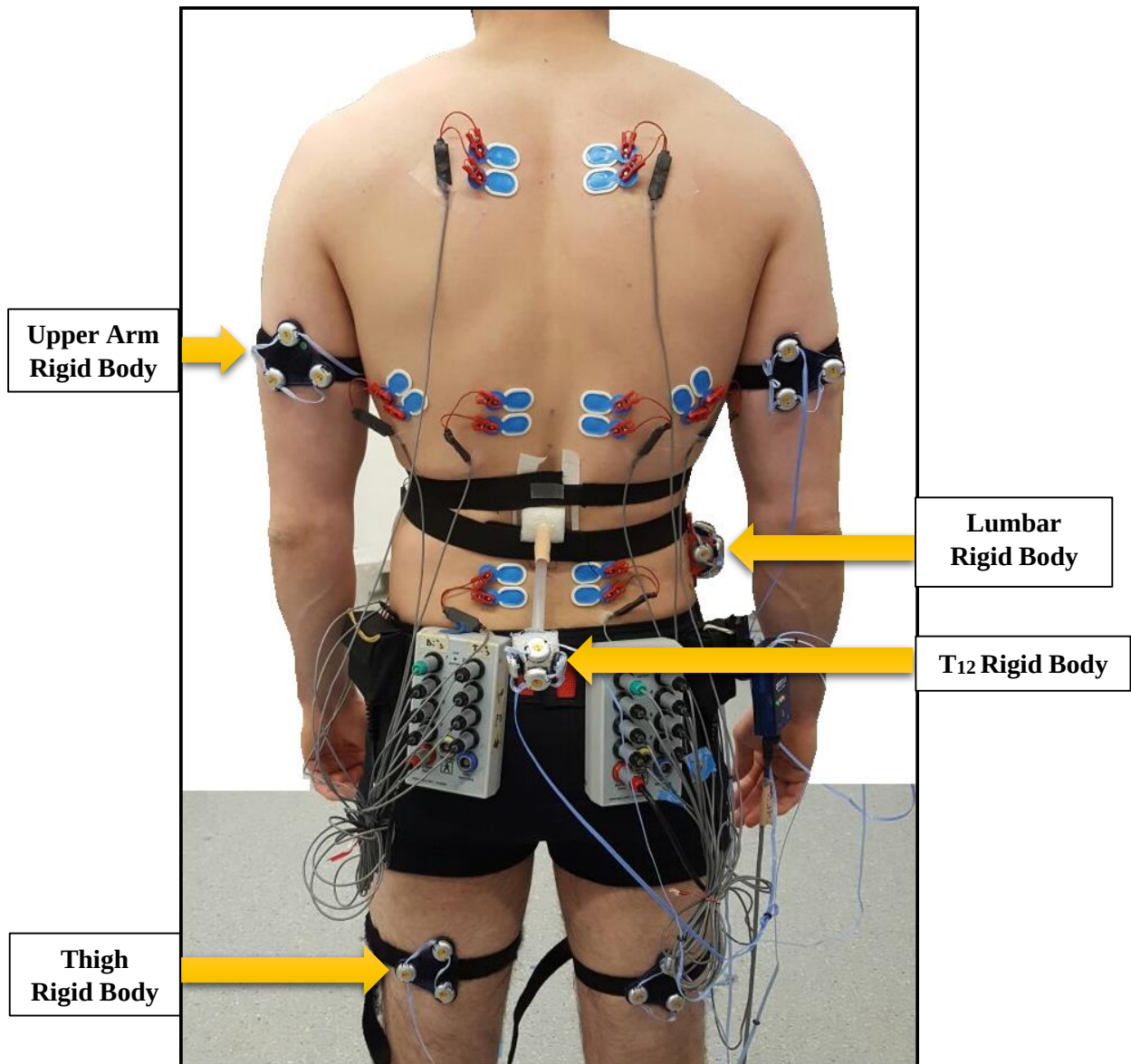


Figure 4.4.A: Set up of motion tracking rigid bodies in the posterior view. Three active marker rigid bodies were taped and strapped bilaterally to the upper arms and thighs. Five active marker custom printed rigid bodies were taped to the right iliac crest and T₁₂ (mounted to custom extension fin).

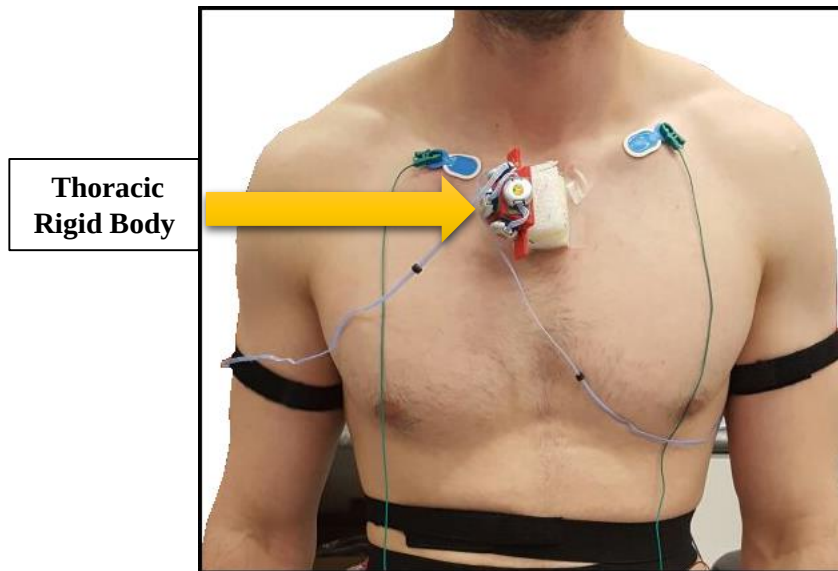


Figure 4.4.B: Set up of motion tracking rigid bodies in the anterior view. Five active marker custom printed rigid bodies with 45° wedge taped to the manubrium.

The body was modelled virtually with multiple rigid body segments: thoracic spine, lumbar spine, bilaterally upper arms and thighs (Figure 4.5). Each segment was defined using specific bony landmarks (a process called digitization) and the segments' motion tracked relative to its associated rigid body outlined previously. Digitization was performed using a NDI Digitizing Probe TM (Figure 4.6; Northern Digital Inc., Waterloo, Canada), which is a predefined rigid body with a small pointer at the end of the probe that defines a precise known 3D spatial location (Gallagher and Callaghan, 2015). By simply pointing the digitizing probe to specific bony landmarks, each landmark was associated with the appropriated rigid body. The thoracic rigid body tracked six bony landmarks (C₇ vertebrae, acromia, xiphoid process, T₁₀ vertebrae), T₁₂ rigid body tracked two bony landmarks (T₁₂ vertebrae: right and left), lumbar rigid body tracked six bony landmarks (iliac crests (IC), anterior superior iliac spines (ASIS), posterior superior iliac spines (PSIS)), upper arm rigid body tracked three bony landmarks each (lateral shoulder joint center, medial and lateral epicondyle) and thigh rigid body tracked 3 bony

landmarks each (greater trochanter (GT), medial and lateral knee epicondyles) (Figure 4.5). 3D spatial location and orientation data from each rigid body was exported and processed subsequently offline for angle calculations.

Each rigid body provided 3D spatial and orientation data about a three-axis coordinate system: Z, X, and Y (Figure 4.8). Positive values indicated flexion, left lateral bend, and left axial twist whereas negative values indicated extension, right lateral bend, and right axial twist respectively for both thoracic and lumbar segments. Lumbar spine was calculated using T₁₂ rigid body relative to the lumbar rigid body. Thoracic spine was calculated using sternum rigid body relative to T₁₂ rigid body.

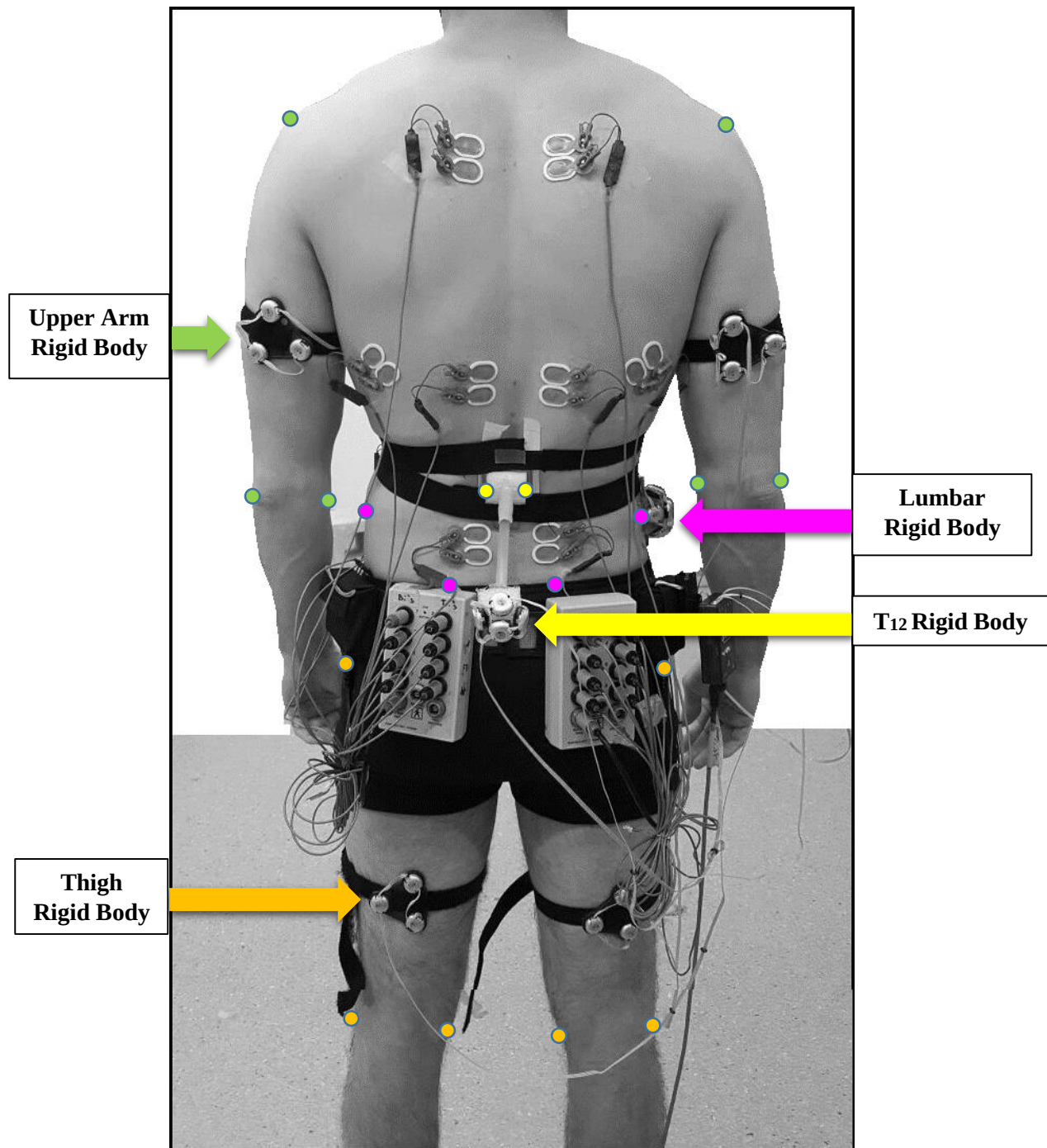


Figure 4.5: Posterior view showing anatomical bony landmarks used for digitization to corresponding rigid bodies to define and track each segment.

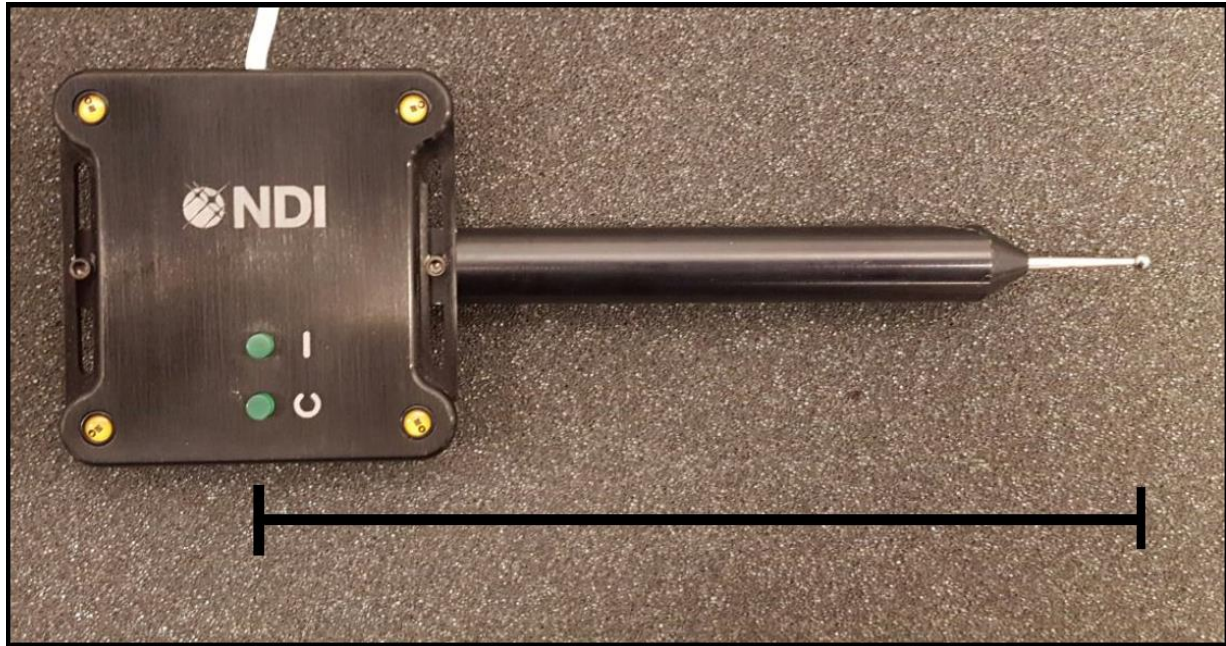


Figure 4.6: Digitization probe shown with four integrated infrared emitting diodes, pointing tip, and a scale of the predefined known 3D spatial location used to associate bony landmarks to rigid bodies.

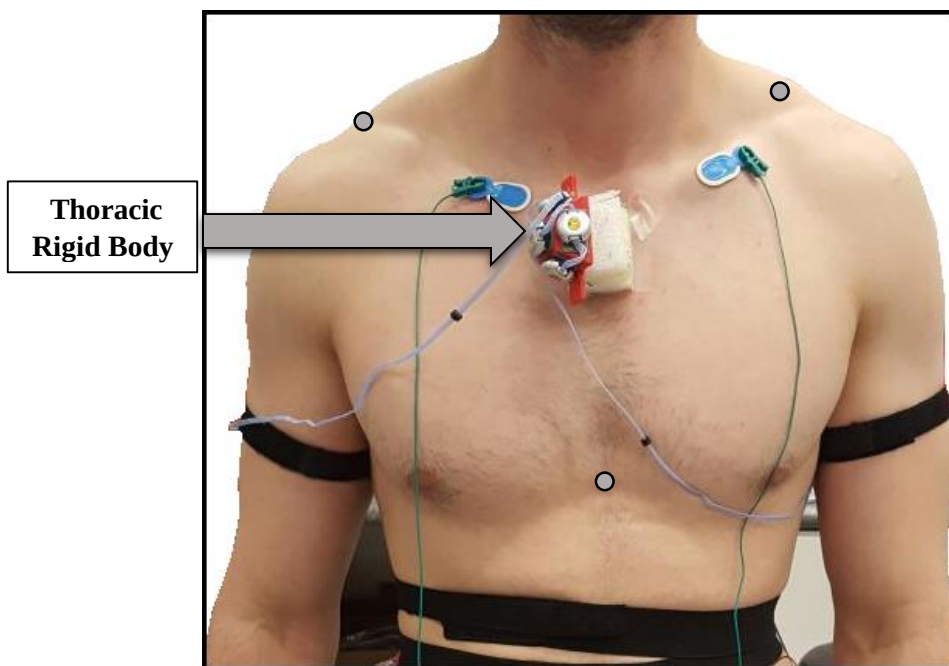


Figure 4.7: Anterior view showing anatomical bony landmarks used for digitization to the corresponding rigid body to define and track the thoracic segment.

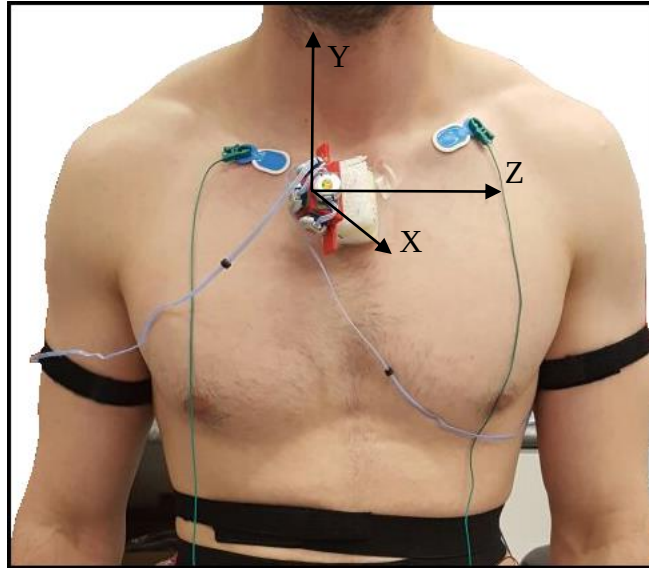


Figure 4.8: Anterior view of the relative coordinate system used and assigned to all rigid bodies.

4.2.2 EMG

EMG data were collected, differentially amplified and sampled at 2048 Hz (frequency response 10-1000 Hz, common mode rejection 115 dB at 60 Hz, input impedance 10 G Ω ; two AMT- 8, Bortec, Calgary, Canada), with Optotrak Data Acquisition Unit (ODAU, Northern Digital, Inc., Waterloo, Ontario, Canada). Sixteen pairs of disposable Ag/Ag-Cl electrodes (Ambu® Blue Sensor N, Ambu A/S, Denmark) were applied bilaterally with a 2.5 cm inter-electrode distance. Electrodes were placed perpendicular to the muscle fibre orientation over the largest part of the muscle belly for the following eight muscles: external oblique (EO), internal oblique (IO), rectus abdominis (RA), lumbar erector spinae (LES), lower-thoracic erector spinae (LTES), upper-thoracic erector spinae (UTES), latissimus dorsi (LD), and gluteus medius (GM) (Figure 4.9). The approximate electrode placement locations are listed for each muscle are listed in Table 4.1. Two additional electrodes were placed over the bony sternal end of the clavicle bilaterally to ground the signals collected and to be used to remove common signal components

(noise) thereby optimizing the quality of the recorded EMG signal (Figure 4.3). These muscles were chosen to characterize the trunk response during prolonged exposures based on previous research: prolonged standing (Nelson-Wong & Callaghan, 2010; 2014), prolonged sitting (Nairn et al., 2013; Schinkel-Ivy et al., 2013) and prolonged seated axial twist (Shan et al., 2013).

Table 4.1: Approximate electrode placement locations over the largest muscle belly of eight muscles of interest.

Muscle	Placement Location
External Oblique (EO)	~ Below rib cage, along line connecting inferior costal margin and contralateral pubic rim ^ε
Internal Oblique (IO)	~ 1 cm medial to ASIS just beneath line joining ASIS's ^ε
Rectus Abdominis (RA)	~ 1 cm above umbilicus, 2 cm lateral to midline ^ε
Lumbar Erector Spinae (LES)	~ Between midline and lateral aspect of body at L1 level ^β
Lower-Thoracic Erector Spinae (LTES)	~ 4 cm lateral to T9 spinous process and lumbar erector spinae or over the largest muscle mass at the level of T9 ^{γ, δ, ζ}
Upper-Thoracic Erector Spinae (UTES)	~ 2.5 cm lateral from the spinous process at T4 or over the largest muscle mass at the level of T4 ^{η, ζ}
Latissimus Dorsi (LD)	~ Upper 1/3 of line connecting post shoulder crease and L1 ^α
Gluteus Medius (GM)	~ 2.5 cm distal to midpoint of iliac crest ^ζ

^αAnders et al. (2005); ^ηBurnett et al. (2009); ^βDanneels et al. (2001); ^γDrake et al. (2006);

^δMcGill (1991); ^εNg et al. (1998); ^ζZipp (1982)

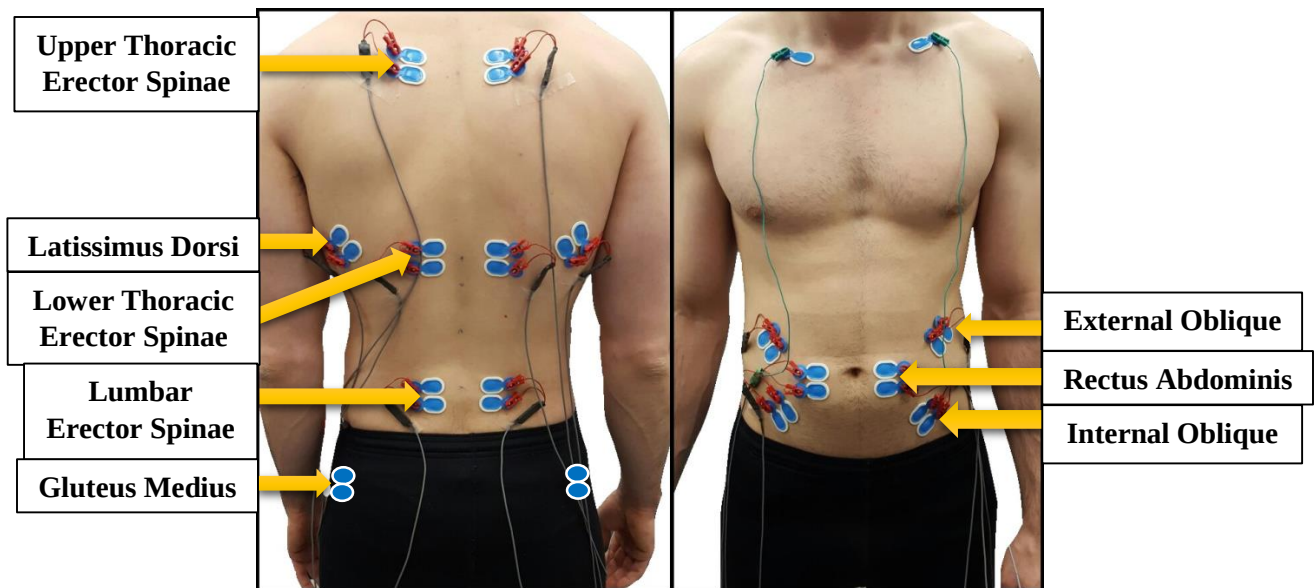


Figure 4.9: *Left: Posterior view showing bilateral electrode placement locations. (Actual electrode placement for Gluteus Medius was directly on the skin under the garment.) Right: Anterior view showing bilateral electrode placement locations.*

Due to the inherent variability in muscle activation between individuals, EMG data were expressed as a percentage of another standardized activation level (normalized). The standard used was a maximum voluntary contraction (MVC) obtained for each muscle by having participants flex or extend in various positions against manual resistance (Siu et al., 2016). A modified sit-up protocol was used to elicit MVC activations for trunk flexors: RA, EO, IO in which participants began seated on the edge of a therapy table, knees flexed, and feet flat on the table. Against manual resistance from the investigator, participants were instructed to isometrically flex, laterally bend to the right and left, and axially twist to right and left (McGill, 1991; 1992). For the trunk extensors, UTES, LTES, and LES, participants began cantilevered at the level of the hip over the edge of a therapy table in prone and manually secured with pressured at the back of the thigh and calves by research assistants. Participants were then instructed to extend against manual resistance while the investigator ensured minimal movement of the participant's torso (McGill, 1991; 1992). To elicit MVC for the LD, participants began seated

with their shoulder abducted to 90°, upper arm externally rotated, and elbow flexed at 90° (standard lateral pull down exercise position). In this position, participants were instructed to pull their elbow downward against manual resistance provided by the investigator (Arlotta et al., 2011). For the GM, maximal activations were elicited with participants on the therapy table in a side lying position. Participants performed a single leg hip abduction (towards the ceiling) against manual resistance (Nelson-Wong et al., 2008).

4.3 Procedures

Experimental procedures involved five main steps: pre-collection preparations, MVC protocols, standing kinematics, supine kinematics, and post-collection outlined with more detail in Figure 4.10. Prior to participating in any procedures, each participant provided informed consent. Anthropometric data were recorded (Table 5.1) and participants' spines were palpated and marked at the following levels: C₇, T₄, T₉, T₁₀, T₁₂, L₃, and S₂. Each electrode placement area was shaved and swabbed with alcohol to promote electrode adherence and minimize signal input impedance. Electrodes were placed on the skin over the aforementioned eight trunk and pelvis muscles bilaterally (again, the specific descriptions are listed in Table 4.1).

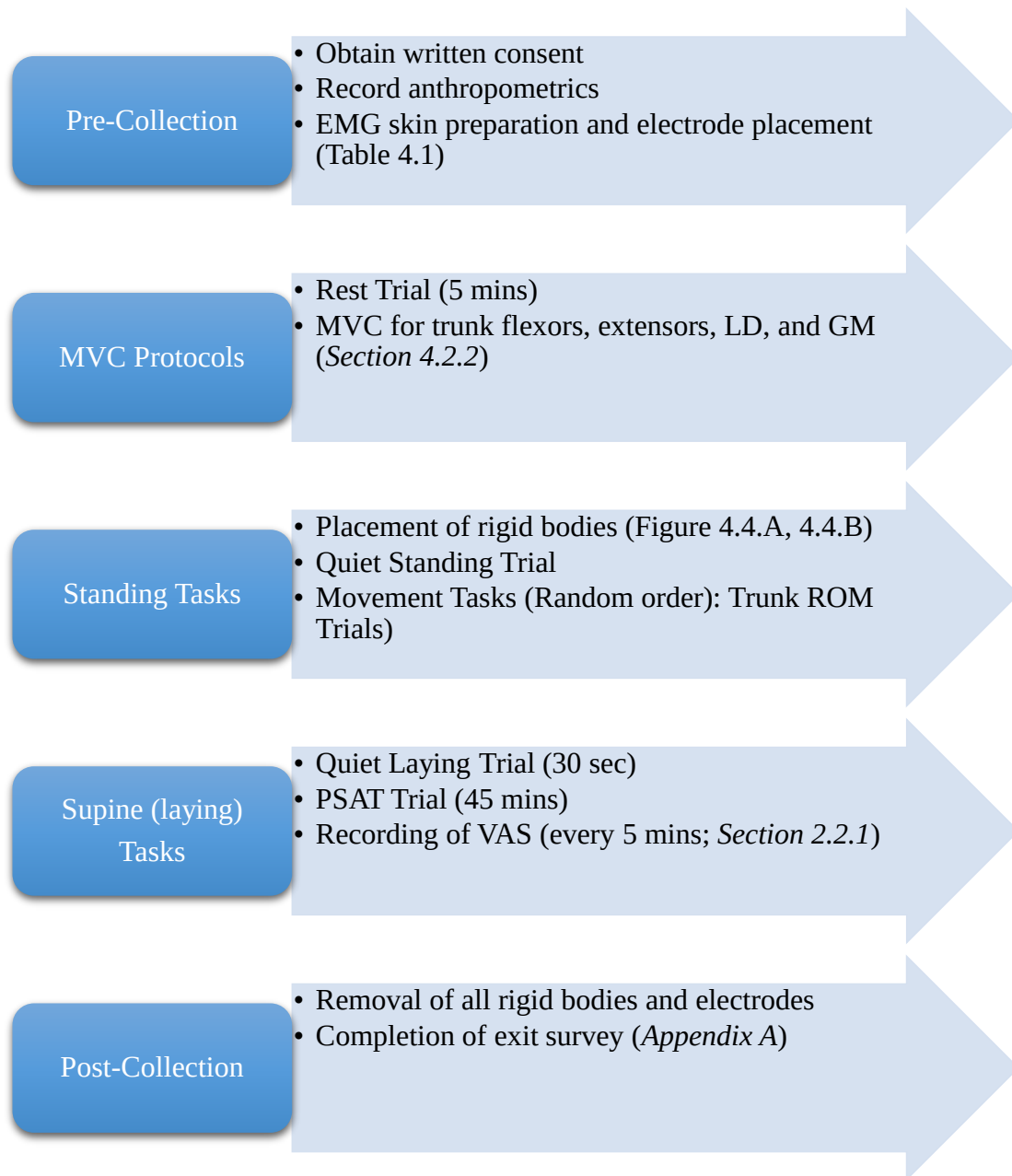


Figure 4.10: Schematic map of order of procedures in protocol

Before MVCs were captured, a 5min resting trial where participants laid quietly was recorded to obtain resting EMG activation that was used in the normalization process (Section 4.2.2). Participants were then briefed for each MVC protocol followed by an opportunity to practice each MVC protocol once at submaximal levels (Section 4.2.2). Each MVC (modified

sit-up, back extension, lateral pull-down, and leg abduction) was performed twice with each repetition lasting 3-5s and with a minimum of 3mins of rest to minimize the onset of muscle fatigue. The average of the highest peak value from the two MVC trials was be used to normalize EMG activation for each muscle.

Participants were then fitted with motion tracking rigid bodies outlined earlier in *Section 4.2.1*. After rigid body application, participants began with a quiet standing trial, by standing quietly, feet shoulder-width apart, and with their arms at their sides for 30 seconds. Then the participants were instructed to perform various ROM movement tasks in a random order to control any order effects. For trunk ROM tasks, participants performed three movements in a controlled manner: full forward flexion and extension, lateral bending and axial twist to the right and left sides three times each direction without moving their feet.

Following the MVC and movement tasks, participants were asked to lay supine on a custom board analogous to a MRI bed for 60s with their hands resting on their abdomen for calibration. After the supine resting trial, participants moved into PSAT by keeping their upper body supine against the board and rotating their lower body as far as they can so that their hips and knees are towards the left (analogous to standing axial twist to the right), but in such a way that they remained fully within the parameter of the MRI compatible spine board (length 1.6m, width 0.46m). This was done to mimic the size and positioning limitations of an MRI bore and specific position was selected to maximize comfort. Participants were supported in their rotated-supine position with straps across the shoulders and waist, as well as foam wedges beneath and between the legs (Figure 4.11). The support of straps and wedging was provided to ensure that the position could be passive and without movement (necessary for MRI). In this position,

participants were asked to remain for as long as they were comfortable, up to a maximum of 45mins.



Figure 4.11: **A-** *Coronal* view of PSAT position with straps across the shoulders and waist, hands across the abdomen while pelvis and legs are twisted to the left by a ratcheting strap. **B-** *Sagittal* view. After extensive pilot work and consultation from a MRI technician, this position and arrangement was chosen on the basis of maximum comfort to the participant where they did not have to actively hold the posture.

Self-reported pain VAS scores were manually recorded from participants at the start (0 mins) of PSAT and then every 5mins thereafter until completion for a maximum total of ten readings. With as minimal movement from the participant as possible, a new unmarked VAS score sheet and pen was provided every 5mins and access to any of the previous VAS scoring sheets was not permitted (Figure 2.1). Following the PSAT trial, all rigid body equipment and

EMG electrodes were removed from the participants and they were asked to complete an exit survey (Appendix A) to capture contextual information such as daily activity, feedback, and types of pain experienced day-to-day. The exit survey included questions such as “How many hours a week on average do you engage in physical activity? What type of physical activity? (i.e. weight lifting, running, etc) Please describe your worst imagine pain.” (Appendix A).

4.4 Data Processing

4.4.1 Kinematics

Kinematic data were low-pass and dual-pass filtered, with a 4th order Butterworth filter using a cutoff frequency of 2.5 Hz (Winter, 2005) with Visual3D v.4TM (C-Motion, Inc., Germantown, USA). Relative joint angles were calculated for the thoracic (sternum relative to T₁₂) and lumbar (T₁₂ relative to right iliac crest) for three axis of movement: Z-flexion/extension, X-lateral bend, Y-axial twist. Again, negative values represent flexion, right lateral bend, and right axial twist while positive values represent extension, left lateral bend, and left axial twist respectively. For standing axial twist, the mean angles from the standing trial were calculated and used for zeroing (indicates a “starting” point from which a ROM is calculated). Similarly, for PSAT, the mean angles from the supine trial were calculated and used for zeroing. Standing ROM values for each axis were calculated by taking the mean of the three maximum angles. PSAT values for each axis were calculated by taking the mean of each axis (as the position was already in maximum) over successive 5min intervals.

4.4.2 EMG

Muscle activation data were processed with Visual3D v.6™ software (C-Motion, Inc., Germantown, USA). Potential heart depolarization contamination was filtered from the raw signal using a dual-pass, 4th order, Butterworth filter, with a cutoff frequency of 30 Hz (Drake & Callaghan, 2006). Data were then full-wave rectified and low-pass filtered with a 4th order, Butterworth filter with a cutoff frequency of 2.5 Hz (Brereton & McGill, 1998; Van Dieen & Kingma, 2005) to produce the linear envelope of the EMG data. For each muscle, EMG data were normalized to the MVC for each respective muscle and expressed as %MVC. Mean activation levels were determined for each muscle during PSAT trial in five-minute intervals.

4.4.3 Self-Reported Pain VAS Score-Transient Pain Development

Each self-reported pain VAS was measured using a ruler in millimeters from the ‘0’ end to where the participant marked (Lee & Kieckhefer, 1989). When the initial VAS score (before PSAT trial) was greater than 0, then the corresponding score was subtracted as bias from subsequent VAS scores for the remaining prolonged supine trial to indicate the change in VAS (Nairn et al., 2013; Schinkel-Ivy et al., 2013). Each participant reported a maximum of 10 VAS scores (mm): one prior to starting PSAT, then nine more every 5mins up to a maximum of 45mins. Participants were not allowed to see any of the previous pain rating VAS scores to prevent any bias effects. Based on individual series of VAS scores, each participant was separated into pain groups (PD, NPD): PD if any scores exceeded a 10mm change from baseline (>10mm), and NPD if all scores did not exceed a 10mm change from baseline (<10mm).

4.5 Data Analysis

All statistical analyses were performed using SAS Version 9.3 (SAS Institute, Inc., Cary, NC, USA). For comparisons between pain groups (PD, NPD) where there were no significant effects of pain group, data were collapsed across pain group. Differences between pain group (PD, NPD) on anthropometric data (age, height, and weight) were compared using one-way ANOVAs.

To compare spine kinematic in neutral between standing and supine positions, the thoracic and lumbar spine kinematics (mean relative joint angles) were examined with two-way repeated measures ANOVAs for pain group (PD, NPD) and repeated measure of position (standing neutral, supine neutral).

To compare spine kinematics in axial twist between standing and supine positions the thoracic and lumbar spine kinematics (mean relative joint angles) were examined with two-way repeated measures ANOVAs for pain group (PD, NPD) and repeated measure of position (standing axial twist, supine axial twist). As standing axial twist was performed in both directions (right, left), the effect of twist direction (right, left) on thoracic and lumbar spine kinematics in the primary axis (axial twist) and coupled off-axes (flexion-extension, lateral bend) were compared with a two-way repeated measures ANOVA for pain group (PD, NPD) and repeated measure of direction (right, left). Data were collapsed across direction if there were no significant effects of direction were found, otherwise only values from the corresponding (right) direction was used in standing axial twist to compare to supine axial twist (only performed to the right).

To investigate the development of transient pain over the duration of PSAT, a two-way repeated measures to compare mean self-reported pain VAS score between pain groups (PD, NPD) and up to nine 5min epochs of time (5, 10, 15, 20, 25, 30, 35, 40, 45mins) was completed.

Lastly, in an attempt to characterize transient pain development with biomechanical measures (primary axis and coupled off-axis kinematics and EMG activity), biomechanical measures were compared between pain groups (PD, NPD) and 5min time epochs. Mean relative joint angles for the thoracic and lumbar spine and average EMG levels for eight bilateral muscles were compared using two-way repeated measures ANOVAs between pain group (PD, NPD) and up to nine 5min epochs of time (5, 10, 15, 20, 25, 30, 35, 40, 45mins).

The alpha level was set to 0.05 and used to indicate statistical significance, with Tukey's post-hoc testing used to detect differences between 5min time epochs. A statistician from York University's Statistical Consulting services was consulted prior to collection to ensure the appropriateness of analyses.

5. Results

5.1 Participant Characteristics

Information about the 20 male participants in this study are presented in Table 5.1. No main effects of pain group were reported for age, height, or weight (Table 5.1), $p>0.071$.

Table 5.1: Summary of anthropometric data and statistics by pain group. Main effect of pain group was not found to be significantly different, $p>0.071$.

Pain Group	PD (n=12)	NPD (n=8)	Pain F-Statistic
Age (yrs)	21.6 (4.89)	24.8 (5.65)	$F_{1,18}= 3.66, p=0.071$
Height (m)	1.73 (0.12)	1.73 (0.10)	$F_{1,18}= 0.00, p=1.000$
Weight (kg)	78.9 (14.9)	73.6 (17.3)	$F_{1,18}= 1.07, p=0.313$

5.2 Standing and Supine: Neutral and Axial Twist

To address the methodological implication of a supine position used in MRI to a functional standing position, two kinematic comparisons of thoracic and lumbar spine were conducted between standing and supine positions. First relative joint angles were quantified according to three orthogonal axes (Y-axial twist, X- lateral bend, and Z- flexion-extension) between positions in neutral postures. Subsequently, between positions in axial twist postures, relative joint angles were quantified according to primary axis (Y-axial twist) and off-axis motion (X-lateral bend, and Z-flexion-extension).

5.2.1 Standing vs Supine: Neutral

Significant effects of position were found on the relative joint angles of the thoracic and lumbar spine in all three axis between standing and supine in neutral postures (F stats and p-values are listed in Table 5.2). No effect of pain group or interaction between pain group and

position was reported (Table 5.2). Axial twist (around the y axis) angles (SD) for the thoracic ($p=0.008$) was found to increase to the right from standing $3.70^{\circ}(6.08)$ to supine $2.28^{\circ}(7.42)$ while the lumbar ($p=0.005$) was found to increase to the left from $0.52^{\circ}(6.75)$ to $3.82^{\circ}(6.75)$ respectively. Lateral bend (around the x axis) angles (SD) for the thoracic ($p<0.001$) were found to increase to the left from standing $0.83^{\circ}(1.12)$ to supine $-2.90^{\circ}(1.12)$ and similarly, lumbar angles ($p<0.001$) were found to increase to the left from $0.95^{\circ}(5.86)$ to $6.1899^{\circ}(5.86)$ respectively. Flexion-extension (around the z axis) angles (SD) for the thoracic ($p<0.001$) was found to increase extension from standing $-13.37^{\circ}(7.42)$ to supine $-6.97^{\circ}(6.44)$ and conversely, the lumbar ($p<0.001$) was found to increase flexion from $26.91^{\circ}(9.74)$ to $14.85^{\circ}(8.05)$ respectively. Large standard deviations indicated variability between participants, however significant differences were detected in the consistent degree of change between standing and supine positions (Figure 5.1). Across the thoracic and lumbar spine, kinematic differences (angles) in all three axes were exhibited when comparing a standing position to supine.

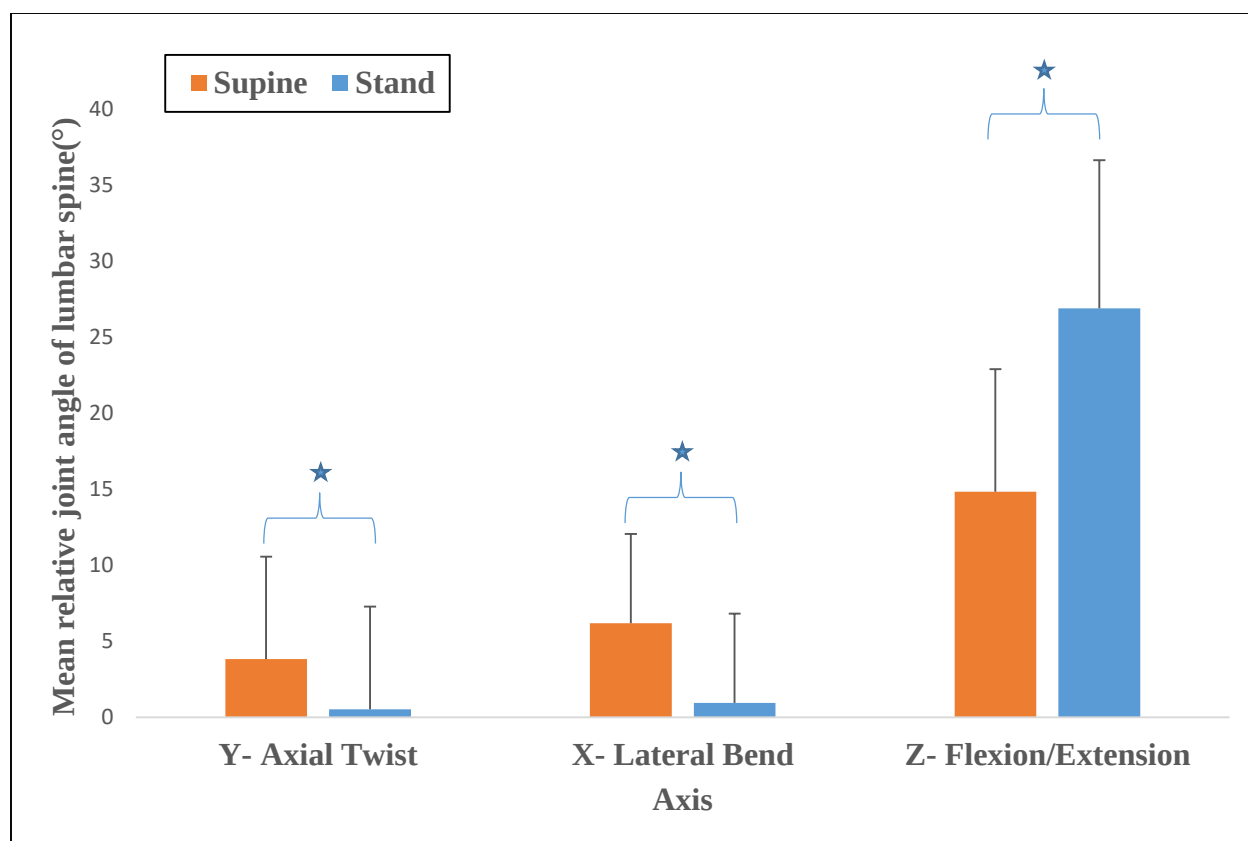


Figure 5.1: Mean relative joint angles (SD) of the lumbar spine between standing neutral and supine neutral. Significant effect of position in all three axes where supine neutral exhibited greater axial twist to the left, lateral bend to the left, and less extension. Asterisk indicates significant post-hoc comparisons, $p < 0.005$.

Table 5.2: For mean joint angles of both spine regions and all directions there was a significant main effect of position found ($p < 0.008$) in both the thoracic and lumbar spine (as indicated in bold and with an asterisk).

Effect	Position F-Statistic	Pain Group F-Statistic	Position x Pain Group F-Statistic
<i>Thoracic Spine</i>			
Y- Axial Twist	$F_{1,18}=8.68, p=0.008^*$	$F_{1,18}=0.69, p=0.417$	$F_{1,18}=2.17, p=0.158$
X- Lateral Bend	$F_{1,18}=19.2, p<0.001^*$	$F_{1,18}=0.81, p=0.378$	$F_{1,18}=1.96, p=0.178$
Z- Flexion-Extension	$F_{1,18}=63.7, p<0.001^*$	$F_{1,18}=0.36, p=0.555$	$F_{1,18}=0.13, p=0.718$
<i>Lumbar Spine</i>			
Y- Axial Twist	$F_{1,18}=9.94, p=0.005^*$	$F_{1,18}=2.76, p=0.113$	$F_{1,18}=0.99, p=0.333$
X- Lateral Bend	$F_{1,18}=41.4, p<0.001^*$	$F_{1,18}=0.94, p=0.346$	$F_{1,18}=0.15, p=0.702$
Z- Flexion-Extension	$F_{1,18}=105.6, p<0.001^*$	$F_{1,18}=0.90, p=0.356$	$F_{1,18}=0.75, p=0.397$

5.2.2 Standing vs Supine: Axial Twist

In the primary axis (axial twist), no main effect of direction in the standing axial twist (right and left) was found on the magnitude of mean relative joint angles. Conversely, in the off-axes (lateral bend and flexion-extension) main effect of direction was found for the lumbar spine only (Table 5.3). No significant effect of pain or interaction between pain and direction in either primary axis or off-axes were reported (Table 5.3). During axial twist to the right and left, there was significant off-axis lateral bend ($p=0.026$) in the lumbar spine by 6.8° (2.5) and 5.5° (2.8) respectively (Figure 5.2). During axial twist to the right and left, there was significant off-axis flexion-extension ($p<0.01$), in the lumbar spine by 14.3° (4.0) and 9.3° (4.0) respectively (Figure 5.2).

Table 5.3: Summary of statistical analysis results for the magnitude of mean joint angles of all spine regions and directions. Main effect was direction and found to be significantly different ($p<0.026$) in off-axes lateral bend and flexion-extension for the lumbar spine indicated in bold and with an asterisk.

Effect	Direction F-Statistic	Pain Group F-Statistic	Direction x Pain Group F-Statistic
<i>Thoracic Spine</i>			
Y- Axial Twist	$F_{1,18}=0.14, p=0.713$	$F_{1,18}=0.03, p=0.863$	$F_{1,18}=3.03, p=0.10$
X- Lateral Bend	$F_{1,18}=3.08, p=0.096$	$F_{1,18}=2.18, p=0.156$	$F_{1,18}=0.912, p=0.352$
Z- Flexion-Extension	$F_{1,18}=0.10, p=0.76$	$F_{1,18}=0.42, p=0.523$	$F_{1,18}=0.12, p=0.731$
<i>Lumbar Spine</i>			
Y- Axial Twist	$F_{1,18}=0.01, p=0.919$	$F_{1,18}=0.03, p=0.861$	$F_{1,18}=0.001, p=0.982$
X- Lateral Bend	$F_{1,18}=5.82, p=0.026^*$	$F_{1,18}=0.77, p=0.392$	$F_{1,18}=1.62, p=0.218$
Z- Flexion-Extension	$F_{1,18}=16.0, p<0.01^*$	$F_{1,18}=1.02, p=0.326$	$F_{1,18}=2.83, p=0.109$

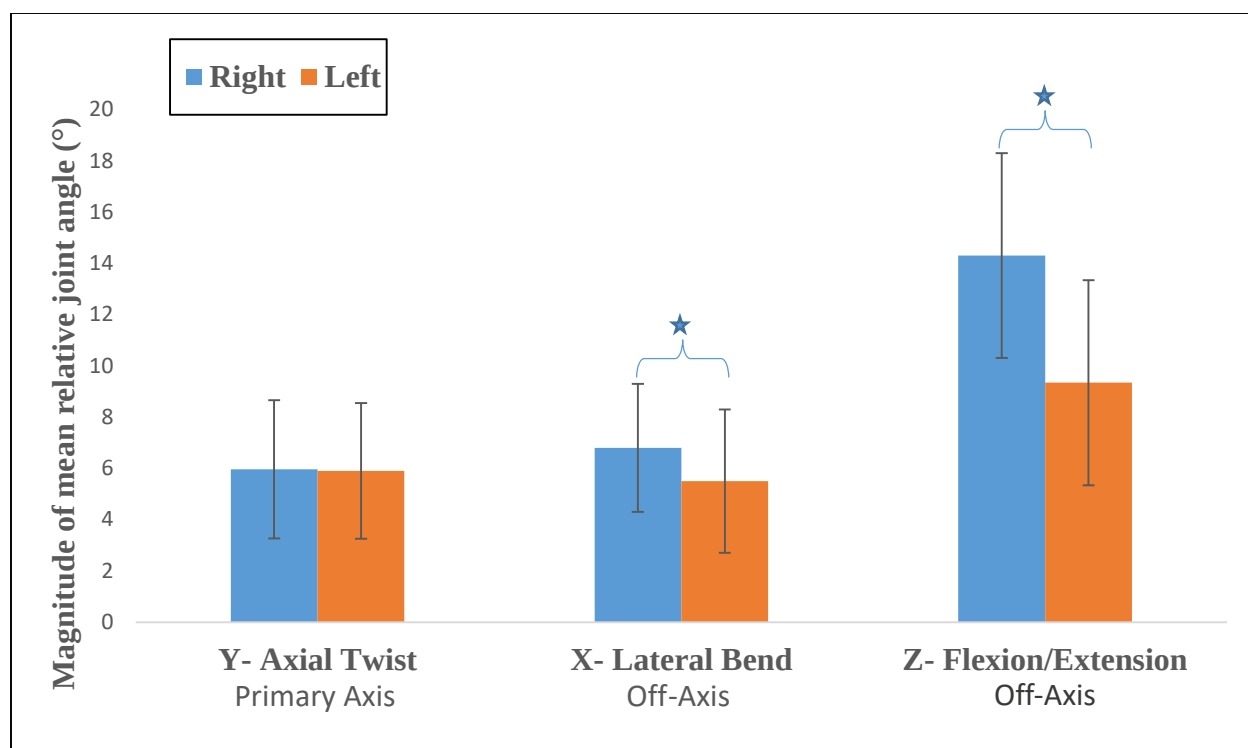


Figure 5.2: Magnitude of mean relative joint angles (SD) of the lumbar spine between standing axial twist to the right and left directions. Significant effect of direction on the off-axes (x-lateral bend, z-flexion-extension) where standing axial twist to the right exhibited more lateral bend and flexion/extension than standing axial twist to the left. No effect of direction on primary axis (y-axial twist). Asterisk indicates significant post-hoc comparisons, $p < 0.026$.

Kinematic differences were reported between the directions of standing axial twist, subsequently standing axial twist to the right was compared with supine axial twist (also to the right). A main effect of position was reported in the off-axis lateral bend ($p < 0.01$), for the lumbar spine, and reported significant differences were standing axial twist and PSAT were $-6.8^\circ(2.5)$ and $2.6^\circ(5.3)$ respectively (Figure 5.3). Standing axial twist reported small significant differences between right and left directions while standing axial twist (to the right) and supine axial twist (to the right) reported significant differences between positions in off-axis lateral bend for the lumbar spine.

Table 5.4: Summary of statistical analysis results for mean joint angles of all spine regions and directions. Main effect was position and found to be significantly different ($p<0.001$) indicated in bold and with an asterisk.

Effect	Position F-Statistic	Pain Group F-Statistic	Position x Pain Group F-Statistic
<i>Thoracic Spine</i>			
Y- Axial Twist	$F_{1,18}= 4.09, p=0.057$	$F_{1,18}=0.72, p=0.406$	$F_{1,18}=0.65, p=0.429$
X- Lateral Bend	$F_{1,18}= 2.89, p=0.106$	$F_{1,18}=0.28, p=0.602$	$F_{1,18}=0.55, p=0.465$
Z- Flexion-Extension	$F_{1,18}= 0.71, p=0.41$	$F_{1,18}=0.03, p=0.863$	$F_{1,18}=0.28, p=0.604$
<i>Lumbar Spine</i>			
Y- Axial Twist	$F_{1,18}= 0.71, p=0.409$	$F_{1,18}=0.01, p=0.927$	$F_{1,18}=0.02, p=0.894$
X- Lateral Bend	$F_{1,18}= 70.79, p<0.001^*$	$F_{1,18}=0.10, p=0.754$	$F_{1,18}=1.03, p=0.323$
Z- Flexion-Extension	$F_{1,18}= 0.33, p=0.572$	$F_{1,18}=2.25, p=0.150$	$F_{1,18}=0.84, p=0.371$

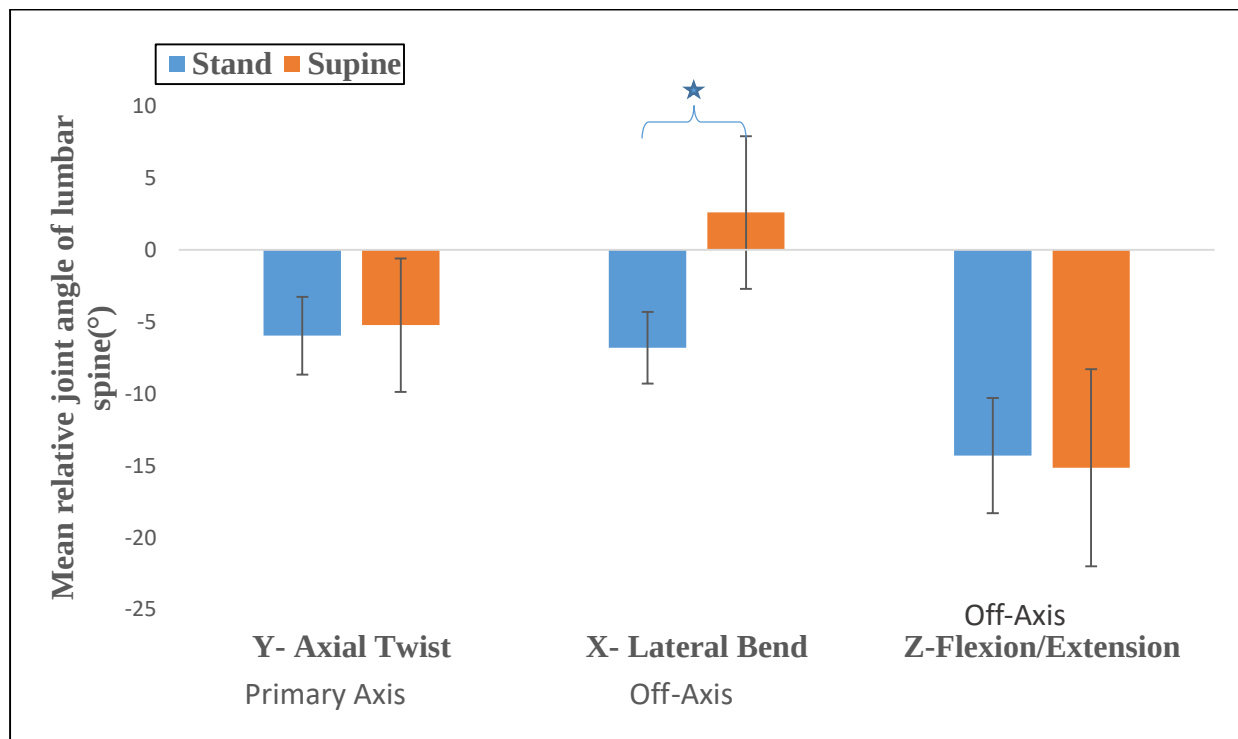


Figure 5.3: Mean relative joint angles (SD) of the lumbar spine between standing axial twist and supine axial twist. Significant effect of position on off-axis (x-lateral bend) where supine axial twist exhibited greater lateral bend to the left compared to standing axial twist. No effect of position on primary axis (y-axial twist) or off-axis (flexion/extension). Positive numbers indicate direction to left while negative numbers indicate direction to the right. Asterisk indicates significant post-hoc comparisons, $p<0.001$.

5.3 PSAT- Prolonged Supine Axial Twist

The amount of pain experienced (measured by VAS score) was used to differentiate between PDs (>10mm) and NPDs (<10mm). Subsequently, the VAS score between pain groups, and time epochs were compared with particular interest when 10mm and 20mm cutoffs were exceeded (indicative of minimum clinically relevant pain and clinical pain, respectively). Lastly, kinematic and EMG biomechanical measures were compared between pain groups and across time to characterize transient pain development during PSAT.

5.3.1 Evaluating Transient Pain Development during PSAT

Significant effect of pain was found between PD and NPD groups ($p<0.01$) where the mean of max (SD) self-reported pain VAS score for PD was 32.0mm (13.6) and NPD was 3.0mm (4.3) respectively (Figure 5.4). Median (IQR) VAS score for PD was 33mm (-5.9 to 67.1) and NPD 0mm (-7.5 to 12.5). A distinct difference between the max VAS scores (irrespective of time) was exhibited during PSAT between PD and NPD groups.

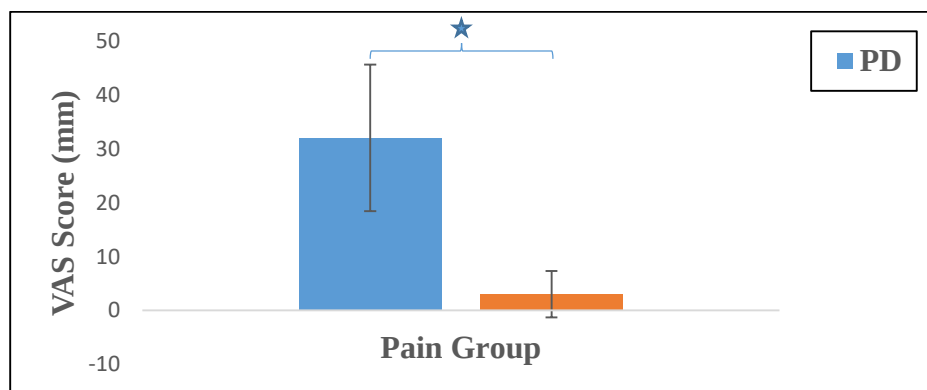


Figure 5.4: Mean of max self-reported pain scores (from initial baseline) for both PD and NPD's collapsed over the 45-minute PSAT trial with SD bars showing that PDs reported significantly greater max self-reported pain than NPDs. Asterisk indicates significant post-hoc comparisons, $p<0.001$.

To represent the progression of transient pain with successive 5min epochs, Figure 5.5 represents the mean VAS score (in millimeters) from the initial baseline score taken for both PD and NPD's over the length of the 45-minute PSAT trial in 5min epochs. An interaction effect was found between pain group and time ($p < 0.001$). Mean VAS score was significantly greater for PD than NPD after 25min (Figure 5.5). While no significant increases in pain reported for the NPD group over time, the PD group reported significantly increased VAS scores after 15min ($p < 0.001$) (Figure 5.5). Across the duration of PSAT, a clear differentiation in the mean VAS scores between pain groups was found starting at 25mins. Further, for those who developed transient pain, significant increases in mean VAS occurred after 15mins where the 10mm cutoff was breached between 15-20mins and 20mm cutoff between 25-30mins.

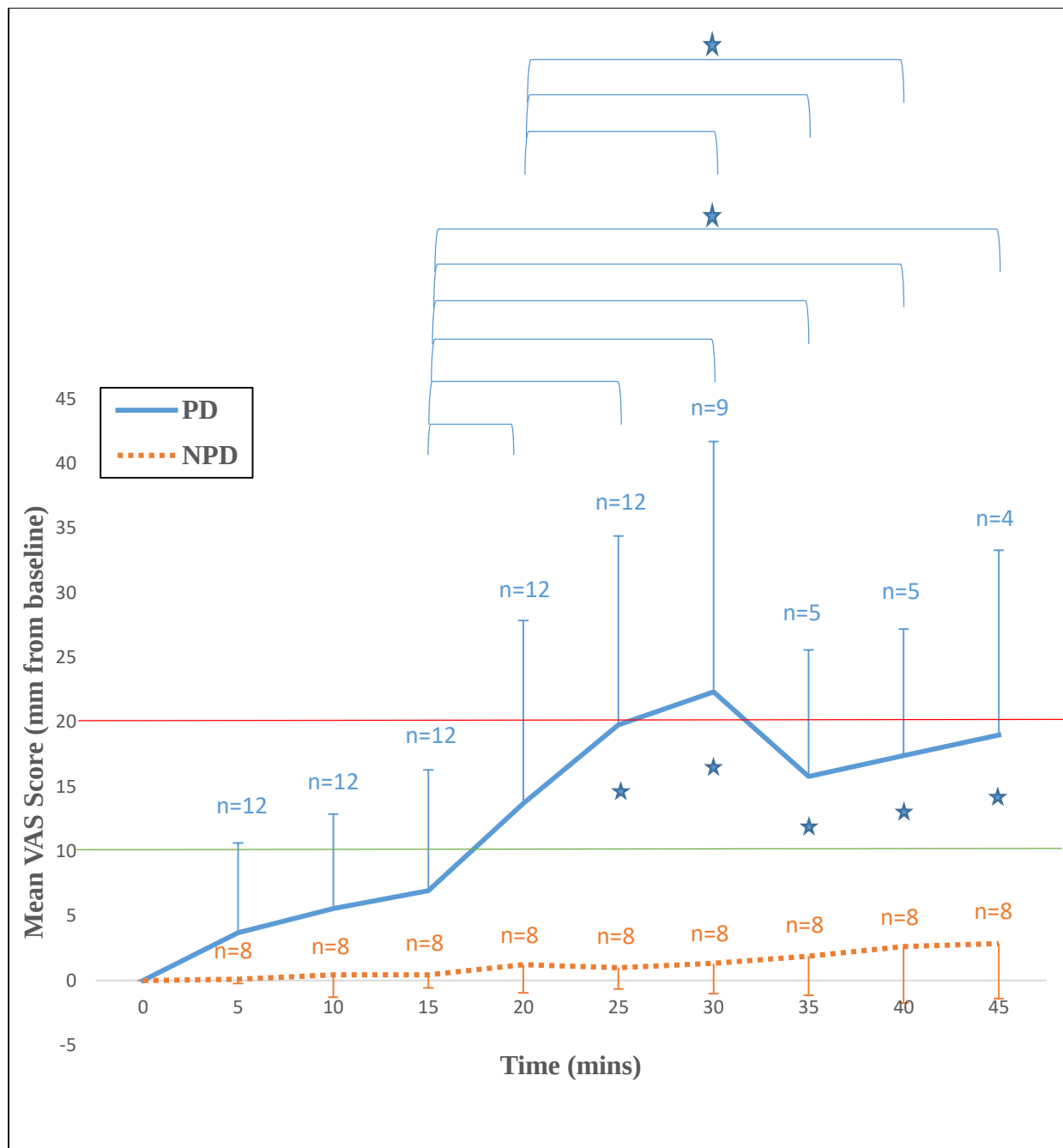


Figure 5.5: Mean (SD) self-reported pain score (from initial baseline) for both PD and NPD's at 5-minute epochs over the 45-minute PSAT trial. Sample size count is indicated at each 5-minute interval. Green horizontal line represents the 10mm self-reported pain cut-off indicative of minimum clinically relevant pain while the red horizontal line represents the 20mm self-reported pain cuffoff indicative of clinical pain. Asterisk indicates significant post-hoc comparisons, $p < 0.05$. Significant interaction between pain groups and time from $t=25\text{mins}$ to $t=45\text{mins}$, ($p < 0.001$).

5.3.2 Evaluating Kinematics during PSAT

For both the thoracic and lumbar spine regions, and in all three axis, no main effects of pain ($p>0.111$) or time ($p>0.121$) on the mean relative joint angles, as well as no interaction effects between pain and time ($p>0.718$), were found to be significant (Table 5.5). Comparing the mean relative joint angle from $t=5$ mins to $t=45$ mins for each spine region and axis small differences were exhibited. For axial twist of the lumbar spine exhibited a mean change (SD) of 1.1° (5.1) and thoracic spine 0.72° (4.2) (Figure 5.6, Figure 5.7). For lateral bend of the lumbar spine exhibited a mean change of 2.4° (10.5) and thoracic spine 2.0° (10.3) (Figure 5.8, Figure 5.9). For flexion-extension of the lumbar spine exhibited a mean change of 2.2° (11.6) and thoracic spine 0.8° (8.5) (Figure 5.10, Figure 5.11). Small differences in mean relative joint angles between the start and end of PSAT indicated that minimal creep had occurred.

Table 5.5: Summary of statistical analysis results for kinematic relative joint angles of all spine regions and directions. Main effects were pain and time while interaction effect was pain x time. Effects were not found to be significantly different, $p>0.111$.

Effect	Pain F-Statistic	Time F-Statistic	Pain x Time F-Statistic
<i>Thoracic Spine</i>			
Y	$F_{1,19}=1.06, p=0.317$	$F_{8,126}=0.88, p=0.539$	$F_{8,126}=0.12, p=0.998$
X	$F_{1,19}=0.55, p=0.467$	$F_{8,126}=0.25, p=0.980$	$F_{8,126}=0.09, p=0.999$
Z	$F_{1,19}=1.91, p=0.183$	$F_{8,126}=0.17, p=0.995$	$F_{8,126}=0.07, p=0.999$
<i>Lumbar Spine</i>			
Y	$F_{1,19}=1.30, p=0.268$	$F_{8,125}=1.63, p=0.121$	$F_{8,125}=0.67, p=0.718$
X	$F_{1,19}=0.00, p=0.998$	$F_{8,125}=0.43, p=0.904$	$F_{8,125}=0.40, p=0.916$
Z	$F_{1,19}=2.79, p=0.111$	$F_{8,125}=0.13, p=0.998$	$F_{8,125}=0.24, p=0.983$

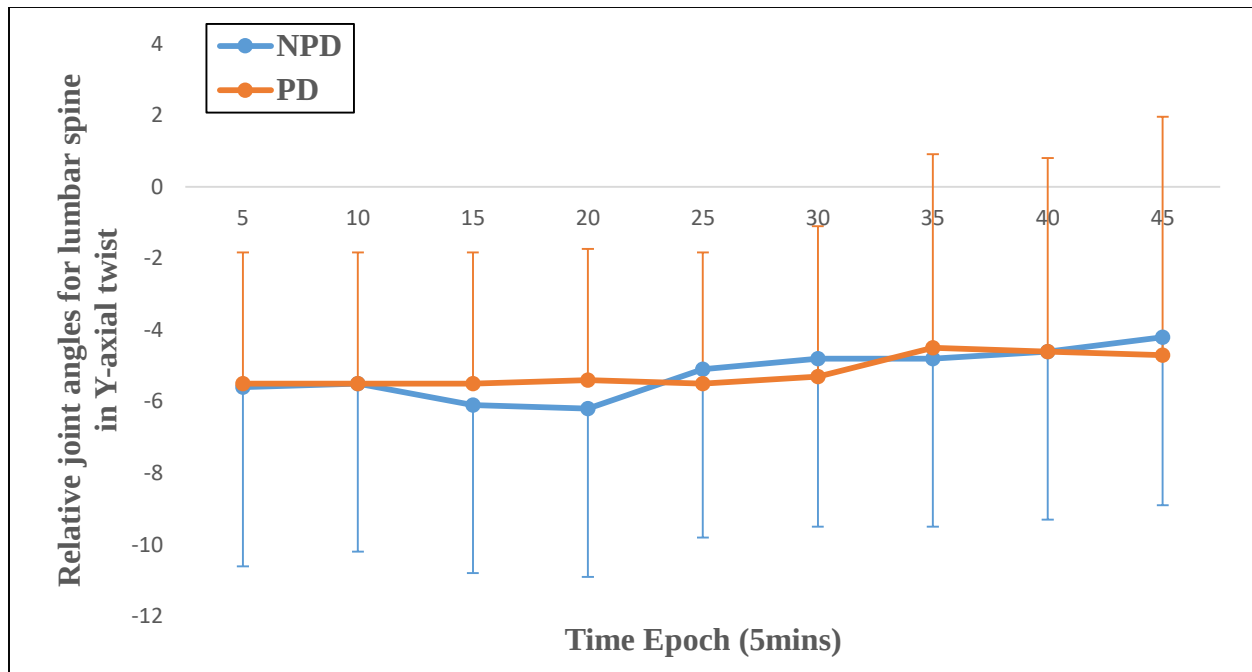


Figure 5.6: Mean (SD) relative joint angle for lumbar spine in axial twist (y axis) across nine 5min epochs with no significant effect of pain group, time, or interaction between pain and time, $p>0.121$.

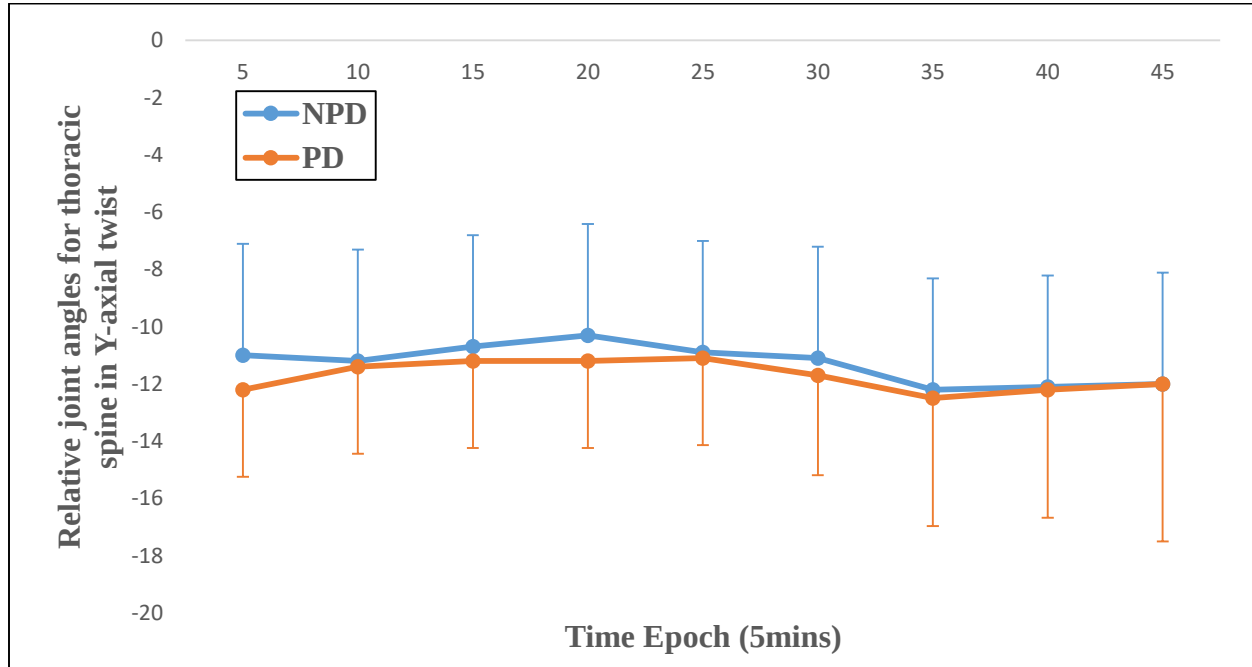


Figure 5.7: Mean (SD) relative joint angle for thoracic spine in axial twist (y axis) across nine 5min epochs with no significant effect of pain group, time, or interaction between pain and time, $p>0.317$.

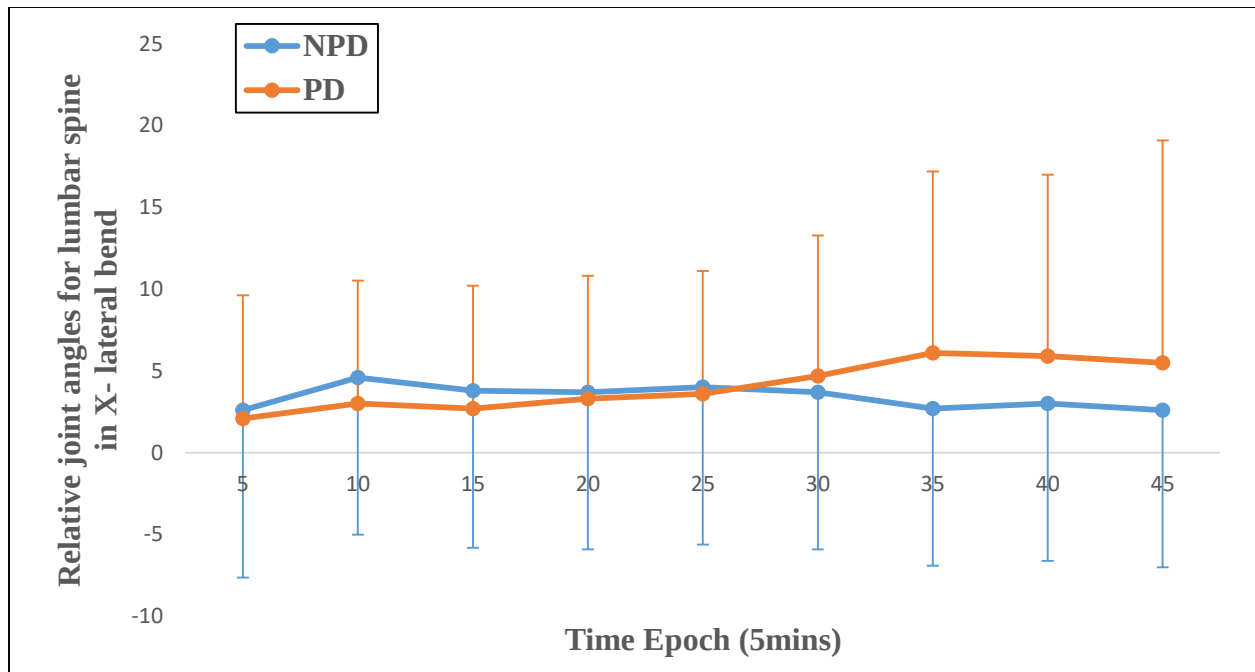


Figure 5.8: Mean (SD) relative joint angle for lumbar spine in lateral bend (x axis) across nine 5min epochs with no significant effect of pain group, time, or interaction between pain and time, $p>0.904$.

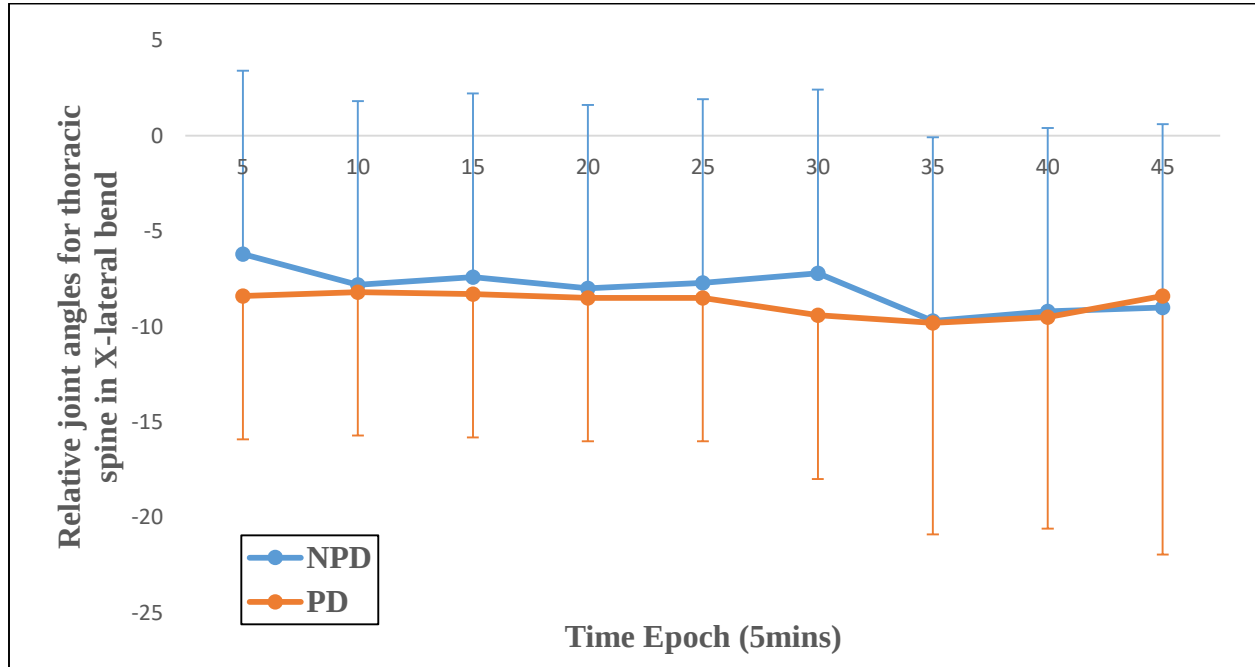


Figure 5.9: Mean (SD) relative joint angle for thoracic spine in lateral bend (x axis) across nine 5min epochs with no significant effect of pain group, time, or interaction between pain and time, $p>0.467$.

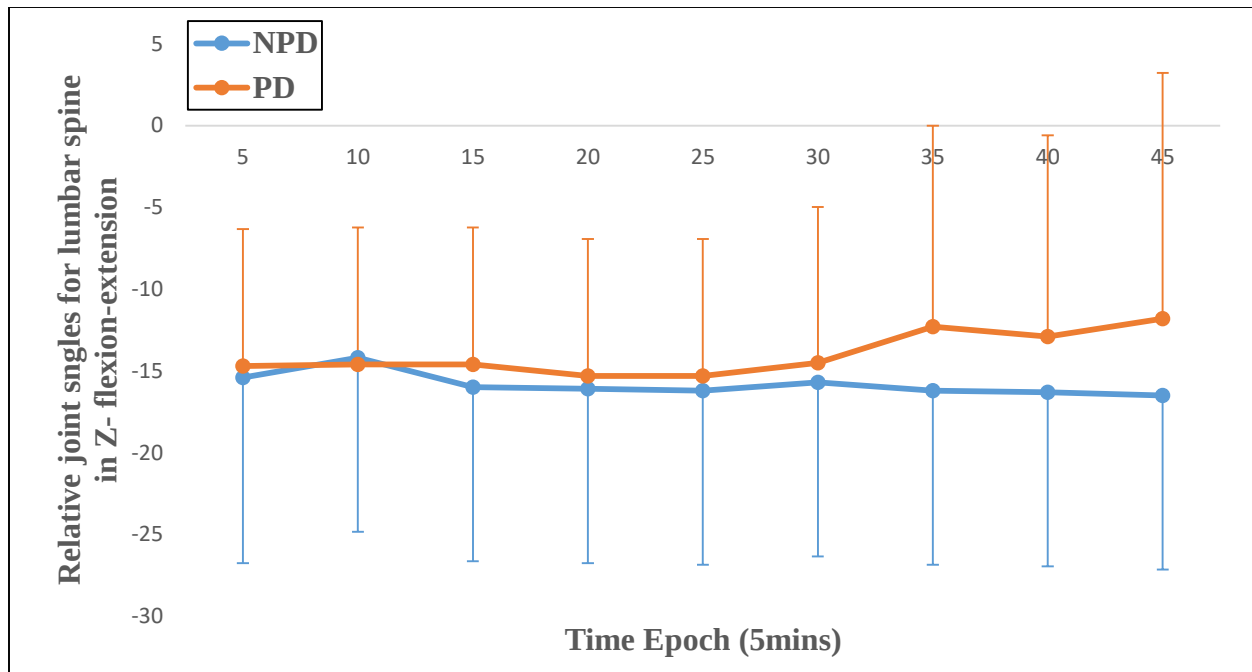


Figure 5.10: Mean (SD) relative joint angle for lumbar spine in flexion-extension (z axis) across nine 5min epochs with no significant effect of pain group, time, or interaction between pain and time, $p>0.111$.

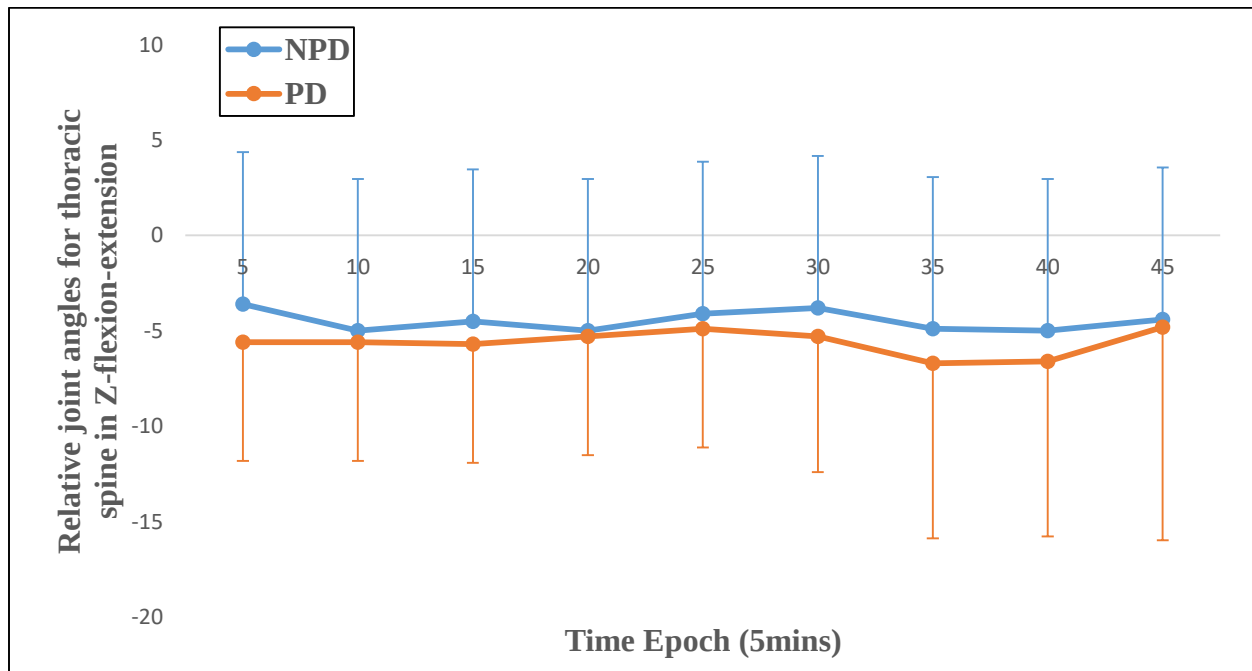


Figure 5.11: Mean (SD) relative joint angle for thoracic spine in flexion-extension (z axis) across nine 5min epochs with no significant effect of pain group, time, or interaction between pain and time, $p>0.183$.

5.3.3 Evaluating Electromyography during PSAT

For all 8 muscles, bilaterally, there were no main effects of pain ($p>0.201$), or time ($p>0.107$), on mean EMG (expressed as %Max), and no interaction effects between pain and time ($p>0.237$), were found to be significantly different (Figure 5.7). For each of the 16 muscles across each 5min time epoch, the largest mean activation levels were within 5%MVC. Largest mean activation levels (SD) for LEO was 1.5%MVC (1.9), LGM 2.5%MVC (2.5), LIO 1.3%MVC (1.8), LL₃ 2.3%MVC (3.0), LLD 1.3%MVC (2.2), LRA 2.6%MVC (2.5), LT₄ 2.5%MVC (3.4), LT₉ 3.8%MVC (5.4), REO was 3.7%MVC (5.5), RGM 3.2%MVC (2.5), RIO 4.5%MVC (11.1), RL₃ 1.5%MVC (2.0), RRA 4.8%MVC (3.4), RT₄ 3.2%MVC (4.3), RT₉ 1.2%MVC (1.8). Irrespective of pain group or time, mean EMG of each muscle remained consistently low during PSAT as shown in Figure 5.12 and 5.13.

Table 5.6: Summary of statistical analysis results for EMG (%Max) of all eight muscle bilaterally. Main effects were pain and time while interaction effect was pain x time. Effects was not found to be significantly different ($p < 0.107$).

Effect	Pain F-Statistic	Time F-Statistic	Pain x Time F-Statistic
<i>Left Side</i>			
EO	$F_{1,18}=0.05, p=0.831$	$F_{8,117}=0.35, p=0.995$	$F_{8,117}=0.27, p=0.9735$
GM	$F_{1,18}=1.59, p=0.224$	$F_{8,115}=0.70, p=0.687$	$F_{8,115}=0.43, p=0.903$
IO	$F_{1,18}=1.32, p=0.266$	$F_{8,116}=0.76, p=0.640$	$F_{8,116}=1.01, p=0.434$
L ₃	$F_{1,16}=0.23, p=0.639$	$F_{8,100}=1.58, p=0.141$	$F_{8,110}=1.33, p=0.237$
LD	$F_{1,18}=0.18, p=0.680$	$F_{8,116}=0.35, p=0.943$	$F_{8,116}=0.65, p=0.736$
RA	$F_{1,17}=0.67, p=0.424$	$F_{8,111}=0.50, p=0.857$	$F_{8,111}=0.28, p=0.971$
T ₄	$F_{1,18}=0.24, p=0.628$	$F_{8,118}=1.69, p=0.107$	$F_{8,118}=1.05, p=0.405$
T ₉	$F_{1,18}=1.22, p=0.285$	$F_{8,118}=1.57, p=0.142$	$F_{8,118}=0.91, p=0.507$
<i>Right Side</i>			
EO	$F_{1,17}=0.02, p=0.878$	$F_{8,110}=0.56, p=0.807$	$F_{8,110}=0.29, p=0.969$
GM	$F_{1,18}=1.77, p=0.201$	$F_{8,111}=0.74, p=0.655$	$F_{8,111}=0.25, p=0.980$
IO	$F_{1,18}=0.01, p=0.907$	$F_{8,118}=0.26, p=0.977$	$F_{8,118}=0.31, p=0.961$
L ₃	$F_{1,17}=0.53, p=0.477$	$F_{8,110}=0.43, p=0.901$	$F_{8,110}=0.11, p=0.999$
LD	-	-	-
RA	$F_{1,18}=1.21, p=0.285$	$F_{8,117}=1.21, p=0.298$	$F_{8,117}=0.86, p=0.556$
T ₄	$F_{1,18}=1.05, p=0.318$	$F_{8,118}=0.26, p=0.977$	$F_{8,118}=0.66, p=0.723$
T ₉	$F_{1,18}=0.20, p=0.663$	$F_{8,118}=0.29, p=0.967$	$F_{8,118}=0.64, p=0.745$

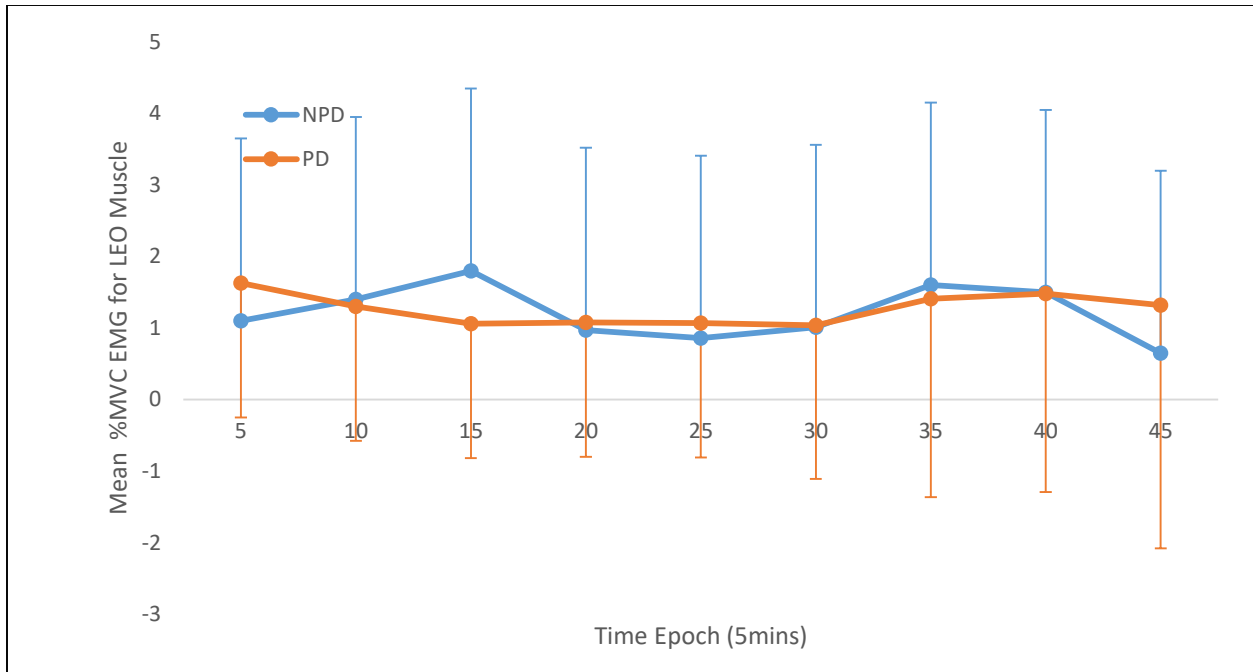


Figure 5.12: Example of mean (SD) activation expressed as %MVC for the LEO muscle across nine 5min epochs with no significant effect of pain group, time, or interaction between pain and time, $p>0.831$.

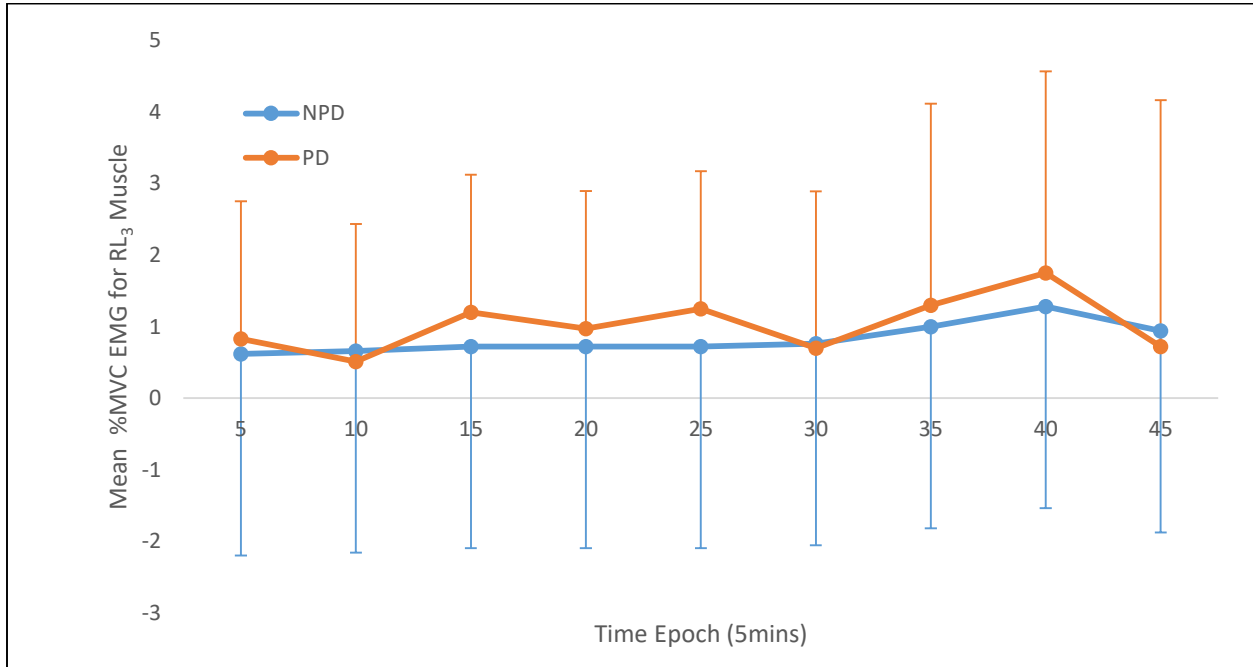


Figure 5.13: Example of mean (SD) activation expressed as %MVC for the RL₃ muscle across nine 5min epochs with no significant effect of pain group, time, or interaction between pain and time, $p>0.477$.

5.4 Summary of Key Points

First, the kinematics of standing and supine in neutral were compared and yielded significant differences in all three axes. Most notably in the lumbar spine, important differences were highlighted in axial twist and flexion-extension.

Comparing standing axial twist between right and left directions, significant off-axes kinematic differences in lateral-bend and flexion-extension were reported. Further, the kinematics between standing axial twist to the right and supine axial twist to the right, yielded a significant off-axis difference in lateral bend for the lumbar spine while axial twist and flexion-extension were comparable.

Based on self-reported VAS scores and a 10mm cutoff indicative of minimum clinically relevant pain, PSAT differentiated into PD (n=12) and NPD (n=8) pain groups. Further, the mean VAS score of PD exceeded the 10mm cutoff by 20mins and exceeded the 20mm cutoff by 30mins indicative of clinical pain. In short, by 20mins the PD group had reported clinically relevant pain, and by 30mins the PD group had reported pain scores that exceeded clinical acceptable levels. No differences were reported between pain groups or time in kinematic and EMG measures. Further, kinematic and EMG evaluation confirmed that creep and muscle activation was minimal over the duration of PSAT.

6. Discussion

This thesis posed three main goals to compare spine kinematics (angles) between various MRI-applicable standing and supine positions in neutral and twisted spine postures, as well as document the development of transient pain, and finally characterize transient pain with muscle activation, and unintentional movement over the duration of a conventional MRI procedure. Overall, the results highlight important kinematic differences between standing and supine during neutral and axial twist postures. These angular differences are relevant for diagnostic imaging (conventional radiographs, computed tomography, MRI) to help ensure maximum value to clinicians and researchers. By understanding the kinematic differences, participants can be optimally positioned to capture all structures that could potentially be involved with pain (Andreasen et al., 2007). With results from this thesis, attention and efforts should be paid to not only primary axis but also off-axis motions in lateral bend and flexion-extension. With the focus on off-axis motions, external efforts and adjustments can be incorporated such as wedging to improve control over the twisted position in supine and minimize the impact about the off=axes (lateral bend and flexion-extension).

There was a clear differentiation between individuals who reported the development of transient pain and those who did not during PSAT. Additionally for those who did, the progression of transient pain generally increased with time. As transient pain development is commonly reported in many other types of prolonged exposure protocols, these results are relevant to the understanding and to serve as a guideline to proactively minimize unnecessary repercussions to participants while partaking in a MRI and PSAT. Lastly, an attempt was made using two preliminary biomechanical measures to characterize differences between PD and NPD. Although no significant main effects were reported, further investigation is required to

comprehensively explore pain viable pathways during PSAT. As these results were founded on an asymptomatic population, it may serve as reference data to provide context in understanding disease progression, and development of movement and monitoring therapies (Benditz et al., 2017; Schoder et al., 2014).

6.1 Comparison Between Standing and Supine

Kinematics between standing and supine positions were quantified in neutral and axially twisted positions in order to assess the horizontal supine position compared to standing. By quantifying kinematic differences, a better understanding can improve MRI patient positioning and methodology, as well as interpreting generated results.

6.1.1 Comparison Between Standing and Supine: Neutral

Assessing the effect of position on each axis, significant differences were found about all three axes. For the thoracic and lumbar spine, differences between positions in axial twist were 1.4° and 3.3° respectively. As the lumbar spine axial twist ROM is smaller relative to other axes and spine regions, a difference of 3.3° between standing and supine in neutral is relatively significant. This provides new insight into the axial comparison of standing and supine in neutral postures. Differences in lateral bend for the thoracic and lumbar spine were 3.7° and 4.2° respectively. These differences support previous literature regarding lateral bend angles between standing and supine positions and are within an acceptable 5° range (Lee et al., 2013).

Significant differences in flexion-extension between standing and supine positions were +6.4° and -12.1° for the thoracic and lumbar, respectively. Alternatively, in supine, the thoracic was flatter or exhibited less kyphosis and the lumbar was also flatter exhibiting less lordosis.

This pattern has been repeatedly found and supported in literature when comparing the flexion-extension of a standing and supine position. Despite this, larger magnitudes of flexion-extension changes were found in this study compared to literature. For example, Mauch et al. (2010) who reported significantly less lumbar lordosis in supine by only 6.3° compared to standing via vertical MRI. This discrepancy could have been due to methodological differences between internal radiographic and MRI techniques used to calculate angles compared to external 3D motion capture used in this study which may introduce variability from skin movement. Building on existing literature primarily focused on flexion-extension axis differences between stand and supine in neutral, this study additionally quantifies and highlights axial twist and lateral bend axes. All three axis considered, supine (relative to standing) in neutral is comparable only in lateral bend while axial twist exhibited greater twist to the left and flexion-extension exhibited a large significant loss of lumbar lordosis. These differences between standing and supine in neutral could be reasoned by comparing the anatomical structures that dictated spine curvature in each position and the direction gravity acts on the spine. In standing, the curvature of the spine was largely determined by the interacting facet and intervening intervertebral disc stacked into a vertical column aligned with gravity (along compression axis), yielding the classic kyphosis-lordosis shape of the thoracic and lumbar spine. Comparatively, in supine the curvature of the spine in a horizontal position was determined by posterior structures (i.e. spinous process, posterior portion of ribs, PSIS) that individuals were laying on, with gravity acting perpendicular to the vertebral column (along shear axis). Based on these findings, when using supine in neutral to represent standing, it is important to either consider highlighted differences when interpreting data or actively incorporating wedging to offset and minimize highlighted differences in supine.

6.1.2 Comparison Between Standing and Supine: Axial Twist

Prior to comparing the kinematics of axial twist in standing and supine positions, the kinematics of standing axial twist to the right and left directions were compared. In the primary axial twist axis, there was no main effect of direction in either thoracic or lumbar which reinforces previous literature. However, there was a main effect of direction reported in two off-axes (lateral-bend, flexion-extension) for the lumbar only where axial twist to the right exhibited 1.13° more lateral bend and 4.37° more flexion than axial twist to the left.

Between standing axial twist (right) and supine axial twist (right), no effect of position was reported in the primary axial twist axis for either spine regions. Additionally, lumbar axial ROM during standing and supine positions were comparable and within ranges from previous literature. Largely overlooked by literature and a focus of this thesis was investigating off-axis motion (lateral bend and flexion-extension) during axial twist between standing and supine. Significant main effect of position was reported in off-axis lateral bend where PSAT exhibited 9.1° more lateral bend than standing axial twist. Functionally, meaning that during axial twist to the right, the amount of lumbar lateral bend in standing was +6.8° (in the same direction of the axial twist) and conversely in supine was -2.6° (in the opposite direction of the axial twist). Lateral bend during axial twist in the same direction (also called coupled motion) has been well documented in the lumbar spine (Panjabi et al., 1989). However the opposing behaviour of lateral bend (in the opposing direction of the axial twist) in supine may be explained as laying on the table altered the natural angular coupling behaviour previously reported in standing. As the majority of previous literature is limited to quantifying axial twist to strictly the primary axis, these results highlight the need to consider off-axes especially lateral bend in the lumbar spine. Therefore, if a supine axial twist (such as PSAT) is utilized attention and adjustments are

recommended to mimic the coupled lateral bend exhibited in standing in order to best represent the kinematics of the lumbar spine during axial twist.

6.2 PSAT- Prolonged Supine Axial Twist

PSAT was evaluated two ways: first, to understand the course of transient pain development which could be used to outline MRI protocol durations and thereby minimize the possible exposure to participants. Second, to attempt to characterize pain groups as previous biomechanical measures have which may serve to identify at-risk individuals in future studies.

6.2.1 Evaluating Transient Pain Development during PSAT

The PSAT induced transient pain development in 60% of previously asymptomatic participants which was within the 40-65% range reported in prolonged exposure literature (standing, seated, seated axial twist) (Figure 5.4) (Sorensen et al., 2016, Nairn et al., 2013, Schinkel-Ivy et al., 2013, Nelson-Wong & Callaghan, 2010; 2014). Of those who developed transient pain (PD) during PSAT, the mean of max self-reported pain scores collapsed across time, 32.0mm (13.6), was higher than the range found in prolonged standing and seated literature. The significant interaction effect between pain and time reported after 25mins (and for successive time intervals thereafter) indicated there was a difference in the amount of pain reported between PDs and NPDs, where PDs reported consistently greater level of pain than NPDs. 25mins for a significant difference between pain groups was also much faster than the 60-120mins previously reported in prolonged standing and seated literature. Furthermore PDs exhibited greater mean VAS between 15mins and 20mins and latter time intervals meaning that reported pain increased with time. Most notably, by 20mins mean VAS score had exceed 10mm

indicative of the minimum change for clinical relevance and by 30mins mean VAS had exceed 20mm indicative the maximum change for clinical pain. The contrast in magnitude of pain and time to reach transient pain levels between PSAT and other previous prolonged literature most likely resided in how far the spine deviated from neutral (standing) in each protocol. To elaborate, prolonged standing with a relatively neutral spine involved minimal angular deviation, prolonged seated involved spine flexion, and in PSAT there was both axial twist and lateral bend present. Spine movements and positions deviating from neutral, especially axial twist, have been repeatedly identified as a risk factor for pain (Frymoyer et al., 1983; Marras et al., 1993). Likewise, this thesis supports previous literature that has identified axial twist as a risk factor for pain, and adds that the exposure is potent even when maintained passively.

After 25mins, successive 5min epochs were not significantly different and additionally mean self-reported pain VAS scores were much lower and did not continue to increase as expected. It may be explained that after 25mins due to the loss of 8 of 12 PD, the lower mean VAS scores observed over the last 15mins of PSAT was driven by surviving PDs who were not experiencing above clinical acceptable levels of transient pain. Overall, to minimize the development of clinically relevant transient LBP, a PSAT position in MRI should not exceed 15mins whereas for potential future clinical applications a longer duration of 25mins may be considered.

6.2.2 Characterizing Transient Pain Development during PSAT: Kinematics and EMG

Transient pain development has been linked to deviated kinematics such as twist (Shan et al. 2013) and flexed postures in prolonged sitting (Nairn et al., 2013) and characterized by greater mean EMG (Nairn et al., 2013). Contrary to previous ideologies, no differences in mean

relative lumbar kinematics were reported between pain groups or between time intervals. Given that the lumbar angle was calculated between the gross levels of T₁₂ and S₁, it is possible that kinematic differences resided between one or more individual level (s) of the entire lumbar spine. *In vitro* cadaveric literature has documented varying range between individual lumbar vertebrae (White and Panjabi, 1978). More recent *in vitro* work by Drake & Callaghan (2009) demonstrated that during axial twist coupled with non-neutral postures, that compression of the nerve root (through the intervertebral foramina) was a potential source of pain. Further, Wyke (1970) outlined structures associated with pain receptors of the vertebral column including ligaments, vertebrae, blood vessels of the vertebrae, paravertebral veins, and paravertebral musculature. Despite these potential structures, the implication of nerve root compression remains the most closely plausible during axial twist. Previous literature successfully characterized mean EMG differences between pain groups, no effect of pain or time was found in this study. The two biggest methodological differences between PSAT and previous literature was that participants were in an axially twisted and supported passive position meaning they were rotated but did not have to hold position themselves. The passive position could explain why mean EMG levels were not different between pain groups. Further, this was confirmed by the consistently low mean EMG range. However, McGill et al. (2000) found that even at low activation ranges (as low as 2%) prolonged activation of the ES muscles could result in fatigue and subsequently a viable pathway for transient path development during PSAT. It is noted that additional comparisons were completed on both kinematics and EMG between pain groups and between two time points: t=0 and t=end (every participant's end point) yet differences were not exhibited. Consequently, at the conclusion of this thesis although no preliminary biomechanical measures were associated between pain groups, there were two distinct self-reported pain

responses between pain groups which was important and may merit future efforts for investigation. Future studies should first aim to comprehensively characterize and understand if any biomechanical measures are associated to which then studies may build on to validate PSAT as a clinical tool to screen and predict transient pain development and injury.

6.3 Limitations

There are a few methodological limitations of this study that require attention when considering the results. Recruited participants were university aged, male, and asymptomatic for neck, trunk, and pelvis pain and injury. Therefore, collected data and findings are limited to this specific population. Literature has documented differences in flexibility and tissue tolerances of the lumbar spine between sexes and age (Haley et al., 1986; Jager et al., 1991). Therefore, further studies are required to investigate an older, female, and/or symptomatic populations. The effect of time of data collection and subsequent diurnal spine changes was not specifically controlled for in this study. However, according to Reilly, Tynell, and Troup (1984), approximately 54% diurnal changes (i.e. disc swelling, resistance to ROM) are lost within the first 30mins after rising from waking. Diurnal changes were minimized in this thesis as all participants stood for at least 90mins (setup, calibration, and pre-collection protocols) before any data were collected. For ethical reasons, some participants who developed transient pain did not complete the entire 45-minute duration of PSAT. As a result, within the last 15mins of PSAT (where participant dropout occurred) it is not certain whether Type II error occurred for kinematic and electromyographic comparisons after 30mins.

7. General Thesis Overview

7.1 Revisiting Hypotheses

Hypothesis #1: The angles of the thoracic and lumbar spine measured using three orthogonal axes (Y axial twist, X lateral bend, Z flexion-extension) between standing and supine in neutral will be significantly different in at least one axis.

This hypothesis was ACCEPTED.

Between standing and supine, significant differences were reported in both spine regions and all three axes. Most relevant angles differences were found in axial twist and flexion-extension of the lumbar spine.

Hypothesis #2: The ROM of the thoracic and lumbar spine measured using three orthogonal axes (Y axial twist, X lateral bend, Z flexion-extension) between standing and supine during axial twist will be comparable in the primary axial twist axis and significantly different in at least one off-axis (lateral bend and flexion-extension).

This hypothesis was ACCEPTED.

The axial lumbar ROM was similar between positions whereas a significant difference was found in the lumbar region for off-axis motion. The degree of lateral bend during standing axial twist was toward the left direction and supine axial twist was toward the right direction.

Hypothesis #3: After 30mins of PSAT, at least 40% of participants will report clinically relevant levels of low back pain (>10mm on the pain visual analogue scale (VAS))

This hypothesis was ACCEPTED.

It was found that 60% of participants reported clinically relevant levels of low back pain after 20 minutes of PSAT. Additionally, it was also found that by 30 minutes acceptable levels of clinically relevant low back pain was exceeded by pain developers.

Hypothesis #4: During PSAT, participants who indicate greater than 10mm on the pain VAS scores will have:

- c. Significant differences in primary axis or off-axis kinematics over the duration of PSAT.**
- d. Significant differences in mean EMG of trunk musculature over the duration of PSAT.**

This hypothesis was REJECTED.

The effect of pain and time was not found to be significant on either primary axis, off-axis angles, or EMG activity of any trunk musculature.

8. Conclusion

Recent *in vivo* literature have motivated the investigation of the spine and suspected viable pain mechanisms involved with axial twist. This may be achieved with the gold standard of conventional horizontal MRI, however subsequently gives rise to two concerns: 1. How comparable are findings from a horizontal MRI (that utilizes a supine position) to a standing position in both neutral and axially twisted positions? 2. Due to timely calibrating protocols (up to 45mins), whether healthy asymptomatic individuals would develop transient pain during a prolonged axially twisted protocol and whether pain development could be characterized with other biomechanical measures? Between the standing and supine in neutral, a significant loss of lumbar lordosis (12.1°) and lumbar axial twist (3.3°) was reported. Between standing and supine axial twist, a significant difference (9.1°) was found in the off-axis of lateral bend for the lumbar spine only. Subsequently, in order to ensure and improve comparability to standing and supine positions in neutral postures it is necessary to retain lumbar lordosis and axial twist in supine. While in axial twist postures, it is necessary to restrict the amount of lateral bend in the lumbar spine. Transient pain development was reported for 60% (12/20) of participants and pain developers exhibited clinically relevant levels of low back pain (10mm) by 20mins, additionally those levels increased and exceeded clinical acceptable levels (20mm) by 30mins. For the purposes of minimizing the chance of developing clinically abnormal low back pain during an MRI a maximum of 15 minutes is recommended.

9. References

- Aoki, Y., Sugiura, S., Nakagawa, K., Kakajima,., Takahashi, H., Ohtori, S. et al. (2012). Evaluation of nonspecific low back pain using a new detailed visual analogue scale for patients in motion, standing, and sitting: Characterizing nonspecific low back pain in elderly patients. *Pain Research and Treatment*, 680496: 1-4
- Andreasen, M. L., Langhoff, L., Jensen, T.S., and Albert, H.B. (2007). Reproduction of the lumbar lordosis: A comparison of standing radiographs versus supine magnetic resonance imaging obtained with straightened lower extremities. *Journal of Manipulative and Physiological Therapeutics*, 30(1): 26-30.
- Anders, C., Bretschneider, S., Bernsdorf, A., and Schneider, W., et al. (2005). Activation characteristics of shoulder muscles during maximal and submaximal efforts. *European Journal of Applied Physiology*, 93(5): 540-546.
- Arlotta, M., LoVasco, G., and McLean, L. (2011). Selective recruitment of the lower fibers of the trapezius muscle. *Journal of Electromyography and Kinesiology*, 21: 403-410.
- Benditz, A., Boluki, D., Weber, M., Zeman, F., Grifka, J., and Vollner, F. (2017). Comparison of lumbar lordosis in lateral radiographs in standing position with supine MR imaging in consideration of sacral slope. *Fortschr Röntgenstr*, 189: 233-239.
- Brereton, L. C, and McGill, S. M. (1998). Frequency response of spine extensors during rapid isometric contractions: Effects of muscle length and tension. *Journal of Electromyography and Kinesiology*, 8: 227-232.
- Burnett, A., O’Sullivan, P., Caneiro, J.P., Krug, R., Bochmann, F., and Helgestad, G.W. (2009). An examination of the flexion-relaxation phenomenon in the cervical spine in lumbo-pelvic sitting. *Journal of Electromyography and Kinesiology*, 19(4): e229–236.
- Callaghan, J.P., and Dunk, N.M. (2002). Examination of the flexion relaxation phenomenon in erector spinae muscles during short duration slumped sitting. *Clinical Biomechanics*, 17: 353-360.

- Callaghan, J.P., Gunning, J.L., and McGill, S.M. (1998). The relationship between lumbar spine load and muscle activity during extensor exercises. *Physical Therapy*, 78(1): 8-18.
- Danneels, L. A., Cagnie, B.J., Cool, A.M., Vanderstaeten, G.G., Cambier, D.C., Witvrouw, E.E., et al. (2001). Intra-operator and inter-operator reliability of surface electromyography in the clinical evaluation of back muscles. *Manual Therapy*, 6(3): 145-153.
- DeLeo, J.A., and Winkelstein, B.A. (2002). Physiology of chronic spinal pain syndromes: From animal models to biomechanics. *Spine*, 27(22): 2526-2537.
- Deyo, R.N. and Weinstein, J.N. (2001). Low back pain. *New England Journal of Medicine*, 344(5): 363-370.
- Drake, J.D.M., Aultman, C.D., McGill, S.M., and Callaghan, J.P. (2005). The influence of static axial torque in combined loading on intervertebral joint failure mechanics using a porcine model. *Clinical Biomechanics*, 20(10): 1038-1045.
- Drake, J. D. M., and Callaghan, J. P. (2006). Elimination of electrocardiogram contamination from electromyogram signals: An evaluation of currently used removal techniques. *Journal of Electromyography and Kinesiology*, 16: 175-187.
- Drake, J.D.M., and Callaghan, J.P. (2009). Intervertebral neural foramina deformation due to two types of repetitive combined loading. *Clinical Biomechanics*, 24(1): 1-6.
- Drake, J.D.M., Dobson, H., and Callaghan, J.P. (2008). The influence of posture and loading on inter-facet spacing: An investigation using MRI on porcine spinal units. *Spine*, 33(20): E728-734.
- Drake, J.D.M., Fischer, S.L., Brown, S.H.M., and Callaghan, J.P. (2006). Do exercise balls provide a training advantage for trunk extensor exercises? A biomechanical evaluation. *Journal of Manipulative Physiological Therapeutics*, 29(5): 354-62.

- Dvorak, J., Vajda, E.G., Grob, D., and Panjabi, M.M. (1995). Normal motion of the lumbar spine as related to age and gender. *European Spine Journal*, 4: 18-23.
- Farfan, H.F. (1973). Mechanical disorders of the low back. Philadelphia: Lea and Febiger.
- Floyd, W.F., and Silver, P.H. (1955). The function of the erectors spinae muscles in certain movements and postures in man. *Journal of Physiology*, 129(1): 184-203.
- Formica, D., and Silvestr, S. (2004). Biological effects of exposure to magnetic resonance imaging: an overview. *Biomedical Engineering Online*, 3: 11.
- Friedly, J., Standaert, C., and Chan, L. (2010). Epidemiology of spine care: The back pain dilemma. *Physical Medicine and Rehabilitation Clinics of North America*, 21(4): 659-677.
- Frymoyer, J.W., Pope, M.H., Clements, J.H., Wiler, D.G., MacPherson, B., and Ashikaga, T. (1983). Risk factors in low back pain. *Journal of Bone and Joint Surgery*, 65A: 213-218.
- Fujii, R., Sakaura, H., Mukai, Y., Hosono, N., Ishii, T., Iwasaki, M., et al. (2007). Kinematics of the lumbar spine in trunk rotation: in vivo three-dimensional analysis using magnetic resonance imaging. *European Spine Journal*, 16: 1867-1874.
- Haughton, V.M., Rogers, B., Meyerand, M.E., Resnick, D.K. (2002). Measuring the axial rotation of lumbar vertebrae in vivo with MR imaging. *American Journal of Neuroradiology*, 23: 1110-1116.
- Hoy, D., March, L., Brooks, P., Blyth, F., Woolf, A., Bain, C., et al. (2014). The global burden of low back pain: estimates from the Global Burden of Disease 2010 study. *Annals of the Rheumatic Diseases*, 73(6): 968-974.
- Jager, M., Luttmann, A., & Laurig, W. (1991). Lumbar load during one-handed bricklaying. *International Journal of Industrial Ergonomics*, 8: 261-277.

- Judith, R.M., Gregory, J.S., Aspden, R.M., Smith, F.W., Gilbert, F.J. (2009). The intrinsic shape of the human lumbar spine in the supine, standing, and sitting postures: Characterization using an active shape model. *Journal of Anatomy*, 215: 206-211.
- Kelly, A.-M. (1998). Does the clinically significant difference in visual analog scale pain scores vary with gender, age, or cause of pain? *Academic Emergency Medicine*, 5(11): 1086-1090.
- Kelsey, J., Githens, P.B., White, A.A., Holford, T.R., Walter, S.D., O'Connor, R., et al. (1984). An epidemiology study of lifting and twisting on the job and risk for acute prolapsed lumbar intervertebral disc. *Journal of Orthopaedic Research*, 2: 61-66.
- Lee, A.K., and Kieckhefer, G.M. (1989). Measuring human responses using visual analogue scales. *Western Journal of Nursing Research*, 11(1): 128-132.
- Lee, M.C., Solomito, M., and Patel, A. (2013). Supine magnetic resonance imaging Cobb measurements for idiopathic scoliosis are linearly related to measurements from standing plain radiographs. *Spine*, 38 (11): E656-E661.
- Madsen, R., Jensen, T.S., Pope, M., Sorensen, J.S., and Bendix, T. (2008). The effect of body position and axial load on spinal canal morphology. *Spine*, 33(1): 61-67.
- Marras, W.S., Lavender, S.A., Leurgans, S.E., Rajulu, S.L., Allread, W.G., Fathallah, F.A. et al. (1993). The role of dynamic three-dimensional trunk motion in occupationally-related low back disorders. *Spine*, 18(5): 617-628.
- Mauch, F., Jung, C., Huth, J., and Bauer, G. (2010). Changes in the lumbar spine of athletes from supine to the true-standing position in magnetic resonance imaging. *Spine*, 35(9): 1002-1007.
- Mayberry, G.R. (2016). Understanding axial rotation in the lumbar spine and its effect on associated nerve tissue. (Masters Thesis). Toronto, ON: York University.

- Mayberry, G.R., & Drake, J.D.M. (2017). Effect of axial rotation on lumbar spine intervertebral foramen and associated nerve tissue as quantified by MRI. (*In progress*)
- McGill, S. M. (1992). A myoelectrically based dynamic three-dimensional model to predict loads on lumbar spine tissue during lateral bending. *Journal of Biomechanics*, 25(4): 395-414.
- McGill, S. M. (1991). Electromyographic activity of the abdominal and low back musculature during the generation of isometric and dynamic axial trunk torques: implications for lumbar mechanics. *Journal of Orthopaedic Research*, 9: 91-103.
- McGill, S.M., Hughson, R.L., and Parks, K. (2000). Lumbar erector spinae oxygenation during prolonged contractions: implications for prolonged work. *Ergonomics*, 43(4): 486-49.
- Nairn, B.C., Azar, N.R., and Drake, J.D.M. (2013). Transient pain developers show increased abdominal muscle activity during prolonged sitting. *Journal of Electromyography and Kinesiology*, 23(6): 1421-1427.
- Nelson-Wong, E., and Callaghan, J.P. (2010). Changes in muscle activation patterns and subjective low back pain during prolonged standing in response to an exercise intervention. *Journal of Electromyography and Kinesiology*, 20(6): 1125-1133.
- Nelson-Wong, E., and Callaghan, J.P. (2014). Transient low back pain development during standing predicts future clinical low back pain in previously asymptomatic individuals. *Spine*, 39(6): E379-E383.
- Nelson-Wong, E., Flynn, T., and Callaghan, J.P. (2009). Development of active hip abduction as a screening test for identifying occupational low back pain. *Journal of Orthopaedic and Sports Physical Therapy*, 39(9): 649-657.
- Nelson-Wong, E., Gregory, D.E., Winter, D.A., and Callaghan, J.P. (2008). Gluteus medius muscle activation patterns as a predictor of low back pain during standing. *Clinical Biomechanics*, 23(5): 545-553.

- Ng, J. K.-F., Kippers, V., and Richardson, C.A. (1998). Muscle fibre orientation of abdominal muscles and suggested surface EMG electrode positions. *Electromyography and Clinical Neurophysiology*, 38: 51-58.
- Ochia, R.S., Inoue, N., Renner, S.M., Lorenz, E.P., Lim, T.-H., Andersson, G.B.J., et al. (2006). Three-dimensional in vivo measurement of lumbar spine segmental motion. *Spine*, 31(18): 2073-2078.
- Ochia, R.S., Inoue, N., Takatori, R., Andersson, G.B.J., Howard, S.A. (2007). In vivo measurements of lumbar segmental motion during axial rotation in asymptomatic and chronic low back pain male subjects. *Spine*, 32(13): 1394-1399.
- Panjabi, M.M., Yamamoto, I., Oxland, T.R., and Crisco, J. (1989). How does postures affect the coupling in the lumbar spine? *Spine*, 14(9): 1002-1011.
- Pearcy, M.J. (1985). Stereo radiography of lumbar spine motion. *Acta Orthopaedica Scandinavica*, 56(212): 45.
- Pearcy, M.J., and Tibrewal, S.B. (1984). Axial rotation and lateral bending in the normal lumbar spine measure by three-dimensional radiography. *Spine*, 9: 582.
- Reilly, T., Tynell, A., and Troup, J.D.G. (1984) Circadian variation in human stature. *Chronobiology International*, 1: 121.
- Revill, S.I., Robinson, J.O., Rosen, M., and Hogg, M.I.J. (1976). The reliability of a linear analogue for evaluating pain. *Anaesthesia*, 31: 1191-1198.
- Schinkel-Ivy, A., Nairn, B.C., and Drake, J.D.M. (2013a). Evaluation of methods for quantification of the flexion-relaxation phenomenon in the lumbar erector spinae muscles. *Journal of Manipulative and Physiological Therapeutics*, 36(6): 349-358.

- Schinkel-Ivy, A., Nairn, B.C., and Drake, J.D.M. (2013b). Investigation of trunk muscle co-contraction and its association with low back pain development during prolonged sitting. *Journal of Electromyography and Kinesiology*, 23(4): 778-786.
- Schroder, J., Braumann, K.M., and Reer, R. (2014). Spinal form and function profile: Reference values for clinical use in low back pain. *Orthopade*, 43(9): 841-849.
- Shan, X., Ning, X., Chen, Z., Ding, M., Shi, W., and Yang, S. (2013). Low back pain development response to sustained trunk axial twisting. *European Spine Journal*, 22: 1972-1978.
- Shirado, O., Ito, T., Kaneda, K., and Strax, T.E. (1995). Flexion-relaxation phenomenon in the back muscles. *American Journal of Physical Medicine and Rehabilitation*, 74(2): 139-144.
- Siu, A., Schinkel-Ivy, A., and Drake, J.D.M. (2016). Arm position influences the activation patterns of trunk muscles during trunk range-of-motion movements. *Human Movement Science*, 49: 267-76.
- Sokka, T. (2005). Assessment of pain in rheumatic diseases. *Clinical and Experimental Rheumatology*, 23(39): S77-S84.
- Sorensen, S.J., George, S.Z., Callaghan, J.P., and Van Dillen, L.R. (2016). Psychological factors are related to pain intensity in back-healthy people who develop clinically relevant pain during prolonged standing: a preliminary study. *Journal of injury, function, and rehabilitation*, 8: 1031-1038.
- Summers, S. (2001). Evidence-based practice part 2: Reliability and validity of selected acute pain instruments. *Journal of PeriAnesthesia Nursing*, 16(1): 35-40.
- Troke, M., Moore, A.P., Maillardet, F.J., and Cheek, E. (2005). A normative database of lumbar spine ranges of motion. *Manual Therapy*, 10: 198-206.

- Troke, M., Moore, A.P., Maillardet, F.J., Hough, A., and Cheek, E. (2001). A new, comprehensive normative database of lumbar spine ranges of motion. *Clinical Rehabilitation*, 15: 371-379.
- Troup, J.D.G., Martin, J.W., and Lloyd, D.C. (1981). Back pain in industry: A prospective survey. *Spine*, 6: 61-69.
- Van Dieen, J. H., and Kingma, I. (2005). Effects of antagonistic co-contraction on differences between electromyography based and optimization based estimates of spinal forces. *Ergonomics*, 48(4): 411-426.
- Vos, T. et al. (2015). Global, regional, and national incidence, prevalence, and years lived with disability for 301 acute and chronic diseases and injuries in 188 countries, 1990–2013: a systematic analysis for the Global Burden of Disease Study 2013. *The Lancet*, 386(9995): 743-800.
- Watson, P.J., Booker, C.K., Main, C.J., and Chen, A.C. (1997). Surface electromyography in the identification of chronic low back pain patients: the development of the flexion relaxation ratio. *Clinical Biomechanics*, 12(3): 165-171.
- White, A.A., and Punjabi, M.M. (1978). Clinical biomechanics of the spine. Philadelphia: J.B. Lippincott.
- Wood, K.B., Michael-Schendel, P.S., and Persson, K. (1996). Effect of patient position on the sagittal-plane profile of the thoracolumbar spine. *Journal of Spinal Disorders and Techniques*, 9(2): 165-169.
- Wyke, B. (1970). The neurological basis of thoracic spine pain. *Rheumatology and physical medicine*, 10: 356.
- Yamamoto, I., Punjabi, M.M., and Oxland, T. (1989). Three-dimensional movements of the whole lumbar spine and lumbosacral joint. *Spine*, 14(11): 1256-1260.

Zipp, P. (1982). Recommendations for the Standardization of Lead Positions in Surface Electromyography. *Applied Physiology*, 50: 41-54.

Appendix A: Exit Survey

Exit Survey

1. During the 45 minute prolonged axially twisted trial, did you feel any pain or discomfort besides from the low back area?

Yes_____ No _____

- a. If yes, please describe which area (s) that you felt pain or discomfort.

- b. If yes, was any of the equipment (e.i. straps, wedging, foaming) causing you pain?

2. What is the worst pain you have ever experienced?

3. Please describe your worst imaginable pain.

4. How many hours a week on average do you engage in physical activity?

_____hours

- a. What type of physical activity? (i.e. weight lifting, running, yoga, etc)

5. To your knowledge, do you experience any physical pain or discomfort day-to-day?

Yes_____ No _____

- a. If yes, please describe the circumstance (s).

- b. If yes, please list the area (s) that are affected including which side (right or left)

6. Have you had any physical injury or incident that required any level of medical attention before?

Yes_____ No _____

- a. If yes, please describe the circumstance (s).

- b. If yes, please list the area (s) that are affected including which side (right or left)
