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KINEMATIC ASSESSMENT OF LUMBAR SEGMENTAL INSTABILITY USING DIGITAL FLUOROSCOPIC VIDEO

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KINEMATIC ASSESSMENT OF LUMBAR SEGMENTAL INSTABILITY USING DIGITAL FLUOROSCOPIC VIDEO

by

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Dedication

I dedicate my dissertation to my amazing family. I am a stronger person because of the love and devotion of my husband, John, and my family (my mother, father, and brother); whose love and support make everything possible and worthwhile.

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Lumbar segmental instability (LSI) has been a theoretical and controversial source of low back pain, largely because of the lack of consensus on what constitutes LSI. Digital fluoroscopic videos (DFV) have had limited success in measuring lumbar kinematics because of poor image quality and associated measurement errors. The purposes of this study were to develop a reliable DFV technique to measure lumbar kinematics and determine if the resulting variables distinguish between patients suspected to have LSI and healthy control subjects.

A technique that combined digital image processing and distortion compensation was developed to measure lumbar vertebral kinematics using DFV. In a reliability study with a group of 20 subjects, the average intra-image reliability (ICC) was .986. The average inter-image reliability was .878. The 95% confidence interval for inter-image measurement error was 2° and 1.2 mm.

This technique was applied to two symptom-based groups of subjects (20 with LSI and 20 healthy controls). The DFV were then analyzed by three spine surgeons to determine normality of movement. Subsequently, the groups were reorganized into two motion-based groups (11 with LSI and 14 healthy controls).

Independent t-tests were used to compare the differences between those with LSI and healthy controls. Variables with a $p < .20$ and a positive likelihood ratio (+LR) >2.0, based on a cut-off score on a receiver operator characteristic curve, were considered as possible candidates for a model to distinguish group membership.

A 10 variable model was developed when the reference criterion was the symptom-based groups. This model had the greatest accuracy (87.5%, sensitivity = .95, specificity = .80) when subjects had four or more of the variables present. An eight variable model (+LR >2.5) was developed to distinguish the motion-based groups. This model's greatest accuracy was 96%. The higher +LR values and the greater accuracy of this model demonstrate the effectiveness of expert review process to obtain more homogenous groups.

The technique developed was both reliable and successful in using a cluster of kinematic variables to discriminate between group memberships. These models provide a foundation for the development of a diagnostic prediction rule.

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Chapter 1: Introduction

BACKGROUND

Low Back Pain (LBP) has been cited as a "20th century medical disaster"[150] afflicting 60-80% of adults sometime in their life and 15-20% of Americans each day.[49] In fact, LBP has been the second leading cause of pain after headache[150] and the consequences of LBP are steadily becoming more severe. A theoretical reason for the increasing cost and disability associated with LBP has been diagnostic inaccuracy caused by an outdated anatomical classification system in which a group of movement-based dysfunctions have been inappropriately categorized with anatomical labels (herniated discs, discogenic LBP, facet dysfunction, etc). A lack of clear diagnostic categories has resulted in variance in practice guidelines and sub-optimal care. Anatomically-based classification systems persist, despite the fact that only 15% of all patients with LBP can be given a definitive anatomical diagnosis for their symptoms.[150] Recently, recognizing the importance of movement dysfunctions, researchers have developed new classification systems.[27,83,130] However, one problem that has impeded the institutionalization of a movement-based classification system has been a lack of assessment tools that accurately diagnose these dysfunctions.[3,43,130] Kinematic assessment of lumbar mobility has been suggested as a possible tool that could assist in fostering a movement-based classification system for those with LBP.[55,65,66,79,83,106,144]

One movement-based diagnosis common to many classification systems has been instability of the lumbar spine. Panjabi[109,110] theorized that this instability occurs during mid-range movements under neuromuscular control, not at the end-range of movements influenced by passive osteoligamentous restraint. However, the standard radiological assessment tool of this patient category has been static end-range radiographs.[153] This

dichotomy has offered the perfect opportunity to apply new image processing techniques with traditional video fluoroscopy (VF) to assess the kinematic nature of this dysfunction.

The definition of instability as it relates to the lumbar spine has been controversial and debated since it was first measured radiographically by Knutsson in 1944.[72,79] Historically, definitions of instability referred primarily to patients with frank instabilities (i.e. spondylolisthesis, destruction of the anterior/posterior elements, and cauda equina damage with excessive displacement). This resulted in the development of White and Panjabi's[153] point-valued checklist to determine when those with frank instabilities require surgical fusion of the spine. However, many individuals have suffered with similar symptoms but do not present with frank instabilities that require surgery. These subfailure injuries and associated movement dysfunctions have been difficult to diagnose consistently but have been suspected to be one potential cause of LBP.[42,71] Currently, those without frank instabilities obtain the diagnosis of "lumbar segmental instability" (LSI) based on a patient history and certain inconclusive findings.[79] Other commonly used terms include "clinical instability" or "functional instability". The most common complaint by these patients has been a history of chronic/recurrent LBP, in which they frequently have reported to their provider that "my back went out" which has been believed to represent a slipping feeling associated with movement.[71]

For those with LSI who have not required surgical attention, the treatment of choice has been a lumbar stabilization exercise program focused on retraining the neuromuscular system. This has led researchers at the University of Pittsburgh to develop a treatment-based definition for instability.[58] They found those who presented with two of the four following criteria responded positively to stabilization training (1. a positive prone instability test (PIT), 2. aberrant movement present, 3. average straight leg raise >91^{o}, and 4. age < 40 years old). Aberrant movement was defined as a minimum of

one of the following five signs: 1. a painful arc in flexion, 2. a painful arc on return, 3. a Gower's sign, 4. an instability catch, 5. a reversal of lumbopelvic rhythm (definitions provided in Appendix E). This definition was used to define those with LSI in this study.

Although a cluster of physical signs and symptoms has helped to classify this patient group, a diagnostic 'gold standard' possibly could provide better information about this dysfunction, which may lead to better diagnostic accuracy and better outcomes for these patients. To date, no definitive relationship has been defined between intervertebral motion and the clinical symptoms attributed to LSI. This is in part due to the lack of a non-invasive measurement tool to assess lumbar kinematics.

Historically, providers have relied on static end-range radiographic measurements of hypermobility in flexion and extension to diagnose this condition [increased translation (4-5 mm) or an increased angulation (15-25°, depending on the level of injury)].[126] However, many problems have existed with traditional radiographic assessments of the lumbar spine for instability. First, large variability of normal human movement in asymptomatic individuals has been documented.[32,33,57,103,104,126,145] This has been compounded by the variability of motion that has been documented to occur with age, time with the disesase,[71,134,146] levels of pain,[31,103,127] normal and abnormal coupled movement of the functional spinal units during motion,[32,142,153] and differences in test postures used to analyze the motion.[18,33,67,73,133,158] Second, the images have been assessed statically at end-range motion.[32,33,57,67,72,126,136,153] Static analysis has been found to be inadequate to categorize these patients.[18,73,95,97,143] Finally, traditional measurement techniques have been associated with large measurement error.[25,26,31,119,121,136] Techniques to decrease this error and to improve the ability to standardize the measurement technique, to include proper landmark verification techniques, have been

suggested in order to measure intersegmental motion successfully.[11,16,17,45-48,63,75,77,117,128,133]

A landmark verification protocol developed by Brinckmann et al[16] was designed to compensate for radiographic distortion of the central beam, off-center position, axial rotation, and lateral tilt during the objective determination of the vertebral corner locations. This protocol was designed to limit subjective errors associated with these measurements. Further, Frobin et al[45] enhanced this protocol by developing a measuring technique for sagittal plane translation and angular changes using geometric parameters that are symmetric with respect to the adjacent vertebral bodies. A full explanation of the distortion-compensated vertebral corner selection and the intervertebral measurements of angulation and displacement is presented in the methods section (Chapter 3). The measurement error associated with this technique was determined to be 0.7 to 1.6° for the angular error, and 1.2% to 2.4% of vertebral depth (0.4 to 0.8 mm) for the displacement error.[46] These error measurements are respectively four to five, and 10 times smaller than previously reported measurement errors. This measurement technique, called Distortion Compensated Roentgen Analysis (DCRA), was used in this study to measure intersegmental motion because it has the least amount of reported error for a non-invasive technique.[75]

New image processing technology has provided the opportunity to use VF to visualize vertebral motion. The suggested benefit of VF has been that it allows for the spinal motion to be observed on a continuous basis.[55,65,66,106,144] If these observations could be quantitatively assessed so that kinematic variables of the lumbar spine are reliably produced, they might provide not only a better understanding of normal and abnormal lumbar movement, but possibly also a new test to help define this population. To date, this approach has not been routinely used for the lumbar spine.

STATEMENT OF PURPOSES

The overall purpose of this study was to develop a measurement technique that would allow for the assessment of sagittal plane lumbar kinematics using digital fluoroscopic video (DFV) to describe the kinematic movement patterns of those with LSI compared to those without LBP. The first purpose of this study was to develop a reliable investigational technique to image and analyze sagittal plane kinematics of the lower lumbar spine (L3-S1) using enhanced DFV.

The second purpose of this study was to analyze and describe the sagittal plane kinematics in individuals with and without LSI. Specifically, sagittal plane displacement range, angular range, and displacement and angular relative timing were analyzed during flexion and extension of the lumbar spine. Further, measurements of translational speed were analyzed during flexion of the lumbar spine. These measurements were described not only for the symptom-based groups (CONTROL-I and INST-I), but for more homogenous motion-based groups (CONTROL-F and INST-F), created by the classification of these same individuals from a qualitative motion assessment of the DFV completed by three expert reviewers (spine surgeons).

The final purpose of this study was to establish the construct validity for the kinematic assessment of LSI by the development of a model, similar to a clinical prediction rule (CPR), containing a cluster of kinematic variables that can distinguish group membership. Two models based on two different reference standards; classifications based on symptom status (symptom-based groups) versus classifications based on assessment of normality of movement by three expert-reviewers of the DFV (motion-based groups) were developed. Specifically, comparisons of sensitivity (Sn), specificity (Sp), positive and negative likelihood ratios (+LR, -LR, respectively), and area under the receiver operator characteristic (ROC) curves between the groups were

analyzed with regard to clinic-classification systems (symptom-based group) and expert-judgment (motion-based groups) with regard to the kinematic variables.

RESEARCH HYPOTHESES

1. The application of the DCRA measurement technique directly to digitally enhanced DFV will result in a reliable technique with comparable measurement error based on previously reported application of the DCRA technique to digital drawings of vertebral body outlines from standard static radiographs.
2. Compared to the group of healthy control subjects without a history of LBP (CONTROL-I), subjects diagnosed with LSI of the lower lumbar spine (INST-I) group will have a:
    a. greater range of segmental displacement during flexion and extension.
    b. greater ratio of maximal vertebral displacement range expressed relative to mean intrasubject vertebral displacement range during both flexion and extension.
    c. different rate of attainment of displacement range relative to global motion (L3-S1 lordosis) during the initiation of flexion (0-55%) and the return to upright (55-0%).
    d. greater range of L3-S1 global angular motion (L3-S1 lordosis).
    e. greater range of angular change during flexion and extension.
    f. greater ratio of maximal vertebral angular range expressed relative to mean intrasubject vertebral angular range during both flexion and extension.
    g. different rate of attainment of angular range relative to global motion (L3-S1 lordosis) during the initiation of flexion (0-55% of flexion range) and the return to upright (55-0% of extension range).

h. greater ratio of the maximum translational speed of the vertebral body with the maximum translational speed during flexion compared to the mean translational speed of all segments during flexion.
i. greater range of time from when L3 is at its maximum speed to when S1 is at its maximum speed during flexion.

3. The research questions in hypothesis two were repeated with individuals in the healthy control group who are viewed to have normal motion by the expert reviewers, three spine surgeons, (CONTROL-F) and the individuals who presented with signs of LSI who were viewed by the expert reviewers as having abnormal motion (INST-F).
4. Both the symptom-based groups (CONTROL-I and INST-I) and the motion-based groups (CONTROL-F and INST-F) have motion variables that can be used to distinguish group membership.
5. The motion-based group (CONTROL-F and INST-F) has different kinematic variables that can distinguish between group membership than the symptom-based group (CONTROL-I and INST-I).

SIGNIFICANCE OF STUDY

LBP has been reported to affect 70-80% of all people during their lifetime,[69,99] with a point prevalence of 15-20%.[49] The recurrence of LBP has been reported to be as high as 80%.[60] LSI has been diagnosed in a subgroup of these patients with LBP and has been thought to be associated with those individuals with chronic and recurrent episodes of LBP.[42,50,71] Further, the cost of LBP has continued to rise exponentially. Chronic and recurrent LBP has accounted for over 30% of the total worker's compensation claims in the United States.[150] The majority of these costs have been associated with the increased rate of surgery, especially spinal fusion, in the United States.[19,150] Specifically, Cherkin

et al[19] found that the rate of back surgery in the United States was 40% higher than in the other eleven developed international countries involved in the study. The success rate of a first operation has been reported to be between 60-80%[97,150] with approximately 15% of the outcomes resulting in a worsening of symptoms.[150] The success rate of repetitive surgeries has been reported to decrease, with only a 25% chance of a good result by the third operation. This has resulted in 30% of all back pain resources being spent on fewer than 1% of those with LBP.[97,150] Improved knowledge of spinal kinematics could allow for better selection of surgical candidates and treatments, which would improve the surgical success rates while decreasing the medical costs associated with chronic LBP.

The inability to properly classify patients with LBP has impaired the ability to conduct research on the efficacy of treatment therapies. Treatment modalities that are possibly effective for a subgroup of patients with LBP may prove to be ineffective when studied on a more heterogeneous sample. The ability to properly identify and classify a patient's movement dysfunction associated with LBP could allow for better classification of patients that would allow future research that could specifically address the efficacy of certain treatment protocols explicit to certain subpopulations of those with mechanical LBP.

The continued problem with diagnosing and treating LSI has been a lack of a 'gold standard' criterion that can be used to classify this population. The current radiographic test used to assess this population has been static functional radiographs that measure intersegmental translation and angulation at the end-ranges of motion. Such measurement of motion has been limited because it does not assess dynamic motion throughout the range of motion (ROM) where aberrant motion has been theorized to occur.[110] This study is the first to measure dynamic intersegmental motion using DFV among this population in order to understand the movement strategies of this population.

DELIMITATIONS:

1. Of the four different types of segmental instability discussed by Frymoyer and Selby (axial rotational, translational, retrolisthetic and post-surgical),[50] only translational instability in the sagittal plane during flexion and extension was assessed in this study. Keessen et al[67] and Edwards et al[34] found that sagittal plane motion was ideal for kinematic assessment of the spine because of the amount of intersegmental motion in the sagittal plane relative to the frontal plane and because of a lack of coupled movement patterns during flexion and extension.

2. The experimental group was selected by purposive sampling using the criteria determined by Hicks.[58] The control group was selected to ensure a lack of prior history of LBP within the last three years. To ensure two homogenous samples, strict inclusion and exclusion criteria were necessary. Although the experimental group was defined based on prior research,[58] the boundary of the experimental group was still considered arbitrary secondary to the lack of a 'gold standard' to define this patient population. A different set of entrance criteria may have led to different results.

3. This study only assessed the differences between those with LSI and asymptomatic control subjects. It did not assess the ability of kinematic variables to distinguish between different types of LBP. Therefore, the results of this study only describe the differences between those with suspected LSI and those without LBP. It cannot determine if an observed difference in movement patterns was secondary to LSI or a common trait for those with LBP.

4. The age of the subjects was limited to between 18 and 60 years. LBP has been described as a process that can progress through three stages throughout someone's life: dysfunction, instability, and restabilization via degeneration.[71] Hypomobility has been associated with those with degeneration.[93] It was theorized that by limiting the age, the

likelihood of a more homogenous group would improve and the effects of age-related degeneration would be minimized. Further, those older than 60 years old are more likely to be diagnosed with spinal stenosis than with instability.

5. Muscle guarding and pain have been cited as possible causes for altered movement patterns during radiographic assessments.[31,33] Thus, subjects in the experimental group were required to be in the subacute or chronic phase of their current episode of pain. The referring physical therapist's assessment and the ability to move through the ROM during flexion and extension were used to minimize the possibility that pain and muscle guarding would affect the measured motion patterns.

6. The maximum width of the imaging device (59 cm) limited the size of the subjects enrolled in the study. Subjects in this study had a body mass index (BMI) range between 18 and 32, which covered the classifications from underweight to obese. Although a correlation between weight and LBP has not been established,[10,62,68] this study did not assess individuals in the highest categories of BMI range (35.0 or higher) nor did it assess BMI as a covariate. Minimal impact on the study was expected.

LIMITATIONS:

1. Quality of Image. DFV were designed to visualize motion, but the resolution and quality of these images has remained inferior to standard radiographs. Previous attempts at measuring lumbar kinematics have had limited success secondary to the poor image quality and have mostly been limited to the *in vitro* condition.[14,15,95,160] This study used a series of digital image processing techniques designed to minimize noise and enhance image features prior to the process of locating the vertebral corner locations as an attempt to overcome these limitations. Although this technique has appeared to improve the ability to track the motion of vertebral bodies; the processing techniques used do not allow for the observation of suspected soft-tissue or bone pathology such as

fractures, tumors, or infections which continue to require standard radiographs for assessment.

2. Corner Detection. The ability to determine the accurate location of the vertebral bodies has been a limitation to the use of DFV for the assessment of the lumbar spine.[14-17,45,46,75,95,160] This has been a limitation because the calculations of intervertebral movement patterns rely on the ability to determine the accurate location of the vertebral bodies. To minimize placement errors, the procedure outlined by Brinckmann et al,[16] which first subjectively selects the vertebral corner location estimates and then mathematically estimates the vertebral corner locations based on the geometric principles, was used in this study. The protocol then used the corner locations to detect midpoint locations to further minimize effects of corner location errors.[16] This technique has the least amount of reported error for a non-invasive technique and has minimized the error of previously reported measurement techniques that rely solely on subjective selection of the vertebral corner locations.[75] Although this protocol minimized error, the actual vertebral body motion remains only an approximation.

3. Variability of Movement Patterns. The motion of bending forward and returning to upright can be accomplished with variable amounts of ankle, knee, hip, pelvic, and spinal motion. This variability in movement patterns was theorized to potentially limit the ability to compare like motion patterns across subjects. Further, the field of view (FOV) of the fluoroscopic machine was limited (30 cm diameter). To minimize the variability of human movement and to ensure the L3-S1 segment remained in the FOV throughout the motion, the subjects were placed in a lower extremity-stabilizing device that limited the contribution of the lower extremity joints to the overall movement pattern. The goal of this device was to isolate the spinal motion of interest. Although aberrant movement of contributing joints cannot be completely eliminated,

others [55,106] have successfully used similar devices to minimize unwanted lower extremity movement. However, the impact of the use of these restraints on the movement measured remains unknown.

Chapter 2: Literature Review

OVERVIEW

LBP has a lifetime prevalence estimated between 60-80%[69] and is the most common rheumatologic complaint resulting in medical visits.[97,150] The disability associated with LBP continues to rise, despite the development of better rehabilitation, imaging, and surgical techniques.[150] Improved classification systems and fundamentally different types of diagnostic tests are needed to develop optimal treatment approaches for the different subgroups of patients with LBP.[6,27,43,83,130] This literature review will first discuss the reasons for a movement-based classification system[83] and the diagnosis of one movement-based dysfunction, lumbar instability.[42,109,110] Historical radiographic assessment techniques will then be discussed in terms of different techniques designed to indicate lumbar instability,[3,40,41,46,72,92,93,155,156] associated problems with these techniques,[16,17,31,40,41,46,143] and attempts to improve these techniques.[16,17,45,46] The fundamental limitation of these techniques has been that they attempt to assess motion through static images. Initial dynamic assessments have historically been limited to the *in vitro* situation;[51,52,104,105,111] the results of these studies have provided a foundation of knowledge of lumbar kinematics, although application to the *in vivo* situation has been limited. Finally, recent *in vivo* studies[55,79,90,106,107,144,148] using various techniques will be reviewed. These initial fluoroscopic studies have measured specific aspects of normal and abnormal spinal kinematics and provide the basis for this research project.

PROBLEMS ASSOCIATED WITH THE CLASSIFICATION OF LBP

Only about 15% [74,136,150] of all cases of LBP can be explained by a anatomically-based diagnostic approach. Traditional imaging techniques such as radiographs and

magnetic resonance imaging (MRI) have been notorious for yielding a high rate of false-positive findings (Table 2.1).[57,113,150] In fact, in addition to the increased direct costs associated with the use of these tests, the mere suggestion to patients that findings such as herniated discs and degenerative changes may be a causative factor in their episode of LBP may interfere with recovery by promoting unnecessary anxiety, illness-behavior, and absenteeism from work.[29] Limitations in an anatomically-based classification of LBP have contributed to the epidemic rise in disability and costs associated with the management of these patients,[150] promoting the need for additional classification methods that can improve the decision-making process.

Table 2.1: The false-positive rate of radiographic investigations in normal and asymptomatic people.[150]

	Degenerative and other abnormalities	Disc Prolapse
Plain Radiographs	0-90%	-
CT Scan*	10-35%	10-20%
MRI Scan*	35-90%	20-35%

* Computerized Tomography (CT), Magnetic Resonance Imaging (MRI)

In the absence of relevant pathoanatomic findings in the majority of cases of LBP, alternative classification strategies are needed. Since the mid-1980's, classification systems have been proposed that categorize patients based on location of symptoms and response to treatment in an effort to more accurately establish patient prognosis.[27,83,130] However, diagnosis continues to be problematic secondary to the complexity of the condition.[160] It has been suggested that LBP of mechanical origin may be better

understood if the spinal kinematics of normal and abnormal intersegmental motion were better quantified during dynamic motion patterns.[14,15,95,160]

One problem that impedes the widespread integration of a movement (or treatment)-based classification system into clinical practice has been the inability to accurately characterize relevant subgroups based on movement patterns. The reliability and validity of these newly developed classification systems have been difficult to establish[43] and specific diagnostic tests required to place patients into these symptom-based classification systems need to be developed.[6,130] Marras et al[83] found, using a triaxial goniometer, that global measurements of angular position, velocity and acceleration of the trunk could distinguish those with and without LBP. Local kinematic variables have the potential to distinguish the functional nature of the trunk musculature, seriousness of the movement dysfunction, and progression of rehabilitative programs.[95] Additionally, they could possibly provide definitions for a new movement-based classification system.[83] Kinematic assessment tools, such as DFV analysis, address intersegmental motion of the lumbar spine and have the potential to provide the objective criteria needed to foster development of an accepted movement-based classification system for those with LBP.

LUMBAR SEGMENTAL INSTABILITY (LSI)

One movement-based diagnosis common to many classification systems has been LSI. Many researchers have suggested LSI as a cause of chronic and recurrent LBP.[42,50,71,109,110] Although the inherent instability of the lumbar spine has been a proposed cause of LBP since 1924,[149] the concept of instability has remained complex , controversial, debatable, and poorly understood.[9,33,38,42,103] In general, LSI has been explained as an abnormal segmental response to applied loads, resulting in motion that occurs beyond the segment's normal constraints.[103]

Prevalence and Etiology of LSI

Morgan and King[94] have suggested that LSI has been one of the most common causes of LBP. Pope and Panjabi[123] have suggested that 20-30% of all non-specific LBP can be related to instability. However, Kirkaldy-Willis and Farfan[71] have suggested that all cases of recurrent lumbar dysfunction should be considered as potential instability problems. Instability has been thought to occur when the deformation of tissues under load exceeds the ability of the tissues to recover once the load has been removed.[38] Further, instability has been suggested to occur secondary to a loss in the system's ability to handle compressive and torsional loads.[38]

Kirkaldy-Willis and Farfan[70,71] have developed a three stage process to help describe the degenerative process from repetitive deformation that includes an instability phase. In stage one (dysfunction), clinical symptoms are present, but the diagnosis can only be speculative secondary to a lack of reproducible examination findings.[70,71] Through repetitive deformations, the patient then progresses into stage two (instability) in which abnormal displacements are measurable on radiographs.[70,71] In stage three (restabilization) the degenerative process results in fibrotic and osteophytic changes, which fix the deformity and therefore displays hypomobility.[70,71] This process is consistent with the progression of other degenerative processes in other joints.

Motion of the Lumbar Spine

Historically, instability of the lumbar spine has been based on measuring both global and intersegmental positions of the lumbar spine in the upright posture and at the end ranges of movement. Unfortunately, asymptomatic healthy individuals have a wide-range of variability in total ROM. The maximum range for forward flexion has been measured as approximately 40-60°, 20-35° for extension, 15-20° for lateral rotation (left and right), and 3-18° for rotation (left and right).[81] The total accumulated motion has

been defined as a summation of the motion that occurs at each of the functional spinal units (FSU) of adjacent vertebral bodies of the lumbar spine; which has been described in more detail in the following section titled "Traditional Techniques of Quantifying Lumbar Radiographs". Motion of the spine is three dimensional, resulting in three linear and three rotational directions. These six degrees of freedom result in complex normal biomechanical movement of the lumbar spine. Instability of the FSU can occur with respect to any one of the six degrees of freedom.[123] For example, lumbar flexion typically includes both anterior translation and rotation. Lumbar extension typically involves posterior translation and rotation of each lumbar motion segment in the sagittal plane. Steffen et al [142] assessed spinal motion directly by placing Kirscher wires into the spinous processes of L3 and L4 in 16 healthy men. They found that axial rotation was coupled with active lateral bending in opposite directions in 94% of the subjects[142] (i.e. left axial rotation occurred with right lateral bending). However, the reverse was less consistent (i.e. lateral bending occurring with active axial rotation). Therefore the maintenance of stability of the lumbar spine during movements requires the coordinated actions of multiple motion segments. Additionally, a lack of stability may potentially occur at any lumbar segment in either translational or rotational movements, or both.[42]

The motion of the lumbar spine has also been divided into two zones: the neutral zone (NZ) and the elastic zone (EZ).[110] The NZ has been defined as the ROM that is not restricted by soft tissue structures surrounding the FSU, resulting in a zone of both high flexibility and minimal resistance.[110] Conversely, the EZ has represented the end range of flexion and hyperextension that results in increased stiffness secondary to the passive restraints surrounding the FSU.[110] Panjabi theorized that instability occurs during mid-range movements (within the NZ) under neuromuscular control.[109,110] Mimura et al[93] found that the range of the NZ increased with increased disc degeneration, even when the

total ROM decreased during flexion and extension. From a surgical stabilization standpoint, Panjabi et al[113] found that *in vitro* fixation resulted in an average decrease of 69% in the NZ motion, and only a 39% reduction in the total ROM. These findings support the theory that mid-range measurements in the NZ should be used in assessing spinal instability, rather than total ROM measurements obtained at the static end-range position.[113] Also, measurements of instability should account for these mid-range motions where instability has been theorized to occur. For further theoretical discussion of instability as a cause of LBP, one is directed to Panjabi,[109,110] Fritz et al,[42] and Kirkaldy-Willis and Farfan.[70,71]

Definition of Lumbar Segmental Instability (LSI)

The definition of LSI has been controversial. To properly explain instability, both the condition and diagnostic criteria must be defined. From a mechanical perspective, Pope and Panjabi[123] defined an unstable structure as one that is not in a state of equilibrium. From this perspective, instability can be defined simply as a loss of stiffness.[122,123] McGill et al[86,87] described stability and instability based on states of energy. These mechanical definitions have limited clinical usefulness because of the inability to measure these states in the clinical environment.

Panjabi[110] defined the condition as a "significant decrease in the capacity of the stabilizing system of the spine to maintain the intervertebral neutral zones within the physiological limits so that there is no neurological dysfunction, no major deformity, and no incapacitating pain."[110] While this definition addressed the outcomes of an unstable spine, other definitions principally addressed the movement associated with instability. Dupuis et al[32] offered one such movement-based definition. They stated that a lumbar motion segment was unstable if it demonstrated abnormal movement, either "abnormal in

quality (abnormal coupling patterns) or in quantity (abnormal increased motion)."[32] This definition will be used to measure instability in this study.

Others have correlated the definition of LSI to describe the process underlying spondylolisthesis. Spondylolisthesis literally means "vertebral slipping". Specifically, spondylolisthesis occurs when there has been an anterior slippage of one vertebra on the next lower vertebra resulting from a defect in the pars interarticularis. It has been suggested to affect about 6 to 20% of the population.[103,131]

Although spondylolisthesis has been thought to occur secondary to LSI, the presence of spondylolisthesis does not mean lumbar instability is still present. Possible hypomobility associated with spondylolisthesis has been theorized to occur secondary to a restabilization process that occurs as the degenerative process matures.[103] McGregor et al[91] found that those with pars defect without slippage of the vertebral body (spondylolysis) presented with spinal hypermobility ($p < .01$). On the other hand, those with a degenerative slip tended to be hypomobile ($p < .05$). Although degenerative spondylolisthesis tends to be associated with hypomobility, the pathomechanical mechanism has been thought to be associated with a long-standing problem of segmental instability.[9] Friberg[41] found that not all cases of spondylolisthesis had signs of instability according to traction-compression x-rays. Further, he found that the asymptomatic patients with spondylolisthesis demonstrated minimal to no displacement on traction-compression x-rays, while those with severe and frequent low-back pain demonstrated displacement consistent with instability. This suggested that clinical symptoms correlated with radiographic findings better than the use of the diagnosis of spondylolisthesis to determine instability.[41] Using a cineradiographic technique, Takayanagi et al[144] were able to document the effect of progression on mobility. Those who had a static displacement less than 15% demonstrated hypermobility during active

movement, while those with a static displacement greater than 15% demonstrated hypomobility.[144] The hypomobility associated with a static displacement greater than 15% was attributed to the restabilization process as defined by Kirkaldy-Willis and Farfan.[71] However, Sakamaki et al[132] found that only those with advanced pars defects (severe deformity) resulted in instability as measured by a cephalad deviation of the instantaneous axis of rotation (IAR). Further, McGregor et al[90] found no mobility differences in angle or displacement between those with and without spondylolisthesis in a kinematic assessment using open MRI. The conflicting results associated with spondylolisthesis and LSI suggest that the instability sometimes associated with spondylolisthesis appears to be a symptom-based dysfunction that may not be evident at all stages of the diagnosis by standard imaging techniques. Therefore, the definition of spondylolisthesis does not necessitate LSI and was not used to define LSI for this study.

Diagnosis of Lumbar Segmental Instability (LSI)

Although LSI has been believed to be a common condition in those with LBP, it has remained difficult for the clinical community to determine definitive diagnostic criteria.[42,73,90,98,100] One reason that the definition has become so contentious is that the condition covers a heterogeneous group of individuals with a broad range of disability. The etiology of LSI has been generally believed to involve the relationship of adjacent vertebral bodies during motion; so that excessive translation or rotational movements have been quantified in efforts to define these patients.[73] Different radiological techniques have been developed to try to quantify abnormal movement between adjacent vertebrae.[3,11,32,33,40,41,56,143] These techniques have included standard and functional radiographs (both flexion-extension and traction-compression testing),[3,11,32,33,40,41,46,56,72,82,126,143] biplanar radiography,[117,142,143] Roentgen Stereophotogrammetric Analysis (RSA),[7,63,75] fluoroscopy[55,65,66,106,144,160], and open

MRI.[90] For those with frank instabilities in which preservation of the spinal canal is essential, White and Panjabi[153] developed a point classification system to help surgeons identify patients with instability who require surgery. However, identifying outside of such limited cases of frank instability, no dynamic or static imaging method to date has been defined as the 'gold standard'.[11,78,139] A thorough discussion of these techniques and the problems encountered to date is provided in the section titled "Traditional Techniques of Quantifying Lumbar Radiographs".

Before the discussion of specific diagnostic tests relating to LSI is presented, an overview of accuracy statistics is presented. All diagnostic tests have associated properties that make them either better or worse at identifying those with or those without with a condition. Tests that are better at identifying those with a condition have a higher Sn, while those that are better at identifying those without a condition have a higher Sp. The goal of any diagnostic test is to maximize both Sn and Sp. A ROC curve is a tool that can be used to help find the cut-off value of a diagnostic test that can maximize both of these attributes. Additionally, +LR, -LR help provide an understanding of the result of a test relative to those without the condition. The larger the contrast is between the +LR and –LR the better the diagnostic test. In addition to being able to measure the attribute of a single diagnostic test, the Sn, Sp, +LR, and –LR can be calculated to measure the ability of a cluster of sings and symptoms in distinguishing group membership. Definitions of these ratios have been provided in Table 2.2 and further explanation of the statistical procedures has been provided in Chapter 3. This approach has not only been used for diagnostic tests but has been successful in predicting success and failure with different treatment programs related to the lumbar spine.[20,39,44,58]

In the lumbar spine, when no systemic disease or signs of frank instability are present, the diagnosis of LSI has often been clinically based on some combination of

patient symptoms and pain patterns (Table 2.3).[58,97] In general, LSI has been believed to be a possible diagnosis when minimal provocation results in symptom change from mild to severe or a reduction of symptoms occurs with rest and support.[58,59,71] Although these signs and symptoms (Table 2.3) have been suggested to be associated with LSI, an analysis of their Sn, Sp, +LR, and -LR remains unknown. Therefore the ability of this group of signs and symptoms to distinguish the disorder remains also remains unknown.

Hicks[58] developed a CPR using signs and symptoms typically associated with LBP and specific signs related to instability. He found that patients with a positive PIT, aberrant movement present, average straight leg raise >91^{o}, and age <40 years old responded positively to lumbar stabilization training. Specifically, those that had two or more of these variables resulted in a Sn of 0.83, a Sp of 0.56, and a +LR of 1.9.[58] Further, the lowest -LR (0.18) occurred when subjects had at least two of the following three criteria: no aberrant movement, negative PIT, and fear avoidance behavior questionnaire (FABQ) physical activity subscale less than nine. A Sn of 0.85 and Sp of 0.87 in predicting failure with lumbar stabilization training occurred if the subject had two of these criteria. Although the Hicks[58] study defined LSI based on response to treatment (i.e. a treatment-based classification system), it has been the best study yet to define these patients based on a cluster of symptoms. Therefore, the same criteria were used to diagnose the LSI group for this study. Specifically, all subjects classified with LSI met at least two of the four predictors for success, while not meeting two of the three predictors for failure.

Table 2.2: Definitions related to the Receiver Operator Characteristic (ROC) curves[125,151]

Motion variable result	Diagnosis (Dx) Dx+ (INST*)	Dx- (CONTROL*)	Total
Positive	a (true positive)	b (false positive)	a+b
Negative	c (false negative)	d (true negative)	c+d
Total	a+c	b+d	

Sensitivity (Sn)	a / (a+c) Range: 0 to 1	Proportion of all of those with INST that test positive based on the motion variable. As Sn increases more of those patients with INST are correctly classified.
Specificity (Sp)	d / (b+d) Range: 0 to 1	Proportion of all of those without INST (CONTROL) that test negative based on the motion variable. As Sp increases more of the CONTROL subjects are correctly classified.
Likelihood Ratio of a Positive Test (+LR)	Sn / (1-Sp) Range: 0 to ∞	Proportion of those INST subjects with a positive test relative to CONTROL subjects with a positive test. A high + LR is advantageous.
Likelihood Ratio of a Negative Test (-LR)	(1-Sn) / Sp Range: 0 to ∞	Proportion of INST subjects with a negative test relative to CONTROL subjects with a negative test. A low – LR is advantageous (range 0 to infinity).

*INST = Subjects with lumbar segmental instability; CONTROL = Healthy asymptomatic control subjects without a recent history of LBP.

Table 2.3: Signs and Symptoms Suggestive of Instability[27,32,58,59,71,82,97,114,126]

-Recurrent low back pain with or without transient neurologic symptoms
-Increased symptoms with relatively minor perturbations and routine trivial movements
-Pain or difficulty with forward flexion followed by a "catch" upon returning to upright
-Sway or catch with motion
- Pain immediately upon sitting down and relieved by standing up
-Increasing pain throughout the day
-Aberrant motion
-Complaints of "giving way" or "slipping out"
-Temporary pain relief with manipulation
-Pain relief with rest, wearing a corset, or recumbent positioning
-Radiographic changes
-Positive prone instability test
-Hypermobility/step-off felt on manual examination
-Excessive range of motion with straight leg raise (> 91°)
-Muscle hypertrophy (protective/guarding)
-Younger individuals (< 40 years of age)

TRADITIONAL TECHNIQUES OF QUANTIFYING LUMBAR RADIOGRAPHS

Current Measurement Tools

The lack of a standard definition and diagnostic criteria for quantifying LSI has been a direct reflection of the difficulties associated with the objective measurement tools used to analyze this dysfunction. Since the beginning of the 20th century,[72,92,149]

researchers and clinicians have used radiographic assessments to categorize those with LSI. Traditional techniques involved the assessment of images in the neutral spine, end-range flexion and end-range extension positions, or other combination of static images. These images have been examined for indirect signs of instability and to quantify static displacement of a vertebral body in a single image or between two images. The most basic analysis of radiographic images entails the identification of indirect signs that are suggestive of instability. Some of these signs have included traction spurs,[80] narrowing of the intervertebral space, sclerosis of the vertebral bodies, vacuum phenomenon,[72] spinous process malalignment, vertebral body malalignment in the sagittal plane, and irregular facets on standard radiographs;[70] or a high-intensity zone on MRI.[5] However, the Sn and Sp of indirect signs to diagnose LSI have not been established because of the lack of a 'gold standard' for comparison.

In 1944, Knutsson[72] described the benefits of lateral images performed at the end-range of flexion and extension for assessing lumbar instability. Since then, many measurement techniques and classification systems have been developed to detect and measure instability in the sagittal plane.[3,12,46,92,94,108,155,156] The term 'functional radiography' has been used to describe multiple imaging techniques that calculate the motion between two vertebrae in different postures of the lumbar spine.[103] A common guideline for defining abnormal motion in the sagittal plane during flexion and extension has been: (1) sagittal-plane translation of 4 to 4.5 mm, or 10% to 15% of the vertebral body width, and (2) rotation greater than 15° at L1 to L4, > 20° at L4-L5, or > 25° at L5-S1.[98,126,153] However, consensus on the best imaging and measurement techniques, as well as the appropriate anatomical landmarks that should be tracked, has yet to be reached.

Problems with Current Measurement Tools and Strategies to Overcome These Limitations:

Many problems have been cited with traditional radiographic assessments of the lumbar spine for instability. First, large variability of normal human movement in asymptomatic individuals has been documented.[32,33,57,103,104,126,145] Variability of end-range motion has been found to be compounded by the patient's age, time with a LBP disorder,[71,134,146] level of pain,[31,103,127] normal and abnormal coupled movement of the functional spinal units during motion,[32,142,153] and differences in test postures used to analyzed the static end-range motion.[18,33,67,73,133,158] Second, the images have been assessed statically at end-range motion.[32,33,57,67,72,126,136,153] Static analysis has been found to be inadequate to categorize these patients.[18,73,95,97,143] Finally, measurement error has been a concern when using these techniques.[25,26,31,119,121,136] Techniques to decrease the error and improve the ability to standardize the measurement technique to include proper landmark verification techniques have been cited as an initial step needed to successfully measure intersegmental motion.[11,16,17,45-48,63,75,77,117,128,133]

Variation of Human Movement

Large variation in normal human movement, as measured by static end-range images in asymptomatic individuals, has made classification of normal versus abnormal movement based on ROM values challenging and can lead to invalid conclusions.[32,33,103,104] Although Boden and Weisel[11] and Dvorak et al[33] have measured normal intersegmental translation at 1.3 $\pm$ 0.8 mm and 2.6 - 3.1 mm, respectively, others[57,145] have found greater variability of normal motion. Hayes et al[57] found 20% of the asymptomatic subjects to have greater than 4 mm of translational movement at a particular level. Tallroth et al[145] found that 14%, 29% and 7.1% of asymptomatic individuals had $\geq$ 5 mm of translation at L3-4, L4-5 and L5-S1, respectively. Boden and

Wiesel[11] suggest the contrary; that normal individuals have less than 3.00 mm of dynamic AP translation, and that the "overlap" between normal and abnormal motion can be reduced (eightfold) by better measurement techniques. Muggleton et al[97] suggested that hypermobility under normal neuromuscular control may not be pathologic and therefore it is unwise to infer instability from these measurements of hypermobility alone. The disconcordance of these findings has made establishing an accurate diagnosis of instability based on hypermobility challenging.

In addition to variation in normal movement, performance of flexion and extension with pain may result in varying movement patterns secondary to pain avoidance. Decreased volitional movement or altered movements of patients with pain has also been cited as a potential source of error leading to an underestimation of true intervertebral motion.[31,103] Putto and Tallroth[127] found that adjusting the standard patient position for patient comfort and maximal motion resulted in greater angular mobility. Deyo et al[31] suggested that radiographic images to assess instability should not be taken during acute and painful states.

Age and time with the condition have also been cited as confounding variables in measuring motion of the lumbar spine.[71,146] Sato and Kikuchi[134] measured the natural history of those with radiographic-defined instability. After ten years, 48% of patients still had significant clinical symptoms, while only 20% had radiological signs of instability. These findings support the staging process outlined by Kirkaldy-Willis and Farfan[71] and emphasized the difficulty associated with static radiographic images and clinical symptoms of LBP in the aged patient with degenerative changes.

As previously discussed, normal spinal movement is accomplished through multi-planar coupled movements. These coupled movements have appeared to be disrupted in segmental instability.[32,154] Steffen et al[142] cautioned that coupling patterns demonstrated

inter-subject variation in amplitude and direction. Abnormal coupling of movement has been theorized to occur in all planes of movement. Therefore, measurement techniques performed in a single plane may not reflect the full characteristics of realistic movement patterns. However, sagittal plane motion has typically been assessed because of its larger intervertebral motion can accommodate measurement error better than motion in the frontal or coronal planes and it has less out-of-plane coupled movement patterns.[95]

One problem with comparing lumbar motion (angle and displacement) obtained across different tests has been that the postures used for the test vary and are not standardized.[73] Bronfort and Jocumsen[18] found that there was more motion and less variability when lumbar motion was tested during standing rather than sitting, and that motion measured in the sagittal plane had less variability than frontal plane motion. Saraste et al[133] found no significant difference between measurements in standing and recumbent positions, while Wood et al[158] found that side lying could maximize sagittal plane motion. Pearcy[116] and Muggleton and Allen[96] concurred with Bronfort and Jocumsen[18] and suggested that sagittal plane motion should be studied because it occurs with minimal sidebending and axial rotation, thus minimizing out-of-plane motion. Dvorak et al[33] suggested passive overpressure be applied at the static end-range to maximize motion. Although side lying motion or passive overpressure may result in maximal passive motion, these test positions are inconsistent with the goal of measuring instability and associated movement dysfunction where the concern has been with active functional mid-range movement in the upright posture. Therefore, this study analyzed sagittal plane motion from the upright posture.

Static Images Obtained at End-range

Functional radiographs, in which translation and angular changes are traditionally measured between upright and end-range motions, have been used to define

hypermobility that has been thought to be associated with lumbar instability.[32,33,67,72,126,136,152,153] There has been an interest in functional radiographs because of the belief that anterior-posterior sliding is an early sign of degeneration of the FSU.[72,82] The problem with these techniques has been that the extent of hypermobility has not necessarily been associated with a patient's symptoms,[97] and there has been a high rate of false-positive findings.[57,113] It has been suggested therefore that a movement assessment based on how the motion is achieved might prove to be more diagnostic than the overall quantity of motion.[95] One of the fundamental problems with using traditional imaging techniques to measure instability has been the reliance upon static postural assessment at the end-ROM. Stokes and Frymoyer[143] used biplanar radiography to measure instability in patients with clinical examinations consistent with LSI. They were unable to correlate irregular movement patterns with this group of patients. One conclusion made by Stokes and Frymoyer[143] was that aberrant motion throughout the ROM could have occurred, but it was unable to be assessed using static-end-range images. Bronfort and Jochumsen[18] compared functional radiographs with a qualitative assessment of cineradiographic images and concluded that the aberrant motion pattern observed in cineradiology was not evident on the functional radiographs. Boden and Wiesel[11] and Friberg[41] have also suggested that a more dynamic assessment of lumbar instability is required to assess this population.

One attempt to improve functional radiography of the lumbar spine has been to measure the effects of traction and compression on intervertebral motion, instead of flexion and extension imaging. Friberg et al[41] found that traction-compression images were able to correctly identify those with and without symptomatic spondylolisthesis. However, Pitkanen et al[120] found that traction-compression imaging only correlated with 2% of the patients with clinical symptoms of instability, while the results from the

traditional flexion and extension images correlated with 23% of the patients. This discrepancy highlights the continued need for research in the area of continuous measurements of intervertebral motion instead of static end-range postures. However, functional radiographs have been limited in their ability to image motion throughout a range secondary to dosage limitations[14,73] and their inability to capture real-time motion in the same motion sequence.[73] Therefore a more dynamic technique that can assess motion throughout the ROM, such as DFV, is required to identify aberrant motion.[14,15,73]

Measurement Errors

Errors in reading and quantifying radiographs of the lumbar spine limit its usefulness. Deyo et al[31] studied the inter- and intra-observer variability in reading lumbosacral films. They found a 76% rate of agreement in the distinction between normal and abnormal radiographic findings.[31] Overall, they found that intra-observer variability was less than inter-observer variability. Poor image quality also appeared to be a contributing factor in the cases of disagreement. Polly et al[121] found that among three well trained orthopedic surgeons, the intraobserver intraclass correlation coefficients (ICC) ranged from 0.83 to 0.92 among the four measurement techniques used to measure lumbar lordosis. Interobserver ICC ranged from 0.81 to 0.92. Although this reliability appears high, the error between measurements was reported as 10° between repeated measures, and therefore a substantial amount of change would be required to be detected. Penning et al[119] also found that, with the current techniques, measurement errors obstructed any possible detection of aberrant motion. Therefore, the development of a radiological measurement tool that could standardize interpretation and decrease the measurement error of lumbar films for instability would be important to enhance clinical efficacy.

Many different measurement techniques have been developed over the years, in part because of the lack of success of any one of the previously described measurements to adequately capture the characteristics of this population. Shaffer et al[136] found that the effects of measurement techniques, quality of images, and the effects of tilt and rotation of the spine during imaging affected the consistency and accuracy in assessing sagittal translation in the lumbar spine. Further, high false-negative and high false-positive rates were found in classifying patients with instability even with the most consistent measurement techniques.[136] Danielson et al[25] found that slight changes in patient positioning resulted in 10-15% error in the measurement of vertebral displacement. Error measurements secondary to patient positioning meant that progressive instability of less than 20% has been difficult to detect.[26] This error could be associated with either the patient's actual position or the position of the central beam compared to the patient's position.

In addition to the inter- and intra-rater reliability issues, many researchers have used varying measurement techniques to measure instability. Some used different landmarks, while others used measurement processes that do not account for radiographic magnification. Muggleton and Allen[96] have found that comparison across these measurement techniques has only been possible when the intervertebral angle is 0°. Further, in some of these reports, the measured displacement has been within the measurement error of the technique.[103]

The lack of reliability and accuracy of measurement using current measurement techniques has contributed to the absence of an acceptable 'gold standard' by which to judge the accuracy of other imaging and clinical examination procedures. It has been suggested that improved measurement techniques should reduce the error in the measurement of intersegmental motion.[11,63,77,117,133] Verification of vertebral body

landmarks has been used to decrease error.[16,45,46,128] A landmark verification protocol developed by Brinckmann et al[16] was designed to compensate for radiographic distortion of the central beam, off-center position, axial rotation, and lateral tilt during the objective determination of the location of the vertebral corners. This protocol was designed to limit subjective errors associated with these measurements. Frobin et al[45] enhanced this protocol by developing a measuring technique for sagittal plane translation and angular changes using geometric parameters that are symmetric with respect to the adjacent vertebral bodies. A full explanation of the distortion-compensated vertebral corner location selection and the intervertebral measurements of angulation, displacement, and translation are presented in the methods section (Chapter 3). The measurement error associated with this technique was determined to be 0.7 to 1.6° for the angular error, and 1.2% to 2.4% of vertebral depth (0.4 to 0.8 mm) for the displacement error.[46] These error measurements are respectively four to five, and ten times smaller than previously reported measurement errors.[46] The intraobserver repeated measure test found that the angle and displacement measurements were not significantly different ($p < .05$).[46] The interobserver assessment found a slight, but statistically significant difference in the displacement measurement ($0.5 \pm 1.7\%$ of the mean vertebral depth).[46] Similar results were obtained when this technique was applied to the cervical spine.[47,48] To date, this distortion-compensated technique has never been applied to fluoroscopic images.

Improved measurements of intersegmental motion have focused on standard radiographs because those are used most often in a clinical setting. However, two new imaging tools are proving to also improve the reliability of these measurements: biplanar radiography[117] and RSA.[63] The latter technique has been shown to result in the least amount of measurement error, but it has been limited to post-operative spine patients because it relies on surgically-placed markers on the vertebrae. Leivseth et al[75] compared

the DCRA and RSA techniques and found that the distortion-compensated method had an error of 1.4° with a mean difference of 0.05° for angular measurements, and a 1.25 mm error with a mean difference of 0.5 mm for translational measurements. Some of the measurement error could be attributed to variation in human movement, as the measurements were from different trials. Although measurement errors existed between the two techniques, the distortion-compensated technique is currently better than conventional protocols and is also noninvasive.[75] The relatively new distortion-compensated technique is currently the best non-invasive measurement technique used to assess intersegmental motion, but its use in clinical research has been limited because of its newness.

DYNAMIC/KINEMATIC ASSESSMENTS OF LUMBAR MOTION

Although the functional radiographic techniques described above have provided insight into lumbar motion, and the measurement techniques have improved, the fundamental limitation of these approaches has been that they have only assessed static images at the end-ROM. Dynamic assessment has been proposed in order to measure the motion in the mid-range where aberrant motion related to LSI has been theorized to occur.[18,73,95,97,110]

Since 1827,[146] *in vitro* kinematic analyses have provided a basic foundation for the understanding of lumbar kinematics. Yamamoto et al[159] found that during flexion and extension of the intact lumbar spine, the majority of motion occurred at the lower FSUs (L4-5, L5-S1) compared to the upper FSU. In a measure of 18 normal FSUs, Posner et al[126] found that the maximum normal translation under the preload condition was 1.7 mm $\pm$ 0.6 mm (6% $\pm$ 2%) for L1-L5, 1.0 mm $\pm$ 1.2 mm (4% $\pm$ 4%) for L5-S1 during flexion, and 2.1 mm $\pm$ 0.7 mm (7% $\pm$ 2%) during extension. After serial transection of the supporting ligaments, greater displacements were noted, representing greater levels of

instability.[126] Surgically-induced instability of the *in vitro* lumbar spine has resulted in increased mobility under conditions of graded facetectomies,[2] graded discectomies,[51] and with L4-5 spondylolisthesis.[53] Mimura et al[93] found an increase in the NZ in the presence of disc degeneration, resulted in greater joint laxity in mid-range movements, despite the overall decrease in ROM of the FSU.

Although there has been a focus on measurements of translational and rotational mobility, measurements of instantaneous center of rotation (ICR),[135] velocity, acceleration, and jerk[104,105] have also been used to measure normal and abnormal motion. Seligman et al[135] found that measurements of the ICR were able to detect 94% of the abnormal spines, whereas measurements of excessive ROM were only able to detect 25% of the spines with disc degeneration. The erratic nature of motion that occurred in those with instability was determined to be more important than the static end-range displacements. Ogon et al[104,105] found that velocity, acceleration, deceleration, and jerk increased with surgically-induced instability during flexion and extension without preload. The reverse was true under the preload condition. These abnormal motion characteristics highlight the importance of measuring dynamic motion variables when assessing lumbar instability.

An additional advantage with *In vitro* measurements is that it has allowed for direct measurement of all six degrees of motion under more objective and controlled conditions because the researcher can control the loads, the restraints, and the condition of the specimen (intact or surgically induced injuries that can be validated).[52] However, the results have been difficult to generalize to the *in vivo* condition. Typically, researchers performing *in vitro* studies have studied multiple segments of the same lumbar spine (L2-3, L4-5, and L5-S1) and compared the results among these different levels as though each level was identical. Harada et al[55] found that the different FSU

levels function differently *in vivo*. For example, rotation dominated the movement at the L5-S1 level, while levels L3-4 and L4-5 typically had more translation and less relative rotation than the L5-S1 level.[55] Further, the cadaveric spines tested have typically been devoid of muscles and other restraints that are present under physiological conditions. Kaigle et al[64] found that graded facetectomies resulted in increased intervertebral translation without muscular support, but resulted in less erratic patterns of motion with simulated muscular activity throughout the entire ROM and within the NZ. *In vitro* studies also have not been able to simulate normal human movement. Instead, researchers often have used a load-controlled movement pattern instead of a displacement-controlled movement pattern. Edwards[52] suggested the displacement-controlled method has been better to simulate the *in vivo* condition by allowing better simulation of both translational and rotational components of movement. He conceded that the load-control method has been a convenient way to measure *in vitro* motion under small loads, but has warned that, although load-controlled methods produce 'natural' looking movements, the results don't actually simulate *in vivo* movements and therefore results may be misleading.[52]

The use of preloads during *in vitro* studies historically has been to simulate body weight (preload) onto the FSU.[112] However, the results of Ogon et al[104] under the preload condition revealed a decrease in both translational and angular motion compared to the non-preload state. This has been contradictory to previously published research of segmental movement under conditions of instability.[34,112,135] Edwards et al[34,52] suggested that because the compressive load is considerably larger than the applied moment, and because preloads yield greater stiffness among the FSU, these altered results should be expected. The results from the preload condition may be more appropriate for those with restabilization of the FSU through degenerative changes of the spine with decreased

motion at the FSU. Further, Steffen et al[142] cautioned readers from applying *in vitro* spinal motion results to the *in vivo* condition, because the amount of axial rotation measured *in vivo* during their study was less than in the previous *in vitro* studies.[142] *In vitro* analysis of FSU movement can only simulate the *in vivo* condition, thus the results have limited generalizability.

The capability for *in vivo* kinematic assessment of human movement has been limited in part by technology. Global measurements of trunk ROM, such as motion analysis systems and inclinometers, have been used to measure sagittal plane ROM, however these measurements varied across devices.[137] Initial kinematic analyses have used external devices such as triaxial potentiometers,[89] lumbar monitors,[84] electrogoniometers,[73] external reflective stick markers,[28] and internal devices, such as Kirscher wires surgically implanted in spinous processes in pigs[64] or external spine fixators (ESF).[79] Measurements of global trunk velocity using external devices were able to distinguish those with and without LBP.[84,89] However, Lund et al[79] found that, during comparative three-dimensional movement analysis with an optoelectronic camera system of individuals with ESF, no single kinematic variable was able to identify patients that experienced relief with ESF. Further, the limitations of these techniques have restricted their clinical use. Muggleton et al[97] states that "dynamic imaging offers the potential for improved diagnosis and assessment" of those with mechanical etiology of LBP.

Through improvement in digital image processing, researchers have begun to use a clinically accessible tool, VF, to perform cineradiographic assessment of the lumbar spine to further understand mechanical influences on LBP. VF has been an appealing option for the analysis of kinematic variables because of the continuous analog nature of the image sequence and its reduced radiation exposure compared to standard radiographs.[8] In general, the expected radiation dose for one minute of VF has been

equivalent to a single plain radiograph of the same region,[95] thus limiting the safety considerations with the radiation dose usually associated with multiple static radiographs. Further, it has been suggested that dynamic imaging may decrease the confusion regarding the use of hypermobility measurements to characterize instability.[97]

Although VF has been widely used in the clinical setting for qualitative analysis purposes, its use as a biomechanical quantitative research tool has been limited by problems with distortion and poor image quality and resolution.[8] Specifically the lower doses of radiation used by VF systems have resulted in poor quality images, in which the anatomical landmarks have been difficult to identify.[95] In the late 1980's, Breen et al[14,15] started to examine the role of VF in measuring intervertebral angles and ICR *in vitro* using a calibrated model. During their initial work, the researchers discovered that vertebral location, scaling, out-of-plane distortions, and loss of image quality secondary to soft tissue scatter were severe limitations to this technique.[14,15] Specifically, these researchers found it to be "notoriously difficult to quantify the kinematic behavior of vertebral segments" based on the limitations of the system.[15] Initial work by Cholewicki et al[22] helped to determine ways to correct for the "pin-cushion" distortion and digitizing errors caused by the curved image intensifier and were able to reduce the measurement error to 0.69° for rotational measurements and 0.33 mm for linear measurements in the *in vitro* environment.

Recent innovations based on digital image processing have focused on automation of the process to minimize the time associated with tracing, digitizing, and selecting the anatomical landmarks of interest.[95,160] Problems associated with automating the technique have included: location of neighboring vertebral bodies, changes in brightness and contrast both within a single frame and across frames, distortion from out-of-plane motion, and vertebral marking systems that can automatically recognize the region of

interest.[95] Muggleton and Allen[95] used a template-based algorithm in which cross-correlations were used to match and track the vertebral bodies during motion *in vitro*. Zheng et al[160] attempted to automatically track the motion using edge detection algorithms to detect the vertebral bodies, Fourier descriptors to describe the vertebral shapes, and a Hough Transform to track the motion between frames. In addition, they used the Visual Human Project to create three-dimensional models of the vertebral body than can be scaled to the VF image to create a three-dimensional animated model of the vertebral bodies during motion.[160] Their work included both *in vitro* and *in vivo* images, however the *in vivo* images were limited to severely collimated images which improved the quality of the VF image but decreased the FOV and hence the functional application to a wide-range of movement patterns. The direct application of these techniques to the *in vivo* scenario has been limited because of increased scatter of the image with the increased soft-tissue around the trunk.[21,95] One possible advancement that could improve these suggested techniques has been the use of Open MRI in which non-ionizing high-quality images can be obtained during a limited ROM.[90] However, the availability of these machines remains limited.

While researchers have continued to develop more automated techniques, clinical research using VF and Open MRI has quantified specific aspects of both normal and abnormal movement patterns in both the lumbar and cervical spine.[23,55,61,65,66,73,76,88,90,106,144,147,148,157] In those without LBP, Kanayama et al[65,66] studied motion patterns during flexion and concluded that the motion occurred in a sequential fashion in which the upper segments moved prior to the lower segments during flexion. Specifically, the L4-5 segment began to move after an average 6° of the initiation of L3-4 movement, and the L5-S1 segment moved an average of 8° after L4-5 initiation flexion. The majority of extension occurred at L5-S1 motion segment.[65] Harada et al[55] measured

both flexion and extension and concurred with Kanayama et al[65,66] that flexion occurred in a sequential fashion during flexion. They also found that extension occurred in a reversed sequential fashion. During flexion, the velocity of motion increased with each segment.[55] While, Okawa et al[106] found that motion most often occurred either in a segmental pattern, as previously described, or simultaneously. Finally, Lee et al[73] found that the sequential motion from cephalad to caudal segments occurred during flexion, but on the return to upright the concavity of lordosis increased steadily with no segmental motion pattern described. This slight difference in kinematic patterns measured most likely represents the different movement patterns tested (i.e. seated versus standing, extension versus hyperextension). However, these techniques were limited. Specifically, they only analyzed 3-5 frames/second because of the laborious nature of the digitization process and were limited to angular measurements, which are less reliant on the location of exact vertebral landmarks.[55,65,66,106]

In addition to testing sagittal plane motion, dynamic imaging has been used to assess functional activities. Cholewicki and McGill[23] found that normal movement patterns during weightlifting did not result in extreme motion, and that the subjects maintained a more neutral posture during the lifting activity. One subject experienced LBP during the lift, and upon analysis it was revealed that during the lift that resulted in LBP, the subject exceeded full flexion of L4-5 by 103%.[23] Their conclusion suggested that VF is a tool that could detect abnormal movement patterns. Vander Kooi et al[148] measured the effects of thoracolumbosacral orthoses (TLSO) on lumbar motion and found an overall decrease in angular motion of L3-L5 from 70° to 50° with the TLSO and an overall reduction to 40° when the TLSO plus thigh extender were worn. Further, the relative motion at L3-4 to L4-5 was reduced by 40% with the wearing of the TLSO and by 55% when the TLSO was worn with the thigh extender.[148] Lee et al[73] used VF as a

'gold standard' measurement to compare the results of an electrogoniometer to assess intervertebral motion. Finally, McGregor et al[88] used dynamic MRI to assess intersegmental motion and pelvic tilt in elite oarsmen.

Dynamic imaging has also been used to measure the severity of spondylolisthesis. Okawa et al[106] observed altered movement patterns in which the segment with spondylolisthesis moved prior to the upper segment's motion, and that the dysfunctional segment demonstrated a delayed deflection towards flexion prior to returning to the upright posture. While, Takayanagi et al[144] measured increased intersegmental translation, as well as the flexion-extension angle, during seated flexion and return to upright in patients with L4 degenerative spondylolisthesis with less than 15% slip (compared to those without dysfunction). Conversely, those with greater than a 15% slip demonstrated hypomobility, which was theorized to be consistent with the restabilization process.[144] This dichotomy of hypermobility and hypomobility among those with L4 degenerative spondylolisthesis demonstrated the importance of the natural history of the dysfunction in group selection. McGregor et al[90] found no difference in angular or translational motion in subjects with spondylolisthesis compared to healthy control subjects.

One of the major limitations of VF has been the narrow fluoroscopic field available by this technique. Kanayama et al[65] and Harada et al[55] measured L3-S1 with greater success than Okawa et al,[106] who only measured L2-L5. Okawa et al[106] had to eliminate most of the L5 data because it was not captured in the visual field throughout each individual study. Another complaint of cineradiographic techniques has been the time required to analyze the data. This continues to be reduced with technological advances. Previous studies assessing lumbar motion have found wide variation among individuals; therefore future cineradiographic techniques should try to avoid this problem

through strict inclusion and exclusion criteria for the population in question. Furthermore, to date no studies have used the improved measurement techniques outlined by Brinckmann et al[16] and Frobin et al[45,46] to measure intervertebral motion with VF.

The initial kinematic assessments of lumbar spine via VF have found variations in movement order and movement dysfunctions between those with and without low back disorders. These initial indications suggest that the previous calls for motion assessment during mid-range motion are appropriate and that the measurement of dynamic lumbar kinematics has the potential to classify different populations of LBP. However, these initial studies have limited their populations to either normals or those with different stages of spondylolisthesis. They have not measured lumbar motion in those suspected of LSI. In addition, no study to date has measured multiple kinematic variables, such as; sagittal plane vertebral translation, angular changes, velocity, and lumbar lordosis among those with and without LSI. Based on the review of literature, a better understanding of the kinematic variables among those with LSI is essential to better define this patient population.

Chapter 3: Methods

SUBJECTS

Two groups of volunteers were analyzed for this dissertation. The first group was analyzed for the reliability studies and consisted of 20 male volunteers with and without a history of mechanical low back pain (MLBP). The second group consisted of 40 volunteers (males and females) with and without a history of LSI and was analyzed for the descriptive and comparison group studies. This second group of volunteers was analyzed both based on symptom status (CONTROL-I, and INST-I) and based on the observed motion patterns (CONTROL-F and INST-F), determined by a qualitative review of the DFV by three expert reviewers (spine surgeons).

Subjects for Reliability Studies

The reliability study consisted of a convenience sample of 20 male volunteers (Table 3.1) from the Department of Defense (DoD) beneficiary population. Eleven of the men were diagnosed with MLBP and nine of them had no history of LBP in the last 10 years prior to the study. Females were not included in this portion of the study because of the radiation risk associated with testing a measurement system with unknown reliability.

Volunteers in the MLBP group were seeking care, had limited their work activities, or had limited their recreational activities secondary to MLBP of subacute or chronic nature. Their history of MLBP varied from 1 month to 20 years of symptoms, with all subjects complaining of a minimum of one prior episode of MLBP prior to the current episode. The modified Oswestry Disability Index (ODI; Appendix E) score for the group ranged from 19-44%, with a mean of 30.4 $\pm$ 8.0%. Minimal inclusion and

exclusion criteria were placed on this group to obtain a variety of possible different movement dysfunctions to include both hypo- and hyper-mobile individuals. Individuals with acute pain that restricted sagittal plane motion, neurological changes in strength, or a history of spinal surgery were excluded from this study.

Screening criteria adapted from Hayes et al[57] and an ODI score $\leq$ 4% were used to screen for a lack of LBP in the control group over the last three years. Of these nine individuals, only two had a history of MLBP in high school (10 and 24 years ago) and only one volunteer had a positive ODI score (4%).

Outside of their LBP status, both groups were required to be generally healthy with no history of uncontrolled coronary artery disease (CAD) or hypertension; per self-report. Further, none of the volunteers had a recent history of open abdominal or pelvic surgery that could possibly affect the abdominal muscles supporting the lumbar spine.

Table 3.1: Demographics (Reliability Studies)

	Low Back Pain (n=11)	**Control (n=9)**
Age (years)	36.4 $\pm$ 7.2 (24 - 45)	30.4 $\pm$ 8.0 (19 - 44)
BMI (kg/m^2)	28.4 $\pm$ 2.3 (23.8 - 32.3)	25.5 $\pm$ 3.4 (21.7 - 31.4)
Waist:Hip Ratio	0.917 $\pm$ .038 (0.872 - 1.004)	0.854 $\pm$ 0.062 (0.797 - 0.985)

* Values are mean $\pm$ standard deviation, with range shown in parentheses.

Subjects for the Descriptive and Comparative Group Studies (Symptom-Based Groups)

A purposive sample of 40 males and females aged 22-52 years from the DoD beneficiary population were enrolled in these studies (Table 3.2). One group of 20 volunteers was diagnosed with LSI (INST-I) of the lumbar spine and the other group 20 volunteers were without a history of LBP (CONTROL-I) for at least 10 years prior to the study.

Table 3.2: Demographics (Descriptive and Comparative Group Studies) for symptom-based groups*

	Gender†	INST-I	CONTROL-I
Age (years)	All	36.0 ± 8.0 (24 - 52)	36.0 ± 8.1 (22 - 51)
	Men	36.5 ± 7.7 (25 - 52)	36.4 ± 7.4 (26 - 51)
	Women	34.7 ± 9.2 (24 - 49)	35.0 ± 10.4 (22 - 51)
BMI (kg/m^2)	All	25.9 ± 3.6 (18.6 - 32.4)	25.0 ± 3.7 (17.9 - 31.4)
	Men	26.2 ± 3.7 (18.6 - 32.4)	26.4 ± 3.0 (21.9 - 31.4)
	Women	25.2 ± 3.5 (20.1 - 30.7)	21.6 ± 2.8 (17.9 - 25.3)
Waist:Hip Ratio	All	0.844 ± 0.075 (0.715 - 0.970)	0.845 ± 0.064 (0.737 - 0.985)
	Men	0.871 ± 0.063 (0.770 - 0.970)	0.870 ± 0.057 (0.797 - 0.985)
	Women	0.780 ± 0.063 (0.715 - 0.883)	0.786 ± 0.035 (0.737 - 0.838)
ODI (0-100%)	All	28.6 ± 10.9 (0 - 46)	0.4 ± 1.0 (0 - 4) ‡
FABQ (0-24)	All	16.3 ± 4.1 (7 - 24)	Not applicable

*Values are mean ± standard deviation, with range shown in parentheses.

† Twenty volunteers per group, 14 men and six women

‡Two control volunteers scored 2%, each getting a score of one for the sleep related question, one volunteer scored 4%, scoring one for both prolong sitting and standing

Inclusion/Exclusion Criteria

The strict inclusion/exclusion criteria established for both groups were designed to provide a purposive sample representative of both populations (Table 3.3). All subjects were between 22 - 52 years of age and were in general good health outside of the LBP status. None of the volunteers had a history of spinal surgery or a recent history of open abdominal or pelvic surgery that could affect the abdominal muscles supporting the lumbar spine.

Entrance criteria for those with LSI were based on the work by Hicks[58] presented in Chapter 2. Potential subjects with instability that met two of the four predictors for success with a lumbar stabilization exercise program (a positive PIT, aberrant movement present, average straight leg raise >91^{o}, and < 40 years old) without meeting two of the three predictors for failure (no aberrant movement, negative PIT, and FABQ physical activity subscale score less than nine) met the criteria to be considered an instability subject for this study. The reliability (κ) of different raters to recognize an aberrant movement patterns and the results of a PIT was reported as 0.60 and 0.87, respectively.[59]

On average the volunteers in the INST-I group exceeded the entrance criteria (Table 3.4). Specifically, they averaged 3.3 $\pm$ 0.8 of the +CPR predictors when only two were required. The INST-I subjects had more than the required one of the five possible signs of aberrant motion; they had an average of 2.35 $\pm$ 1.04. Further, they averaged 1.8 $\pm$ 0.70 levels with a positive PIT test and averaged 2.2 $\pm$ 0.62 levels with a positive spring test. Of the –CPR, only one subject had one of the three findings in this category, the other subjects displayed no signs attributed to –CPR. Additionally, 17 of the 20 volunteers reported recurrent episodes of LBP (3: < 3 episodes, 2: 3-5 episodes, 2: 5-10 episodes, 10:>10 episodes). Of these 17 individuals, nine reported that their symptoms

were becoming more frequent, four reported a decrease in frequency, and seven reported no change in frequency.

Screening criteria adapted from Hayes et al[57] and an ODI score $\leq$ 4% were used to screen for a lack of LBP in the CONTROL-I group. In the CONTROL-I group; four individuals had a single prior episode of LBP (10 - 24 years ago) but were included in the study because of the lack of recurrence and the length of time from their prior episode. Two of these individual had fallen on ice and had symptoms lasting two to four weeks in duration, while two had symptoms consistent with mechanical LBP only during high school (10 and 24 years ago).

A Priori Power Analysis

Acknowledging the exploratory nature of this study, a power analysis was performed using normative data for vertebral body translation in those with instability and in controls. Assuming an alpha of .05 and a beta of .20, the proposed sample size of 20 in each group would have a power of 92.8% if the group mean difference were 1.5 mm (4.5 mm translation in the instability group[153] and 3.0 mm of translation in the control group[33]) and the common within-group standard deviation were 1.5 mm. The power would have decreased to 75.3% if the common within-group standard deviation increased to 2.0 mm.

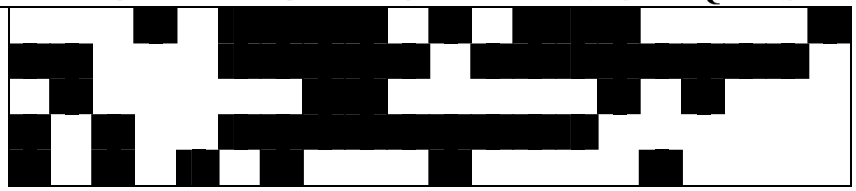
Table 3.3: Inclusion and Exclusion Criteria

LBP Group – Inclusion Criteria	1. LBP within the last year that required medical attention, lost work, or limited recreational activities 2. < 40 years of age* (If 2 other "*" variables present, age can range from 18-60 years) 3. Aberrant movement present*† 4. Positive prone instability test*† 5. Average straight leg raise (@90°)* 6. FABQ – Physical activity subscale (≥ 9) †
LBP Group – Exclusion Criteria	1. Unable to perform the test motion 2. Unable to fit in the machine 3. History of open abdominal, pelvic, or back surgery 4. Foot drop 5. Coronary artery disease/hypertension 6. Pregnancy or LBP associated with recent pregnancy
Control Group – Inclusion Criteria	1. No History of LBP that resulted in medical attention, loss work, or limited recreational activities within the last 3 years 2. 18-60 years of age
Control Group – Exclusion Criteria	1. Oswestry ≥ 4 2. Unable to fit in the machine 3. History of open abdominal, pelvic, or back surgery 4. Foot drop 5. Healthcare visits/history of LBP (within last 3 years) 6. Coronary artery disease/hypertension 7. Pregnancy

* Must have two of the four findings to be considered to have lumbar instability. This decision rule has been reported to have a sensitivity of 0.83 (0.61, 0.94), specificity of 0.56 (0.40, 0.71).[58]

† The lowest negative LR of 0.18 (0.08, 0.38) with lumbar stabilization resulted when the subjects had at least 2 of the 3 criteria present with a sensitivity of 0.85 (0.70, 0.93), specificity of 0.87 (0.62, 0.96).[58]

Table 3.4: Clinical Prediction Rule Findings of the Instability Group[58]

	Test	Specifics	Subjects A B C D E F G H I J K L M N O P Q R S T
+CPR (2 of 4) Included	Aberrant Motion (1 of 5)	Painful Arc in Flexion	
		Painful Arc in Extension	
		Gower's Sign	
		Instability Catch	
		Reversal of Lumbar Motion	
		Sum (Maximum = 5)	3 2 2 1 1 3 4 4 4 2 3 2 3 3 3 2 2 1 1 1
	PIT (1 of 3)	L3	
		L4	
		L5	
		Sum (Maximum = 3)	1 1 2 3 2 1 2 2 2 2 1 2 3 2 3 1 1 1 2 2
	Average SLR	≥ 90°	
	Age	< 40 years	
	Total +CPR	Sum (Maximum = 4)	2 2 3 3 3 4 3 3 4 4 2 3 4 4 3 4 4 4 4 2
-CPR (2 of 3) Excluded	Aberrant Motion	No Positive Findings	
	PIT	No Positive Findings	
	FABQ	<9	
		Sum (Maximum = 3)	0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0

Subjects for the Descriptive and Comparative Group Studies (Motion-Based Groups)

To assess the role of qualitative assessment of DFV on group membership and the kinematic model, subjects were dichotomized a second time into a final group of subjects with instability (INST-F) and a final group of subjects without LBP (CONTROL-F; Table 3.5). Final group assignment was determined based on the expert reviewers (three spine surgeons) average score for global motion assessment on a 5-point ordinal scale (0: Normal Motion, 2: Indeterminate/Neutral, 4: Abnormal Motion). An average score < 2.0 would result in the DFV being labeled as normal motion, while a score > 2.0 would result in the DFV being labeled as abnormal motion. For the six DFV that had an average score of two, agreement among two-raters determined group membership (Figure 3.1). For example, a raw score of (3, 3, 0) would be labeled as abnormal motion, while scores of (1, 1, 4) would be labeled as normal motion. The three subjects' DFV with a score of (1, 2, 3) were labeled as indeterminate. Subjects in the control group who were assessed as having relatively normal motion remained in the control group (CONTROL-F). Subjects who were diagnosed with LSI based on physical examination findings and were viewed as relatively abnormal remained in the instability group (INST-F) for the final analysis. Subjects whose qualitative assessments were indeterminate among the three raters or were viewed to be opposite of their original group assignment were not included in the final analysis.

Subject Recruitment

Six physical therapists from Fort Sam Houston and Randolph Air Force Base, Texas were trained on the screening criteria and the examination procedures. Patients who met these criteria from Sept 03 to Jan 04 and volunteered to participate were

enrolled in the study. Control subjects were recruited with the goal of matching the mean age and gender distribution of each group (Table 3.2). Outside of feedback on the study results, no rewards were provided to encourage participation.

Table 3.5: Demographics (Descriptive and Comparative Group Studies) based on the expert review of the DFV*

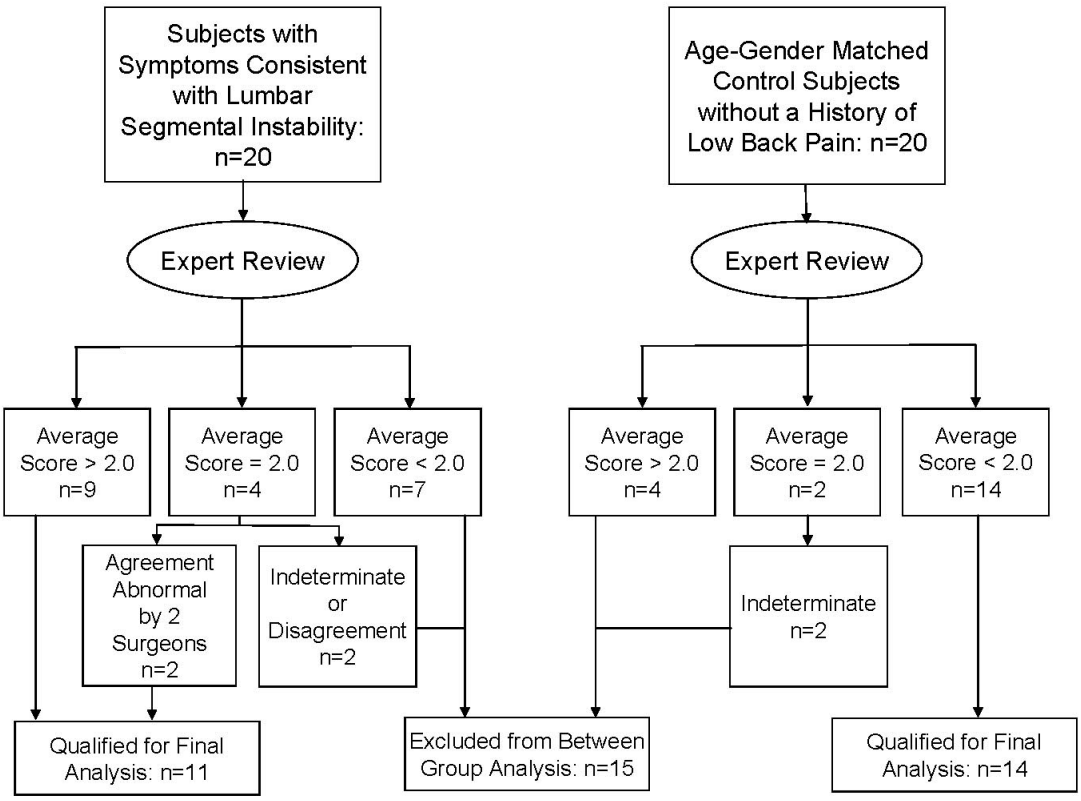
	INST-F[†]	**CONTROL-F**[†]
Age (years)	36.5 ± 9.2 (24 - 52)	34.0 ± 8.3 (22 - 51)
BMI (kg/m^2)	26.8 ± 4.1 (18.6 - 32.4)	25.3 ± 3.3 (20.0 - 31.4)
Waist:Hip Ratio	0.846 ± 0.083 (0.715 - 0.970)	0.839 ± 0.047 (0.773 - 0.930)
Oswestry (0-100%)	26.7 + 13.4 (0 - 46)	0.4 + 1.0 (0 - 4) [‡]
FABQ (0-24)	16.9 ± 4.0 (11 - 24)	Not applicable

* Values are mean ± standard deviation, with range shown in parentheses.

[†] Eleven subjects in the CONTROL-F group (10 Men, 4 Women), fourteen subjects in the INST-F group (7 Men, 4 Women).

[‡] One control volunteer scored 2%, each getting a score of one for the sleep related question; one volunteer scored 4%, scoring one for both prolong sitting and standing.

Figure 3.1: Determination of Final Group Membership



Human Subject Protection

Both research protocols were approved by the Institutional Review Board at the University of Texas in Austin and at Brooke Army Medical Center (BAMC). A radiation safety review was conducted by the radiation health physicist at BAMC. All volunteers were informed about the study (Appendix B), signed informed consent form (Appendix C), health insurance portability & accountability act (HIPAA) form (Appendix D), and all procedures were in accordance with the Declaration of Helsinki.

During the research study the principles of ALARA (as low as reasonably achievable) were followed to minimize radiation while obtaining the required image

quality. The average radiation dose for those in the descriptive and comparison studies was estimated to be 50 millirems. The health risk associated with 50 millirems is extremely small and was calculated by the health physicist to be similar to contracting a fatal lung cancer from smoking only 30 cigarettes.

STUDY DESIGN

This series of studies was exploratory in nature in which DFV were being utilized to measure segmental kinematics of the lumbar spine. The movements analyzed in this study were flexion and extension. Flexion was defined as the bending forward from an upright posture. Extension was defined as the return to the upright posture. Hyperextension, bending backward from the upright posture, was not assessed.

The first set of studies addressed the reliability of this new measurement technique measuring both intra- and inter-image reliability and response stability. The second set of studies was designed to qualitatively and quantitatively describe and compare the movement patterns both between and across group membership. Subjects in these studies were compared both on their symptom status (CONTROL-I and INST-I) and on a motion-based classification (CONTROL-F and INST-F) that was determined by three expert reviewers who were blind to group membership. The final set of studies used the variables in the second set of studies that were determined either to be significant ($p < .05$) or to have a possible trend towards significance ($p < .20$) to determine the benefit of these arthrokinematic variables in distinguishing group membership.

INSTRUMENTATION

The DFV were collected with a Philips Radiographic/Fluoroscopy Diagnost 76 system (Philips Medical Systems, Andover, MA; Illustration 3.1) in its upright position.

Prior researchers have found a measurement error using similar techniques of approximately 1° of rotation error[55] and between 0.6-0.7 mm of positioning error,[55,66] with a distortion of approximately 1% at the margins of the images.[55]

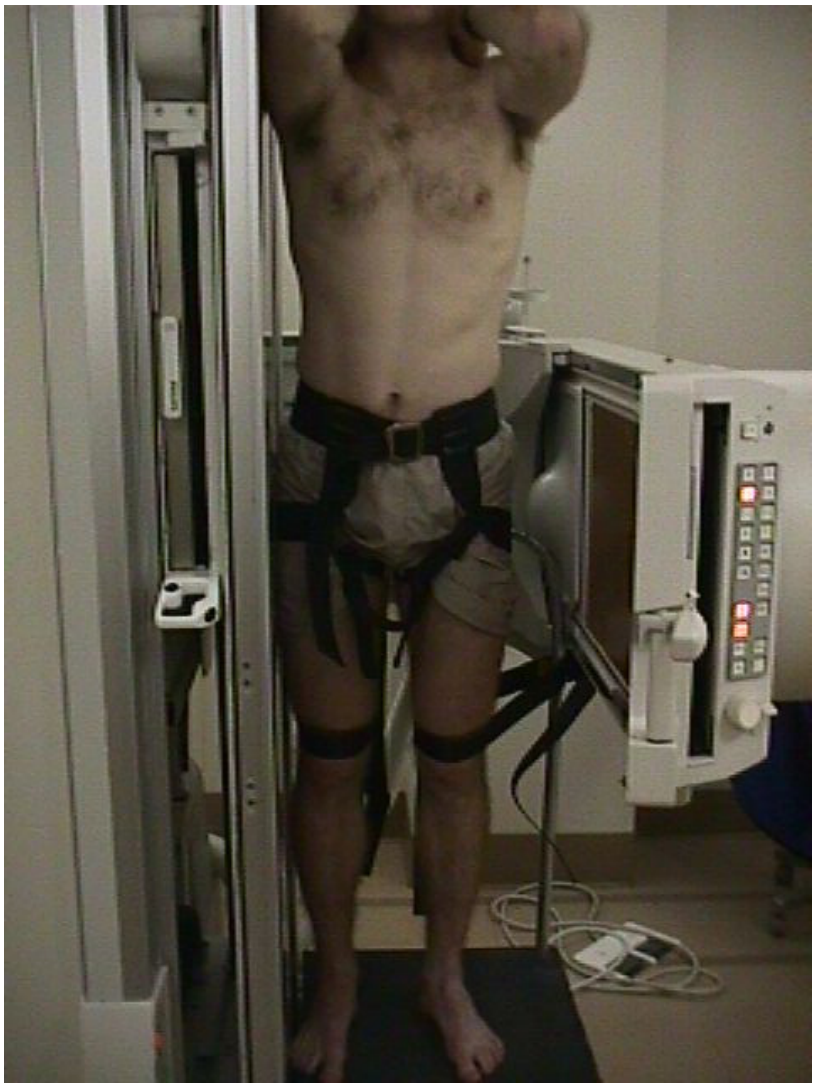
The images were digitized by an I-75 frame grabber (Foresight Imaging, Lowell, MA)[1] that was reported to capture the images at 8 bits per pixel with $\pm$ 1.0 ns pixel jitter.[1] The I-75 frame grabber has a reported pixel rate of 75 MHz and captured the DFV at 30 frames per second.[1] The synchronization time for the frame grabber has been determined to be less than 250μs.[1] The images were stored and processed on a personal computer. Image Pro-Plus (MediaCybernetics, Silver Springs, MD),[24] MATLAB (The Math Works, Natick, MA),[85] Microsoft Excel (Microsoft Computer Corporation, Redmond, WA), and SPSS 11.0 (SPSS Inc. Chicago, IL)[141] were used for analysis.

The ODI (Appendix E) was the condition-specific outcome measurement used both as a screening tool for the control group and to assess the current level of disability associated with the instability group. The reported correlation of repeated testing of the ODI over a 24 hour period was $r = 0.99$ ($n = 22$).[37] Cronbach's alpha ranged from 0.71 to 0.87[37] in three different studies, demonstrating an acceptable degree of internal consistency.

During the pilot study, the non-constrained individuals were observed to move outside of the visual field during movement. Therefore, each subject was placed in a device designed to minimize knee and hip movement, while allowing true lumbar movement (Illustration 3.2). Specifically, subjects were placed in a rock-climbing harness and then secured to a metal railing with belts at the pelvic and knee regions. The belts secured around each knee and the railing were to minimize knee flexion. Two other belts were secured from the back of the rock-climbing harness to the metal railing to minimize pelvic and hip flexion. This device was designed to limit motion while

Illustration 3.1: Philips Radiographic/Fluoroscopy Diagnost 76 (Philips Medical Systems, Andover, MA) system in its upright position

Illustration 3.2: Stabilization Device:



Legend for Illustration 3.2:

This illustration demonstrates a subject in the upright posture in the stabilizing device. The stabilizing device consists of a rock-climbing harness with four nylon straps. Two straps are placed through the rock-climbing harness to the metal railing posterior to the subject to minimize hip and pelvic movement. The two straps around the knee are to prevent knee flexion.

optimizing comfort. Similar devices have been used in previous motion analysis studies of the spine.[106]

PROCEDURES

After potential subjects were screened for appropriateness, DFV were obtained during one test session that lasted approximately 60 minutes. The test procedures described below were consistent across both studies. An overview of the test procedures is provided in Table 3.6.

Pre-DFV Assessment

Patients being cared for by one of the participating physical therapists that met the entrance criteria were given the option to volunteer for the study. The participating therapists performed the required physical examination and had the subjects complete the required screening forms. Potential control subjects were screened telephonically prior to participation to ensure they met the entrance criteria. Women participating in the study who were not post-menopausal were screened for pregnancy by a blood test completed by the BAMC laboratory. All potential subjects wore loose fitting gym clothes and females wore a sports bra to expose the lower trunk area during the test. All subjects were given a list of food to avoid prior to the test to minimize abdominal gas which would interfere with the DFV image and the digitization process.

Upon arrival for the test, all subjects were oriented to the test procedures; entrance criteria were assessed, and subjects provided informed consent. Examples of all screening forms are provided in Appendix E. All subjects walked for five minutes, at a comfortable pace, for a general body warm-up prior to data collection.

Table 3.6: Test Administration

Outline	Procedures
Pre-Test Administration	-Potential subjects were screened for inclusion/exclusion criteria -Potential subjects were informed to wear loose fitting gym clothes -Female potential subjects were informed to wear a sports bra -Female potential subjects underwent a pregnancy test prior to test administration
Orientation	-Questionnaires -Inclusion and exclusion criteria -Informed consent
Pre-Image Collection	-5 minutes of walking -Subject removed shirt (females wore sports bras) -Placed in lower extremity stabilizing device -Calibration image -Instruction of movement pattern -Two practice trials
Image Collection	-Subjects performed a total of 4 movements, the 3rd movement was captured for analysis -Two minute rest and two minutes of walking -Replaced in stabilizing device -Second image captured

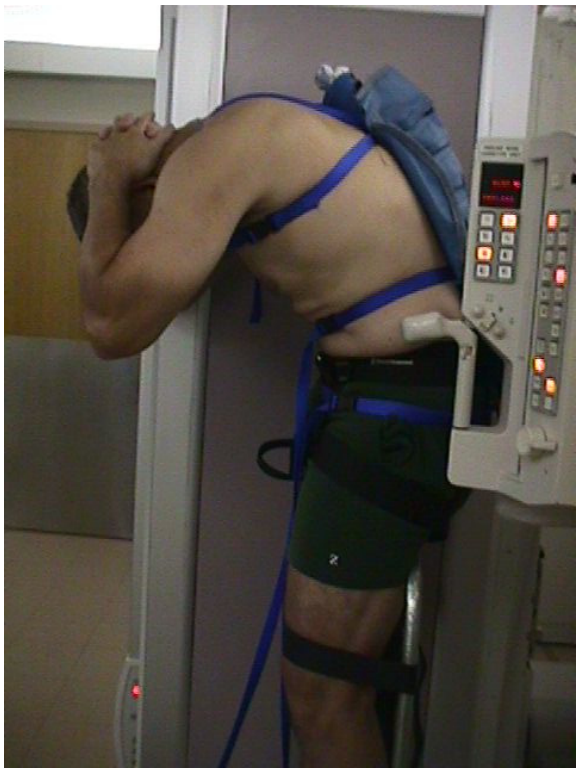
DFV Assessment

Lateral view DFV were obtained at 30 Hz. Proper positioning was essential to minimize out-of-plane motion. First, subjects were placed in the lower extremity stabilizing device (Illustration 3.2) that was designed to limit ankle, knee, hip, pelvic, and out-of-plane motion, while allowing true lumbar motion. Further, patients were positioned with the right side of their body next to the upright table; to minimize out-of-plane motion and to allow enough space so that each subject could perform the test motion without being compromised by the lip of the machine attached to the image intensifier on the left side of the subject.

Calibration images were obtained to ensure that the L3-S1 region was maintained within the FOV during the test movement, to calibrate the pixel width, and to adjust the

kilovolts peak (kVp) to optimize image quality. During two images, a radioopaque ruler was attached both to the subject's side closest to the image intensifier and attached to the upright table on the far side of the subject. The average pixel per millimeter value from these two planes was used to calibrate the DFV for the plane of the spine. During the calibration images the kVp was set to optimize image quality throughout the ROM. A lead harness (Illustration 3.3) was placed on the back of each subject to prevent "white-out" of the image. The lead harness was required because the system automatically adjusted the current based on tissue depth in the FOV, which decreased during flexion and resulted in "white-out" if the lead harness was not present.

Illustration 3.3: Lead-Apron



Legend for Illustration 3.3: The lead apron worn on the back of this subject prevents the image from "white-out" as the system automatically adjusts the current (milliampere) based on the thickness of the tissue in the FOV.

Prior to dynamic DFV assessment, the subjects were instructed in the sagittal plane flexion and extension. Sagittal plane motion was selected not only because it is a movement associated with symptoms in those with LSI, but sagittal plane motion has greater ROM and is associated with only minimal out-of-plane motion as compared to frontal plane motion.[56,96,118] Out-of-plane motion was also minimized by the layout of the DFV system, with an upright table on the subjects right side (Illustration 3.1 and 3.2). Subjects started in an upright posture, with the hands behind the head and the elbows pointing up towards the ceiling. The flexion and extension motion consisted of the subject slowly bending forward in the sagittal plane and returning to upright in approximately 4-5 seconds. Hyperextension (extension beyond the upright posture) was not tested in this study. The motion was required to be slow in nature because of the blurring that would occur with faster movements based on the imaging system.[22] The subjects were given practice trials to ensure they understood the test movement.

Immediately after the practice trials, the subjects performed four cycles of flexion and extension, with the third cycle being captured by the fluoroscopic system. This was done to ensure dynamic motion was captured throughout a full cycle. The subjects were then removed from the stabilizing device and rested for two minutes followed by two minutes of walking. Following the break, the subjects were repositioned in the stabilizing device, and were re-imaged as described previously. These test procedures are similar to those used by Okawa et al,[106]Harada et al,[55] and Takayanagi et al.[144]

DFV ANALYSIS

DFV analysis consisted of three separate steps: image processing, vertebral body detection, and kinematic analysis. During the image processing step the vertebral bodies of the DFV were enhanced so that the edges became more defined. Data extraction consisted of the techniques used to determine the corner locations of the vertebral bodies.

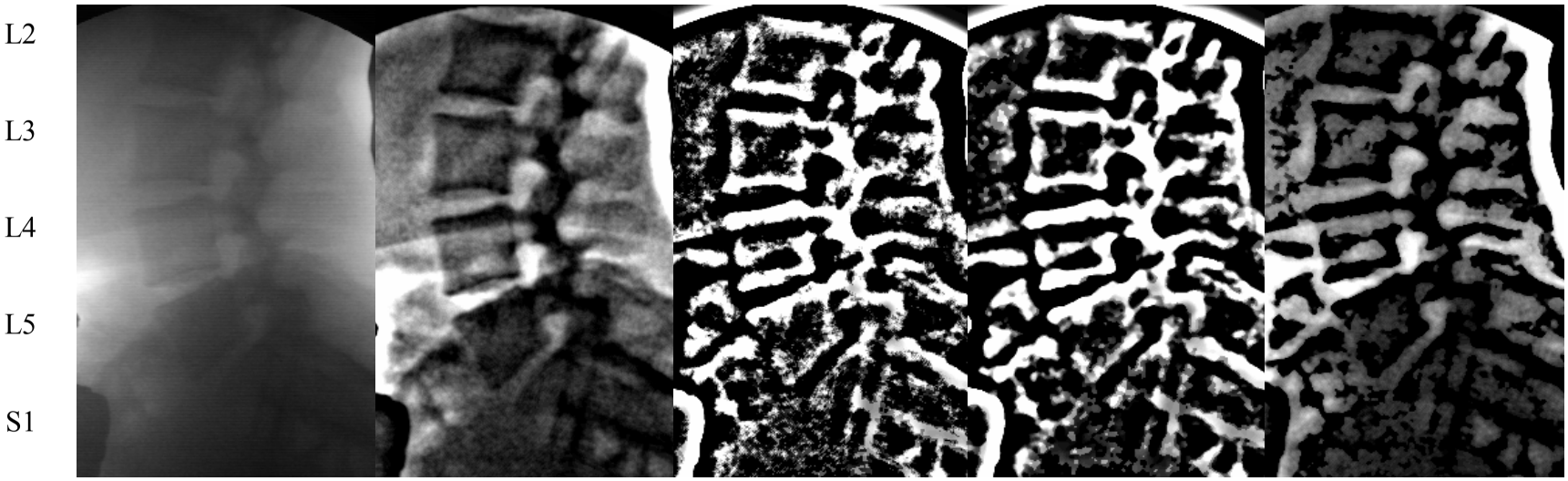
The third step involved kinematic analysis of the motion. This step describes the techniques used to determine global and segmental motion during the test movement. Both Image Pro-Plus (MediaCybernetics, Version 4.5, Carlsbad, CA)[24] and MATLAB (MathWorks, Student Version release 12, Natick, MA)[85] software packages were used to process the images.

Image Processing

The original DFV (Illustration 3.4A) were processed with a combination of four image processing techniques to enhance the borders of the vertebral bodies from the surrounding soft tissue. First, a large aperture band-pass filter was applied to the DFV (Illustration 3.4B) to remove high frequency noise, enhancing image sharpness and contrast while also enhancing the edges of the vertebral bodies. Specifically, a 5 x 5 window was applied for the low-pass portion of the filter, followed by a 71 x 71 window for the high-pass portion of the filter. The spectrum of the band-pass filter has been provided in Illustration 3.5A. During pilot testing of the DFV with two orthopaedic spine surgeons, the results of this filter allowed them to visualize the DFV better than the original and the completely processed DFV (Illustration 3.4E) and therefore these images were used for the surgeon review of the DFV in this study.

Next a large aperture (50 x 50 window) edge detection filter was applied to the DFV (Illustration 3.4C). This filter was designed to enhance the dark features of an image (the vertebral bodies) on a brighter background. The spectrum of the filter has been provided in Illustration 3.5B. A median filter (7 x 7 window) was then applied to the DFV (Illustration 3.4D) to decrease impulse noise, which effectively enhanced the edges of the vertebral bodies for the algorithm that computed the location of the vertebral corners. Finally, the results of the median filtered DFV were subtracted from the results

Illustration 3.4: Image Processing Steps



Legend for Illustration 3.4:

A: The original unprocessed DFV image

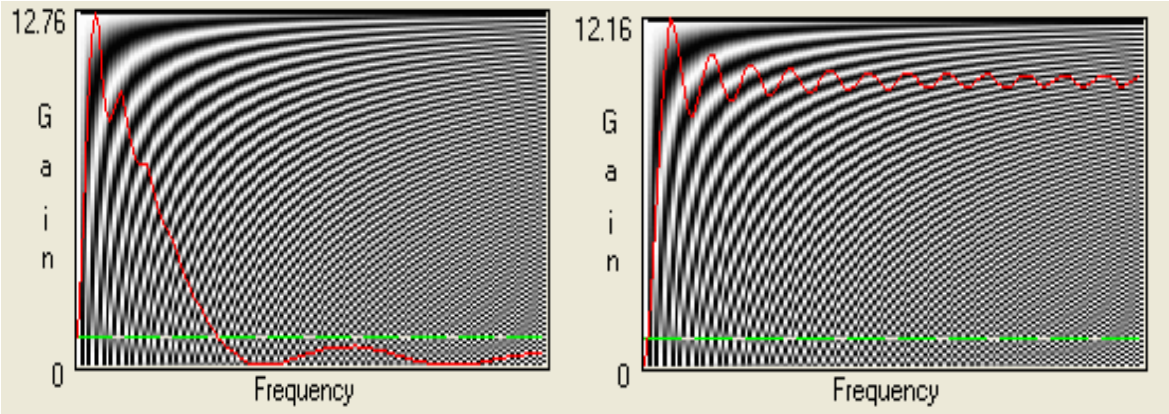
B: Band-passed DFV image

C: Edge- DFV image

D: Median filter DFV image

E: Subtraction (B-D) DFV image

Illustration 3.5: Spectrum Graphs for Band-Pass and Edge- Filters:[24]



A B

Legend for Illustration 3.5:

A: Spectrum graph for band-pass filter (high-size: 71, low-size: 5, strength: 10, pass: 2). An increase to the high-size increased the height of the main lobe (red line). A decrease to the low-size filter size decreased the width of the main lobe. A strength of 10 results in the center pixel being replaced by 100% of the result of the filter. By increasing the pass from 1 to 2 the sidelobes decreased below the green line.

B: Spectrum graph for the Edge- filter (size: 50, strength: 10, pass: 1).

of the band-passed DFV to create a DFV in which most of the edges of the vertebral body appeared as black, while the background area around the vertebral corners were displayed as shades of white to black (Illustration 3.4E). The techniques described were robust and resulted in improved image quality for all subjects regardless of stature and without adjustment across subjects.

Other image processing techniques were attempted prior to the technique described above. To determine the optimal image processing technique a point

placement study was conducted on the five different image processing techniques. It consisted of the selection of ten vertebral corner locations on five different frames, representing different angles of lumbar flexion; each measured five times (250 points per image processing technique). The average difference from mean pixel location for the technique described above was 1.86 $\pm$ 1.63 pixels, while the other four techniques error ranged from 2.28 $\pm$ 1.19 to 2.60 $\pm$ 1.27 pixels. Therefore, the technique described resulted in the least amount of variability in corner selection by the rater.

Vertebral Body Position and Orientation Detection

After the DFV were processed, the next step was to locate the vertebral corners and midpoints. The technique used was based on the work of Frobin et al[45,46] and Brinckmann et al[16,17] in which a combination of manual point placement and computerized algorithms were used to determine the vertebral corner and midpoint locations. The use of midpoint locations to determine kinematic variables was also suggested by Muggleton and Allen[96] and by Harvey et al[56] to minimize the effects of distortion, orientation, out-of-plane motions, and point placement errors.

Vertebral corner locations (numbered 1 to 4) were first estimated by the researcher (Figure 3.2A). After the vertebral corner positions were estimated the anterior and posterior vertebral body midpoint locations were determined (Figure 3.2A). Then the vertebral body midpoint (M) and a 60% posteriorly displaced midpoint (M') locations were calculated (Figure 3.2A) as per the protocol from Frobin et al.[45]

A maximum distance formula was used to determine the objective vertebral corner locations based on the appropriate midpoint location (Figure 3.2A) as described by Brinckmann et al.[16] Specifically, the locations of the objective vertebral corners for L3-L5 were determined based on finding the lowest gray-scale (blackish) value furthest away from the appropriate midpoint location based on a 7x7 pixel width window placed

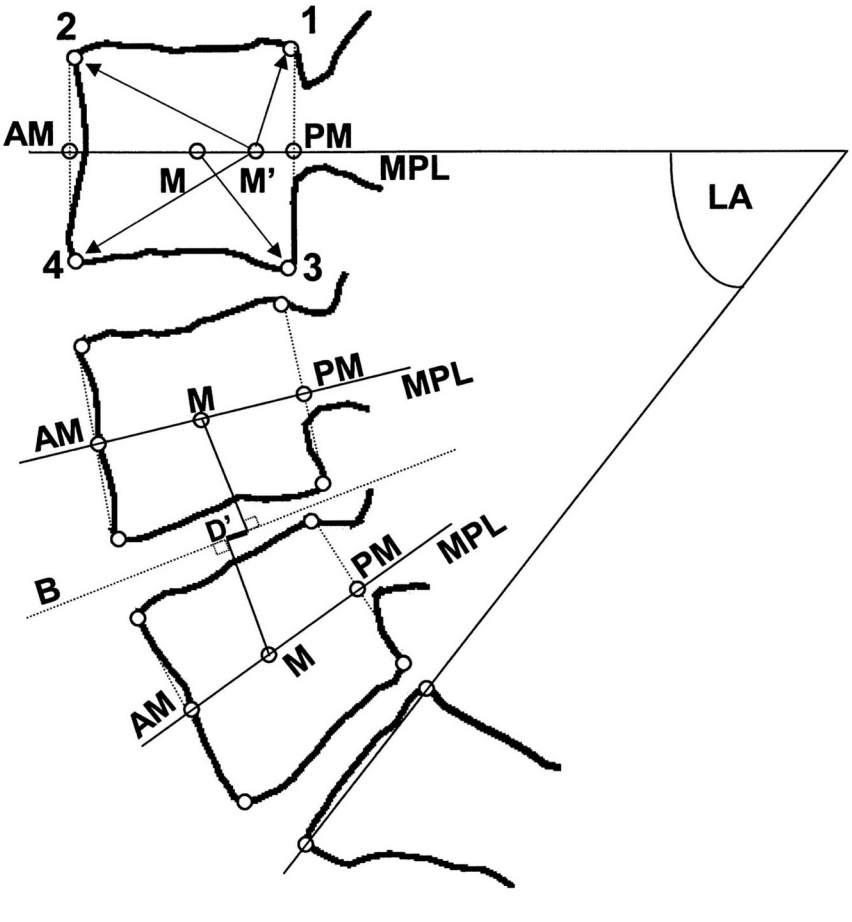
centrally at the current estimated corner location. Three iterations of the computer-algorithm were processed to determine the best estimates of the vertebral corner and midpoint locations. The use of four iterations (one from the researcher and three computer assisted) of the vertebral corner selection process was in agreement with the work by Cholewicki et al[22] to minimize error. The location of first sacral body was determined by it's cephalad corners, the midpoint of that line was determined, and the maximal distance algorithm was applied as described above. Once the four estimates of the vertebral corner and midpoint locations were calculated they were averaged to determine the final locations for that video frame.

Unlike the protocol described by Frobin et al[45,46] and Brinckmann et al[16,17] in which the hand-drawn outlines of the vertebral bodies were digitized, these DFV had adjacent bone and soft tissue that would sometimes interfere with the vertebral corner location algorithm. Therefore, the goal of this algorithm was to ensure a big enough window size to search for the best estimate of the vertebral corner locations, while minimizing the chance of adjacent tissue being labeled inappropriately. Three window sizes were tested: 5 x 5, 7 x 7 and 9 x 9, which would allow the corner locations to vary by 6, 9, and 12 pixels (there were approximately 4 pixels per millimeter), respectively, through the algorithm iterations. The initial window size (5 x 5) was chosen as a starting point based on the point placement error study described previously. A pilot study of 3,836 vertebral corner points found that only 1.3% (14/1096) and 0.5% (5/1096) of the midpoint locations changed when the window sized was increased from 5 x 5 to 7 x 7, and 7 x 7 to 9 x 9, respectively. Therefore, a 7 x 7 window was determined to allow for exploration of the best-estimate of a vertebral corner location, while minimizing the opportunity of adjacent soft-tissue influencing the determination of vertebral corner position.

Once the "best-estimates" of the vertebral corners and midpoints locations were obtained for each frame of the DFV, the estimates were smoothed across the frames to minimize the effect of small contour irregularities and variations in the digital image of a vertebral body during the motion pattern, and to minimize the effects of the image processing technique on the vertebral body contours. This was accomplished by a 4th order Butterworth filter with a 1.5 Hz cut-off frequency. The effects of the 0.75, 1.0 and 1.5 Hz cut-off frequencies are displayed in Figure 3.3. Note that the 1.5 Hz frequency allowed for the "double-hump" movement observed in the original L3 midpoint location graph to be maintained and hence was chosen as the cut-off frequency. These final midpoint locations of each vertebral body and the anterior and posterior vertebral body midpoint locations were used to determine the kinematic variables described in the next section titled "Kinematic Analysis".

Although this protocol was based on the work of Frobin et al[45,46] and Brinckmann et al,[16,17] there are some distinct differences. First, the image processing technique described above allows for the algorithm to be applied directly to the DFV, while Frobin et al[45,46] and Brinckmann et al[16,17] relied on digitization of manual drawings of the vertebral body outlines. A second difference was the detection of the first sacral body (S1) position and orientation. This technique only determined the cephalad border of the sacrum, because it was not possible to visualize routinely the caudal border of the first sacral body with DFV and so to minimize the subjective interpretation of this poorly seen border on DFV. Further, this adjustment allowed for the maximum distance formula to be applied to both cephalad corner locations of S1, unlike the original algorithm in which only one of the four corner locations was able to be processed through the algorithm described. Diagrammatic movies of final vertebral body and corner and midpoint

Figure 3.2: Vertebral Body Detection and Kinematic Analysis Based on the Work by Frobin et al[46] and Saraste et al[133]



3.2A

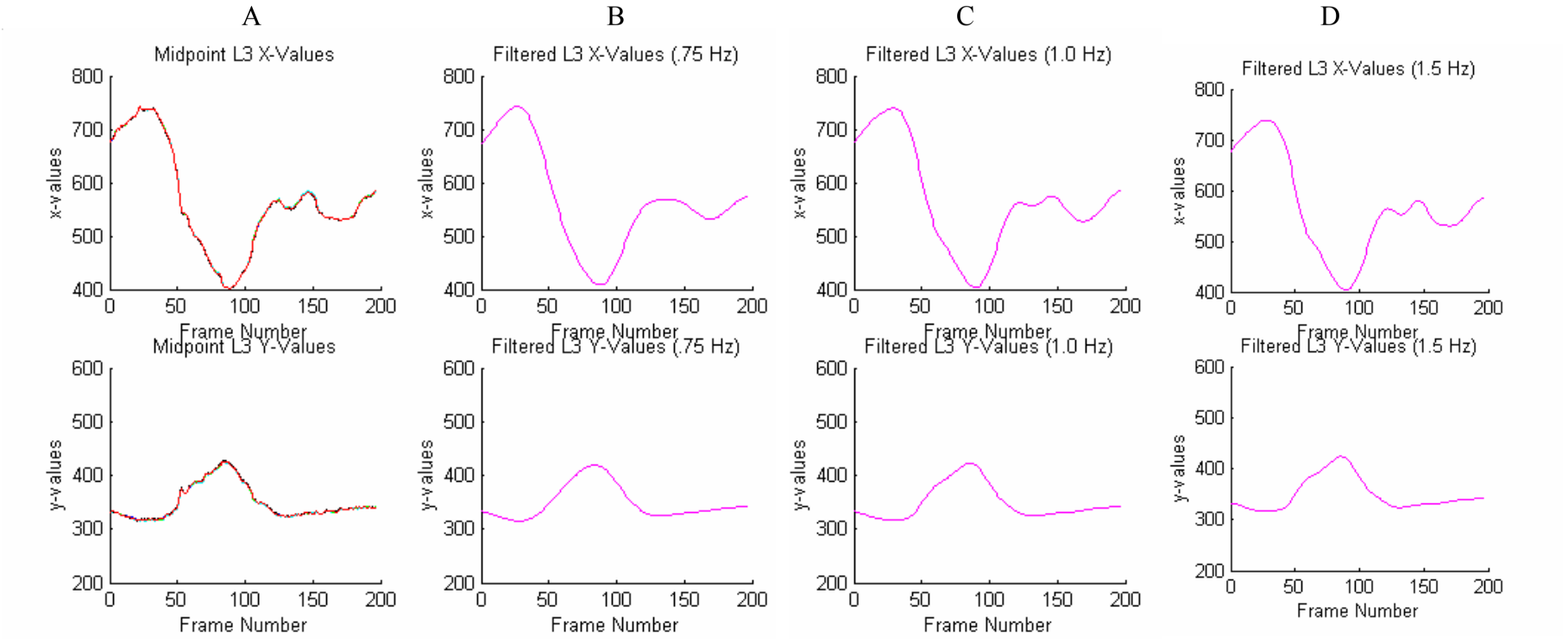
3.2B

Legend for Figure 3.2:

3.2A: The locations of the vertebral corners (numbered 1-4) are demonstrated on L3 vertebral body. The anterior (AM), posterior (PM), and vertebral body (M & M') midpoint locations are also demonstrated. The algorithm to find the vertebral corner locations was based on the maximum distance from the appropriate midpoint location, as demonstrated by the arrows.

3.2B: The intervertebral angle was defined as the angle between adjacent midplane lines (MPL). As demonstrated between L4-L5, the first step to measure intervertebral displacement was to find the difference (D') between the perpendicular projections of the vertebral body center points to the bisectrix (B). Displacement was then determined by dividing (D') by the mean depth of the cephalad vertebral body. L3-S1 lordosis angle (LA) was defined as the angle between the MPL of L3 and the cephalad border of S1.

Figure 3.3: Examples of 4th Order Butterworth Filters:



Legend for Figure 3.3:

Demonstration of the effects of different cut-off frequencies (B: 0.75, C: 1.0, D: 1.5 Hz) on the original data (A). Note the filter with a 1.5 Hz cut-off frequency best maintains the "double-hump" appearance in the L3 X-values during extension.

locations were created as a quality control measure to ensure that the final data points resembled the vertebral movement observed on the DFV.

Kinematic Analysis

Based on the location and orientation of the anterior, posterior, and vertebral body midpoints, global and segmental motion were determined. The global angle of L3-S1 lordosis was determined based on the review by Saraste et al[133] (Figure 3.2). Lordosis (L3-S1) was determined as the angle between the midplane line of L3 and the cephalad border of S1. Upright posture at the start and end of motion was defined as a local maximum of the lordosis angle at the start of flexion and upon the return to upright. Then the point that represented the end of flexion and the start of extension was defined as a local minimum of the lordosis angle at the center of the period between flexion and extension.

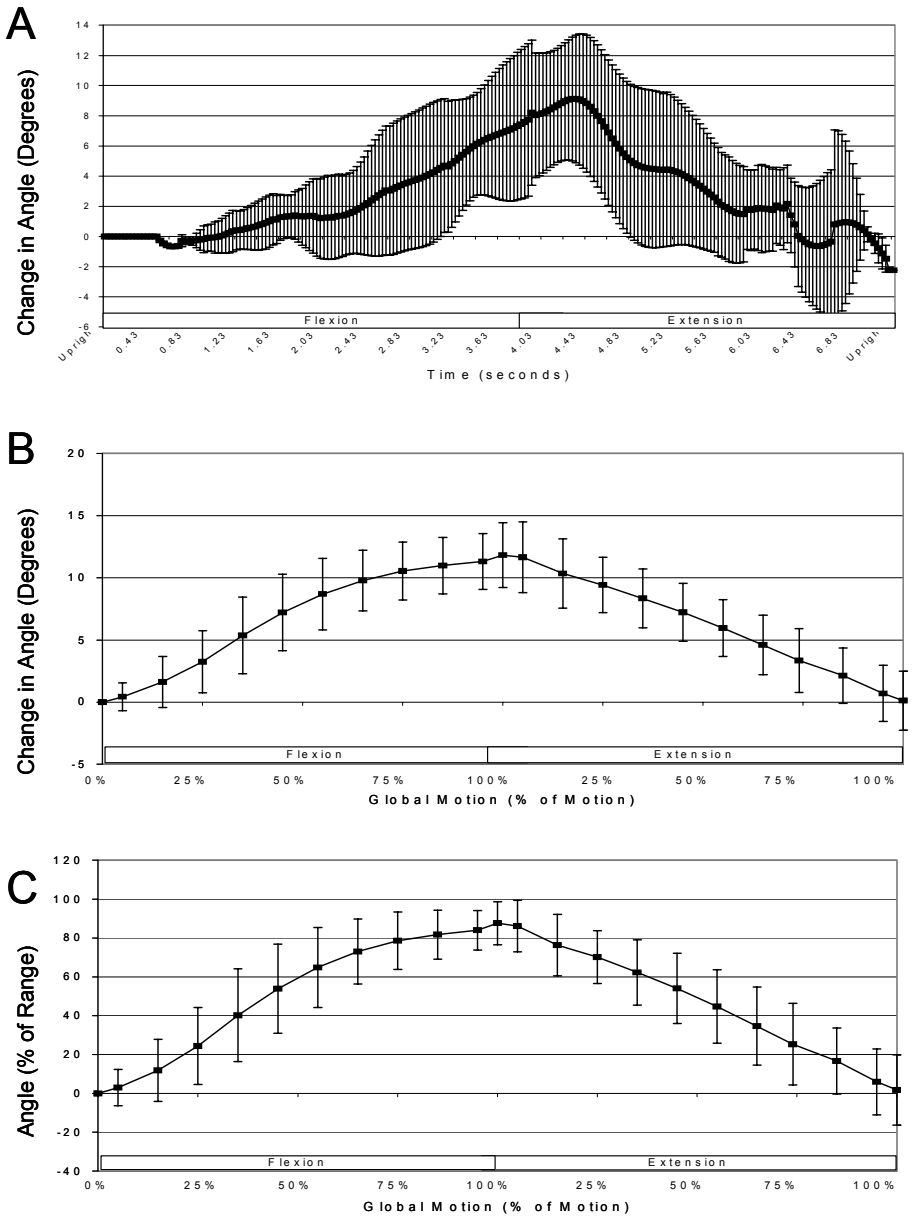
Intersegmental motion (angle and displacement) was calculated as described by Frobin et al.[46] The intersegmental angle was determined as the angle between the two adjacent midplane lines (Figure 3.2B). The midplane lines were formed based on the anterior and posterior midpoint locations of each vertebral body. Intersegmental displacement was determined as the distance between the perpendicular projections of adjacent vertebral body center points to the bisectrix between adjacent vertebral bodies. This value was divided by the mean depth of the cephalad vertebral body to normalize the results and to compensate for distortion (Figure 3.2B). Anterior (positive) migration occurred if the cephalad vertebral body's projection to the bisectrix was anterior to the caudal vertebral body's projection. Posterior (negative) displacement was defined when the reverse occurred. Measurement of displacement by a bisectrix and the division by the mean depth of the cephalad vertebral body were in agreement with the measurement technique ideals outlined by Muggleton and Allen[96] to have a symmetrical measurement

of displacement that is compensated for distortion in the FOV. Translational speed was determined based on the time derivative of the displacement data.

Further, it was theorized that the segment level in which instability was present would vary among subjects with different pathology. Therefore, a ratio (an "instability ratio") of the dependent measures described above required standardizing the measurement across subjects. The instability ratio defined for this study was the maximal range of a single segment divided by the mean of all segmental ranges. This allowed for a higher "instability index" for those with one hypermobile segment compared to the mean, and a lower "instability index" for those with equivalent motion among all three segments. This "instability ratio" was calculated for angle, displacement, and translational speed. In addition to the instability ratios described above, the more traditional measurements of segmental range, mean, minima and maxima were also calculated to describe the motion pattern. Further, total displacement and angular range values across the segments were calculated to determine the percent of motion occurring at each segmental level.

Timing of the vertebral movement pattern was based on the work by Kanayama et al.[65] To measure the rate of attainment of angle and displacement data, the change in the kinematic variable from the upright posture in the direction of flexion was standardized based on the global L3-S1 lordosis angle instead of the time domain (Figure 3.4A to B). The global motion was standardized for each subject by first selecting the upright, flexed, and returned to upright postures to represent the start of motion, the end of flexion, and the end of the return to upright motion. From these anchor points, the motion was divided into 10% increments, with the average of upright to 10% of global flexion represented by the 5% marker, and the average from the 10-20% of global flexion represented by the 15% marker, etc (Figure 3.4B). To control for variation in segmental

Figure 3.4: 3.4A: An example of the angle or displacement trajectory as a change from the upright posture (°) in the direction of flexion with respect to time (s). 3.4B: Then the angle or displacement trajectory was plotted as a change from the upright posture (°) in the direction of flexion as a function of the percent of global angular motion (L3-S1 lordosis). 3.4C: The trajectory was then normalized by dividing the trajectory by its range value (%) and plotted as a function of the percent of global angular motion.



range, each variable was divided by its segmental range (Figure 3.4C); resulting in a range of 100% of motion for each segment. The slope between successive markers was determined to represent the rate of attainment of angle or displacement range (%) as a function of global motion (%).

Reliability Analysis

Both intra-image and inter-image intra-rater reliability were analyzed. Intra-image reliability was tested to analyze the reliability of the point-placement technique and the computer algorithm. Still images of 20 subjects were analyzed in the upright and flexed postures (40 single images). The average of three measurements represented a single trial. This analysis resulted in a total of 240 analyzed images, or a total of 3,360 individually placed points. The subject order was randomized by a second party and the randomized order varied between each measurement trial. By analyzing alternating upright and flexed images, recall bias on the vertebral corner point placement locations was minimized.

The use of only the upright and flexed images, instead of continuous data, required that the algorithm did not smooth the point placements with a low-pass filter, therefore the means of three separate point placements with the associated nine computer generated point placements were used to represent each image. The average intersegmental midplane angle and displacement values for each FSU (Figure 3.2B) and L3-S1 lordosis (Figure 3.2) were calculated in each posture.

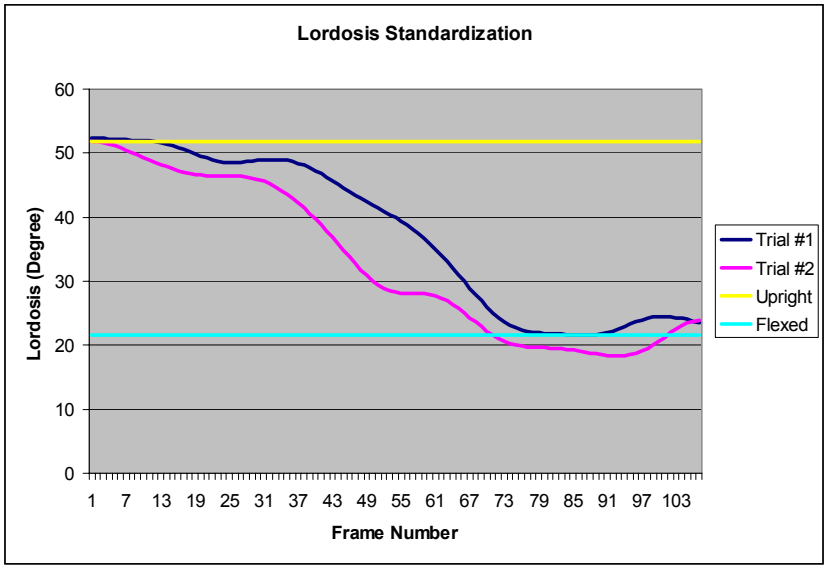
The inter-image reliability study was designed to assess the reliability of images obtained on two separate movement trials. As previously described in the "DFV Assessment" section; the DFV were separated by a two-minute rest and two-minute walk break. This would allow the assessment of the increased error that was expected secondary to both variation of human movement between trials and the error associated

with repositioning of the subject in the FOV. However, this design was selected to minimize threats to internal validity (history and maturation) associated with repeated measures on separate occasions by having the subject tested on the same day. Additionally, the measurement of the first and second movement trials by the rater were separated by a minimum of two months between analyses to minimize rater bias.

The DFV were analyzed from the upright position through the end-range flexion. The average time required for this motion was 2.27 $\pm$ .67 seconds, resulting in an average of 68 $\pm$ 20 frames per motion sequence, or 952 $\pm$ 280 point placements per motion sequence; for a total of 2,739 frames or 38,346 point placements.

To assess the intersegmental motion based on a common global motion pattern, each set of DFV images for a subject was standardized to a common lordosis angle for both the upright and flexed postures (Figure 3.5). The standardized upright posture was the minimum lordotic angle of agreement in the upright postures, while the standardized flexed posture was the maximum lordotic angle of agreement in the flexed postures.

Figure 3.5: Example of how the lordotic range was standardized. The yellow and light blue lines indicate the upper and lower limits of the common lordotic range between both trials of motion.



Qualitative DFV Analysis

Diagnosis of musculoskeletal complaints traditionally has been determined based on a combination of subjective complaints, physical examination findings, and radiological assessments. To ensure homogenous groups for comparison, the DFV were qualitatively analyzed by three expert reviewers. The three reviewers consisted of two orthopaedic spine surgeons (OS1, OS2) and one neurosurgeon spine specialist (NS). All reviewers received a training session that included background information of the study, a familiarization with the DCRA measurement technique, and examples of the DFV from the pilot study. The 40 DFV were randomly organized using a random number generator and a rule to ensure that no more than three subjects from one symptom-based group (control vs. instability) were presented in sequence. Further, the surgeons were blinded to subject history. The surgeons analyzed the static upright image and the DFV of all forty subjects and assessed for movement quality, stability of the spine, and the value of the DFV as an assessment tool (Appendix E). This information was analyzed not only to help describe the observed motion patterns, but also analyzed to assess whether the information provided was beneficial and different from traditional observations of static imaging.

DATA ANALYSIS

All statistical analyses were performed using MATLAB (MathWorks, Student Version release 12, Natick, MA),[85] SPSS (Version 12, Chicago, IL),[141] Confidence Interval Analysis, Version 2.0 (Trevor Bryant, University of Southampton, UK), and Microsoft Excel (Microsoft Computer Corporation, Redmond, WA). Descriptive statistics were performed on all dependent variables and demographic data.

Intra-Rater Reliability

An ICC, model (2, k), was calculated to determine a reliability coefficient. Model two was chosen because it was more conservative than model three, it was designed to allow greater generalizability than model three, and it acknowledges the role of the computer algorithm in determining the kinematic variables.[125] The kinematic variables were calculated based on averaged measurements; therefore the averaged version of the ICC was calculated (k). In the analysis of intra-image reliability, k = 12, because each image was a mean of three cycles of the algorithm, each representing the mean of four anatomical landmark locations. In the analysis of inter-image reliability, k = 4 to represent a single cycle of the algorithm for each movement analyzed. The standard error of the measurement (SEM) was calculated to determine the response stability of each measure.[125] In addition to the reliability measures calculated, the mean difference and the standard deviation of the point placements of the intra-image analysis were calculated to compare this alteration of the DCRA technique with the original protocol.[46]

Expert Review Analysis

Frequency and agreement statistics were performed to assess the qualitative analysis of the DFV (qualitative assessment tool is provided in Appendix E). For the two questions with a five-point ordinal scale, percent agreement was calculated using both a three-reviewer and two-reviewer criteria. Agreement among the three reviewers required that all scores were on one side of the indeterminate choice (indeterminate value =2), one score of indeterminate among the three reviewers was permissible (i.e. raw scores of 0, 1, 2 or 2, 3, 4 would be considered in agreement). When there was not agreement among the three reviewers, agreement among two reviewers was determined. Two-rater agreement required that both scores were on either side of the indeterminate value and that neither of the two scores was the indeterminate value (i.e. raw scores of 0 and 1 or 3

and 4 would be considered in agreement). Percent agreement in the other questions was based on the number of reviewers who selected the exact same response. To compare the definitions used among the three reviewers for determination of global motion patterns and global stability patterns both frequency counts and Pearson product-moment coefficient of correlations were calculated.

Within-Subject Analysis

To describe segmental level differences in angular range, displacement range (L3-4, L4-5, and L5-S1) and translational speed (L3, L4, L5, and S1) an ANOVA was calculated. To describe the rate of attainment of angular and displacement range, for the segmental levels (L3-4, L4-5, and L5-S1) across the motion pattern (0-25%, 25-55%, 55-75%, and 75-100%) a 3×4 ANOVA was calculated for both flexion and extension. Post-hoc independent t-tests with a Bonferroni correction were used to determine significant paired differences from a significant interaction or main effect. The Bonferroni procedure controls the overall family-wise α-level to .05, therefore the probability of committing a Type-I error was no greater than .05 for any single comparison.[124] A significant interaction between a main or an interaction effect by group membership resulted in the post-hoc analysis being performed on each group separately. If a group interaction did not occur, the post-hoc analysis was completed on the entire sample. This was exploratory research, thus qualitative graphical analyses of kinematic data were performed to describe further the observed motion variables and to determine possible trends in the data.

Between-Group Analysis

To describe the movement pattern, descriptive statistics were calculated on all dependent measures based on group membership. Independent t-tests were performed on

all of the angle and displacement descriptive variables (mean, maxima, minima, range, and the instability ratio) for both flexion and extension, on each segmental level (L3-4, L4-5, and L5-S1). Further, independent t-tests were performed on the rate of attainment of angle and displacement range during the initiation of flexion and the end of the return to upright posture for each segmental level (L3-4, L4-5, and L5-S1). These analyses were performed for both the symptom-based groups (CONTROL-I and INST-I) and the motion-based groups (CONTROL-F and INST-F) to detect differences between the groups. An α-level $<.05$ was required to be considered significant, and an α-level $< .20$ was required to be considered a possible trend. The liberal uncorrected values of the multiple independent t-tests were chosen to identify possible variables that could be used to distinguish group membership using the ROC curves, described below. Further, the exploratory nature of this study was designed to identify possible variables that should be used in future studies using this new technology, therefore the possibility of committing a Type II error was considered to be more significant than the possibility of committing a Type I error. All data were screened to insure they met the assumptions for inferential statistical analysis.

Distinguishing Group Membership

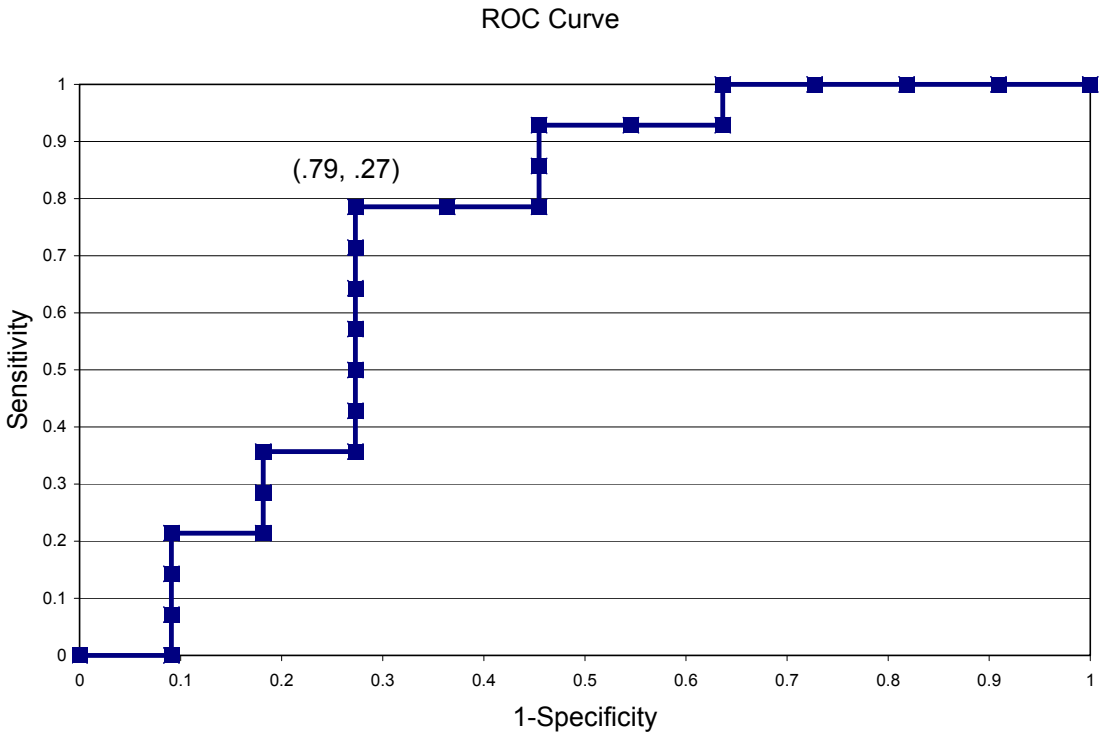
To determine if assessment of DFV was able to distinguish group membership a kinematic model was developed. The steps used to develop this model follow the procedures used to develop a CPR. First, kinematic variables with a $p < .20$ from the independent t-tests were considered as possible criteria for the model. Then, these variables were plotted individually on an ROC curve to determine if a cut-off value maximizing the distinction between control and clinical instability patients was possible. The cut-off value was determined by calculating Sn and Sp values for all possible cut-off points, then plotting the Sn and (1-Sp) values on a ROC curve (Figure 3.6).[125] The point

on the curve nearest the upper left-hand corner represents the value with the best diagnostic accuracy, and if present, this point was used as the cut-off defining a positive test.[30] If a cut-off value was present, this variable was considered as a potential discriminator between group membership.

The area under the ROC curve, which represents the probability of correctly identifying normal and abnormal responses,[125] was calculated for each variable. Then the average area under the curve was calculated for those variables that were deemed to be possible criteria for a model as a measure of the ability of the different 'gold-standards' for determining the condition status based on these sets of variables. The average area was calculated based on three different classifications of the study participants: 1) symptom-based groups, 2) motion-based groups, and 3) a grouping based on the qualitative analysis of the DFV by the surgeons regardless of initial group membership (those viewed as abnormal motion versus normal motion, regardless of initial group membership).

The Sn, Sp, +LR, and -LR were calculated for each variable that had an identifiable cut-off point on its ROC curve. Definitions of these terms are provided in Table 2.2. Variables with a +LR >2.0 were used to identify a cluster of these motion variables that were able to distinguish between group membership. Based on a 2 x 2 table (presence or absence of LSI versus dichotomized grouping based on a cluster of kinematic variables) the Sn, Sp, +LR, and –LR were calculated for each level of clustered variables. The 95% confidence interval for Sn and Sp were calculated using the Wilson's method.[4] For the +LR and –LR, the 95% confidence intervals were calculated using the score method.[4,101] This analysis was completed on both the symptom-based and motion-based groups to allow for an analysis of each reference criterion in distinguishing group membership.

Figure 3.6: Receiver operator characteristic (ROC) curve of a single kinematic variable. Each point represents a subject in the study. If the value in the upper left-hand corner is chosen for the cut-off value, this variable would have a sensitivity of 0.79 and 1- specificity of .27. The goal is to maximize sensitivity and minimize 1-specficity.



Chapter 4: Results

This chapter presents the results pertaining to the reliability analysis of the proposed measurement technique, kinematic analysis of the motion from the symptom-based group (INST-I & CONTROL-I), analysis of the qualitative review of the DFV by the expert reviewers, kinematic analysis of the motion from the motion-based group (INST-F & CONTROL-F), and the ability of the kinematic variables to distinguish group membership. The sections pertaining to the symptom and motion-based groups contain analyses describing the differences between the segmental levels during the motion pattern (within-group analysis) and differences in the kinematic variables between the instability and control groups.

RELIABILITY

Intra-Image Reliability

The analysis of the rater's point placement technique revealed a mean difference in the displacement ratio of the paired measurements across segments for displacement of 0.0005 ± 0.0148 ($0.05 \pm 1.48\%$), while the mean difference of the paired measurements across segments for midplane angle was $0.015 \pm 0.992°$. The intra-image reliability for intersegmental angle and displacement range, ICC (2, 12), were between 0.96 - 0.99 (Table 4.1). The SEM ranged from 0.4 to 0.7° and 0.57 to 0.89% displacement (0.2 to 0.3 mm based on a standard vertebral depth of 35 mm; Table 4.1).

Inter-Image Reliability

The average inter-image reliability, ICC (2, 4), for minimum and maximum intersegmental angle was 0.91 (range: 0.82 to 0.94) and displacement was 0.84 (range: 0.64 to 0.93; Table 4.2). The SEM ranged from 0.7 to 1.4° and 1.2 to 2.1% displacement

(0.4 to 0.7 mm based on a standard vertebral depth of 35 mm; Table 4.2). The average SEM across all segments was 1.0° and 0.6 mm (Table 4.2).

Table 4.1: Intra-image intraclass correlation coefficient (ICC) and standard error of the measurement (SEM)

Segment	ICC (2,12)	Standard Error of the Measurement*		95% CI* (+/- 2 SEM)
Midplane Angle Range (Degrees)				
L3-4	0.988	0.40°		0.81°
L4-5	0.966	0.72°		1.44°
L5-S1	0.993	0.58°		1.17°
Average	0.982	0.57°		1.14°
Intersegmental Displacement Range (Ratio Data)†				
L3-4	0.988	0.005711	0.20 mm	0.40 mm
L4-5	0.981	0.008983	0.31 mm	0.63 mm
L5-S1	0.989	0.007758	0.27 mm	0.54 mm
Average	0.986	0.007484	0.26 mm	0.52 mm

*Example for intersegmental displacement was based on a vertebral depth of 35 mm and was presented in millimeters (i.e. 0.005711 × 35 mm = 0.1999 mm)

Table 4.2: Inter-image intraclass correlation coefficient (ICC) and standard error of the measurement (SEM)

Segment	ICC (2,4)	Standard Error of the Measurement*		95% CI* (+/- 2 SEM)
Midplane Angle (Degrees)				
L3-4 Minimum	.944	0.68°		1.36°
L3-4 Maximum	.816	1.42°		2.85°
L4-5 Minimum	.934	0.97°		1.95°
L4-5 Maximum	.915	1.12°		2.24°
L5-S1 Minimum	.940	0.80°		1.61°
L5-S1 Maximum	.925	0.99°		1.99°
Average	.913	1.00°		2.00°
Intersegmental Displacement (Ratio Data)†				
L3-4 Minimum	.637	0.01717	0.60 mm	1.20 mm
L3-4 Maximum	.765	0.01667	0.58 mm	1.17 mm
L4-5 Minimum	.903	0.01352	0.47 mm	0.95 mm
L4-5 Maximum	.904	0.01248	0.44 mm	0.87 mm
L5-S1 Minimum	.933	0.01856	0.65 mm	1.30 mm
L5-S1 Maximum	.913	0.02088	0.73 mm	1.46 mm
Average	.842	0.01655	0.58 mm	1.16 mm

*****Example for intersegmental displacement was based on a vertebral depth of 35 mm and was presented in millimeters (i.e. 0.01717 × 35 mm = 0.6009 mm)

COMPARATIVE & DESCRIPTIVE STATISTICS FOR SYMPTOM-BASED GROUPS

Angular Range (Flexion and Extension)

Measurements of global angle (L3-S1 lordosis) and intersegmental angle (L3-4, L4-5, and L5-S1) were analyzed to describe and compare the angular kinematic patterns of these groups. Global angular motion, as measured by L3-S1 lordosis, was equivalent between the INST-I and CONTROL-I groups (Figure 4.1A). The range of global motion of each group was approximately 33 $\pm$ 6° ($p = .871$), with an upright L3-S1 lordosis of approximately 39-41° ($p = .532$) and a L3-S1 lordosis angle of approximately 6 - 7° ($p =$

.681) at end-range flexion (Table 4.3). Independent t-tests on segmental angular motion values (mean, minimum, maximum, range) were equivalent across groups (INST-I & CONTROL-I) for all segmental levels (Table 4.4, Figures 4.2-4.5). Greater variability during flexion can be noted at the L4-5 segment in the INST-I group (Figure 4.3A).

Table 4.3: Global motion: L3-S1 lordosis angle

Lordosis Angle (degrees)	CONTROL-I (n=20)	INST-I (n=20)	p-value
Minimum	6.81 $\pm$ 8.31	5.78 $\pm$ 7.45	.681
Maximum	40.51 $\pm$ 7.53	39.14 $\pm$ 6.09	.532
Range	33.70 $\pm$ 6.67	33.36 $\pm$ 6.11	.871

Segmental angular motion as a percent of total angular motion (from L3-4 to L5-S1) was analyzed using an ANOVA. A main effect for level (L3-4, L4-5, and L5-S1; $p < .001$) was determined, but there was not an interaction between level and group membership ($p = .812$). Mauchly's test of sphericity was significant; therefore a Greenhouse-Geisser correction was used. Post-hoc analysis with a Bonferroni correction revealed the percent of segmental angular motion was greater in the L3-4 and L4-5 segments compared to the L5-S1 segment ($p \leq .001$), regardless of group membership. There was no difference between the percent of angular motion at L3-4 and L4-5 ($p = 1.000$). Segments L3-4 and L4-5 each represent about 36% of the total motion, while segment L5-S1 represents 28% of the motion (Table 4.5, Figure 4.6).

Figure 4.1: 4.1A: Trajectory of the global L3-S1 lordosis angle (change from the upright posture in the direction of flexion) with respect to time. Maximal value for L3-S1 lordosis angle was plotted at 3.96 seconds for all subjects. 4.1B: Trajectory of the average change in L3-S1 lordosis angle with respect to percent of global motion. 4.1C: Trajectory of the normalized global angle (⁄Range*100) with respect to percentage of global motion.

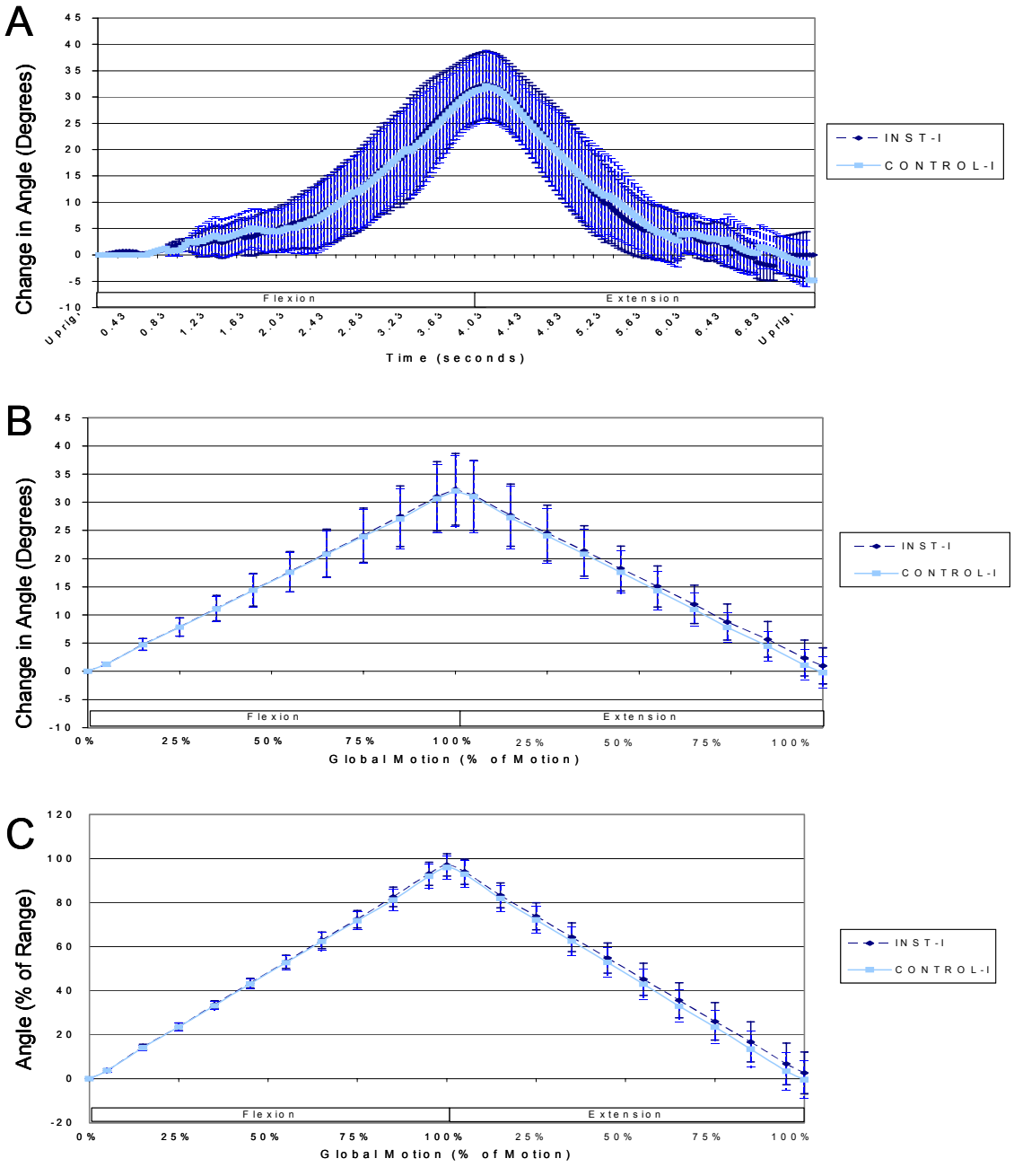


Table 4.4: Descriptive statistics for segmental angle data

Level	Value	Flexion (degrees)			Extension (degrees)		
		CONTROL-I (n=20)	INST-I (n=20)	p-value	CONTROL-I (n=20)	INST-I (n=20)	p-value
L3-4	**Mean**	2.75 ± 3.42	3.15 ± 2.87	.692	3.58 ± 3.16	4.12 ± 2.75	.562
	Maximum	10.16 ± 3.24	10.55 ± 3.39	.716	9.67 ± 3.99	10.23 ± 2.82	.612
	Minimum	-3.01 ± 3.07	-2.41 ± 2.74	.517	-2.87 ± 2.94	-2.06 ± 2.84	.385
	Range	13.18 ± 2.64	12.96 ± 2.87	.803	12.53 ± 3.01	12.29 ± 2.07	.766
L4-5	**Mean**	8.76 ± 4.72	8.63 ± 3.39	.925	9.74 ± 4.08	8.66 ± 3.78	.389
	Maximum	15.65 ± 4.31	15.44 ± 3.73	.871	15.84 ± 4.14	14.30 ± 2.64	.170
	Minimum	2.34 ± 3.81	1.94 ± 3.76	.736	2.73 ± 3.99	2.05 ± 3.94	.589
	Range	13.31 ± 2.43	13.51 ± 3.02	.821	13.10 ± 1.83	12.25 ± 3.08	.292
L5-S1	**Mean**	10.38 ± 2.89	10.42 ± 4.21	.967	10.41 ± 2.35	9.75 ± 4.05	.530
	Maximum	15.55 ± 3.28	14.64 ± 5.33	.523	15.71 ± 3.86	14.36 ± 4.49	.314
	Minimum	5.32 ± 2.91	4.91 ± 4.06	.721	5.24 ± 3.10	4.80 ± 4.17	.709
	Range	10.23 ± 3.37	9.73 ± 3.56	.650	10.47 ± 4.83	9.56 ± 3.12	.482
All	**Instability ratio***	1.23 ± 0.12	1.24 ± 0.15	.797	1.23 ± 0.13	1.21 ± 0.17	.675

*Maximum range of a single segment across all segments/ mean range of all segments

Figure 4.2A-C: 4.2A: Trajectory of the L3-4 segmental angle (change from the upright posture in the direction of flexion) with respect to time. Subjects were standardized across time by plotting the maximal value for L3-S1 lordosis angle at 3.96 seconds for all subjects. 4.2B: Trajectory of the average change in the L3-4 segmental angle with respect to percentage of global motion of L3-S1 lordosis angle. 4.2C: Trajectory of the normalized L3-4 angle (⁄Range*100) with respect to percentage of global motion.

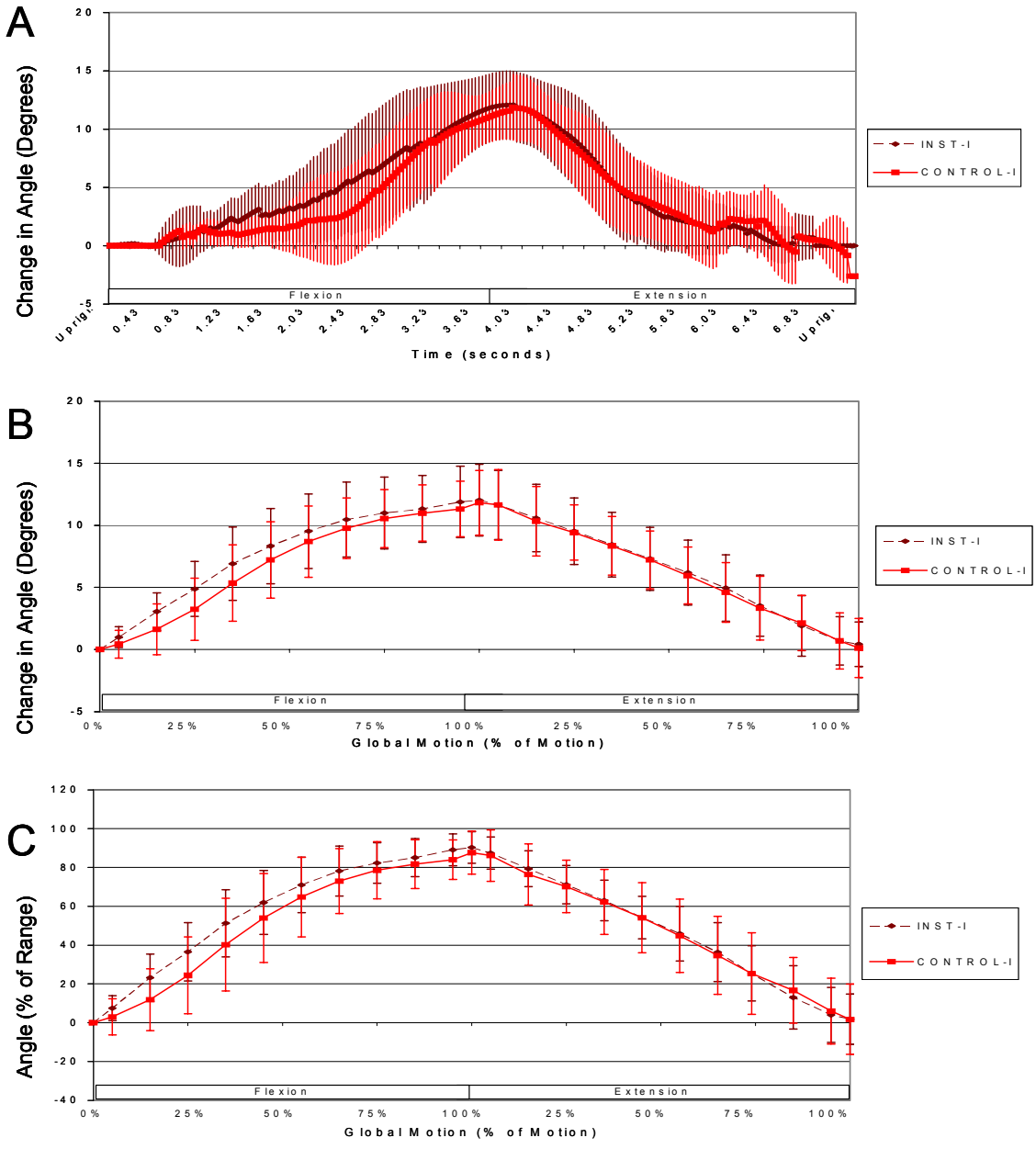


Figure 4.3A-C: 4.3A: Trajectory of the L4-5 segmental angle (change from the upright posture in the direction of flexion) with respect to time. Subjects were standardized across time by plotting the maximal value for L3-S1 lordosis angle at 3.96 seconds for all subjects. 4.3B: Trajectory of the average change in the L4-5 segmental angle with respect to percentage of global motion of L3-S1 lordosis angle. 4.3C: Trajectory of the normalized L4-5 angle (⁄Range*100) with respect to percentage of global motion.

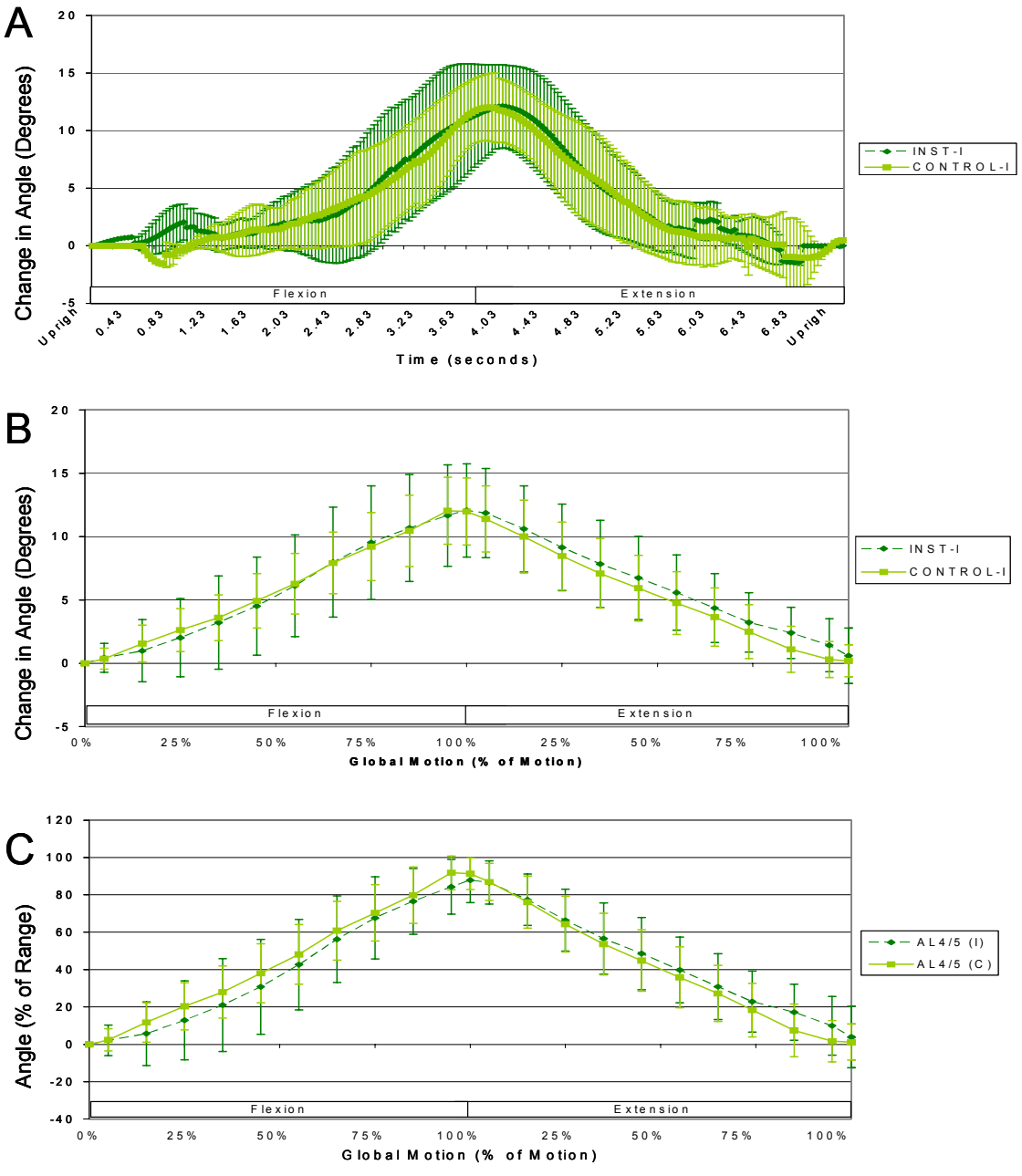


Figure 4.4A-C: 4.4A: Trajectory of the L5-S1 segmental angle (change from the upright posture in the direction of flexion) with respect to time. Subjects were standardized across time by plotting the maximal value for L3-S1 lordosis angle at 3.96 seconds for all subjects. 4.4B: Trajectory of the average change in the L5-S1 segmental angle with respect to percentage of global motion of L3-S1 lordosis angle. 4.4C: Trajectory of the normalized L5-S1 angle (/Range*100) with respect to percentage of global motion.

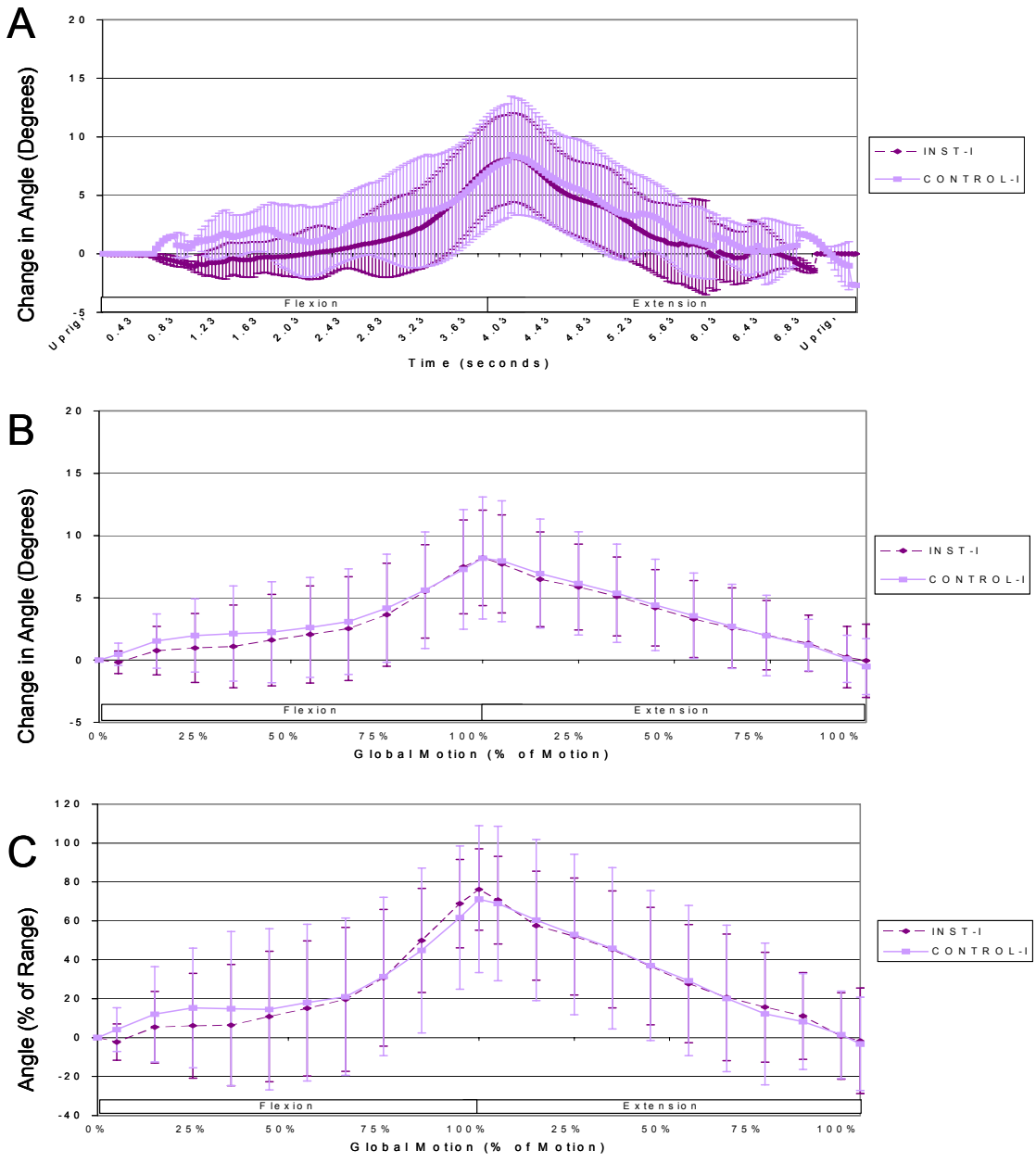


Figure 4.5A-C: Comparison of angle trajectory of lordosis and segmental angle range (4.5A) with respect to time, (4.5B) with respect to global motion, and (4.5C), and normalized angle with respect to global motion.

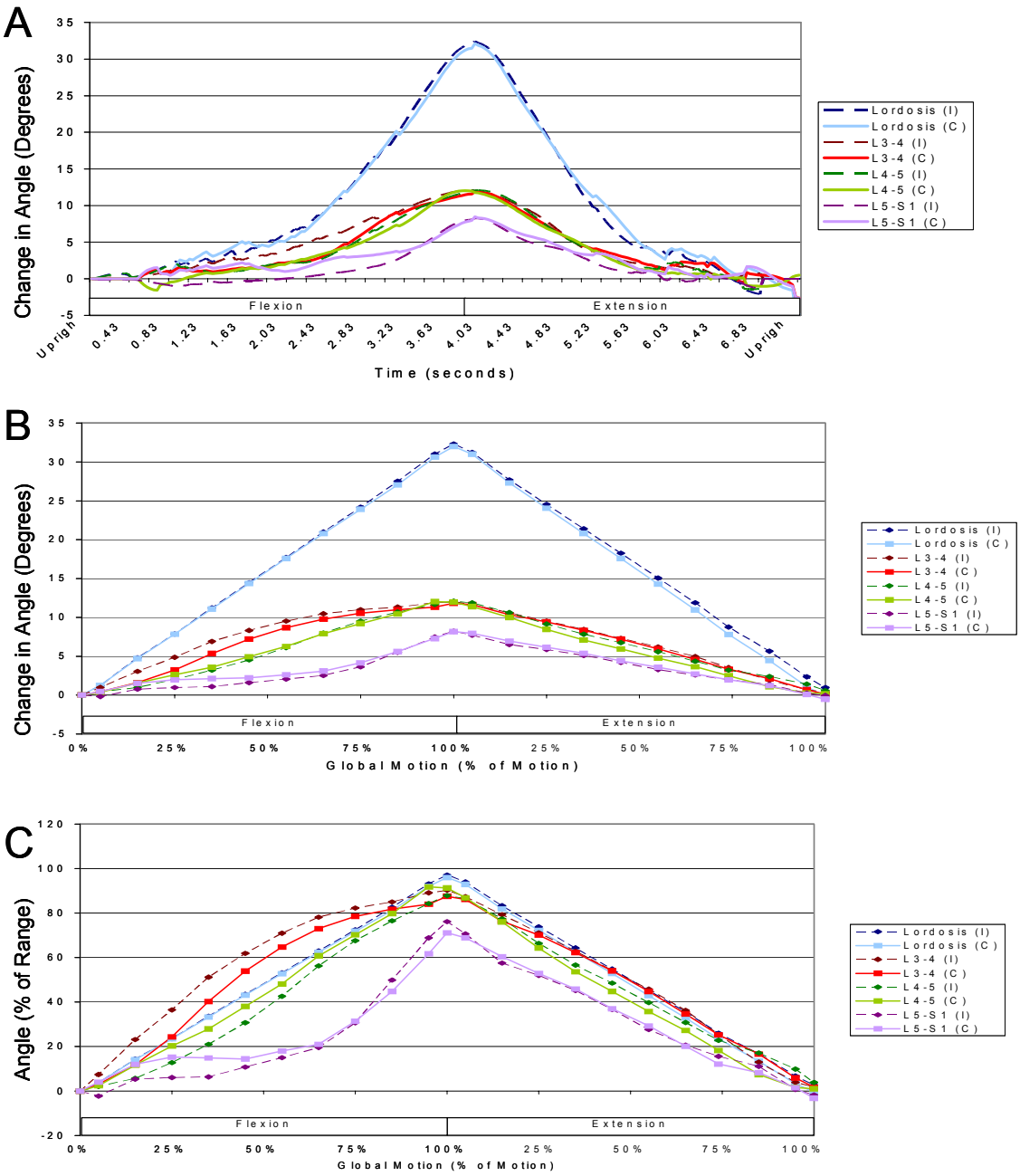
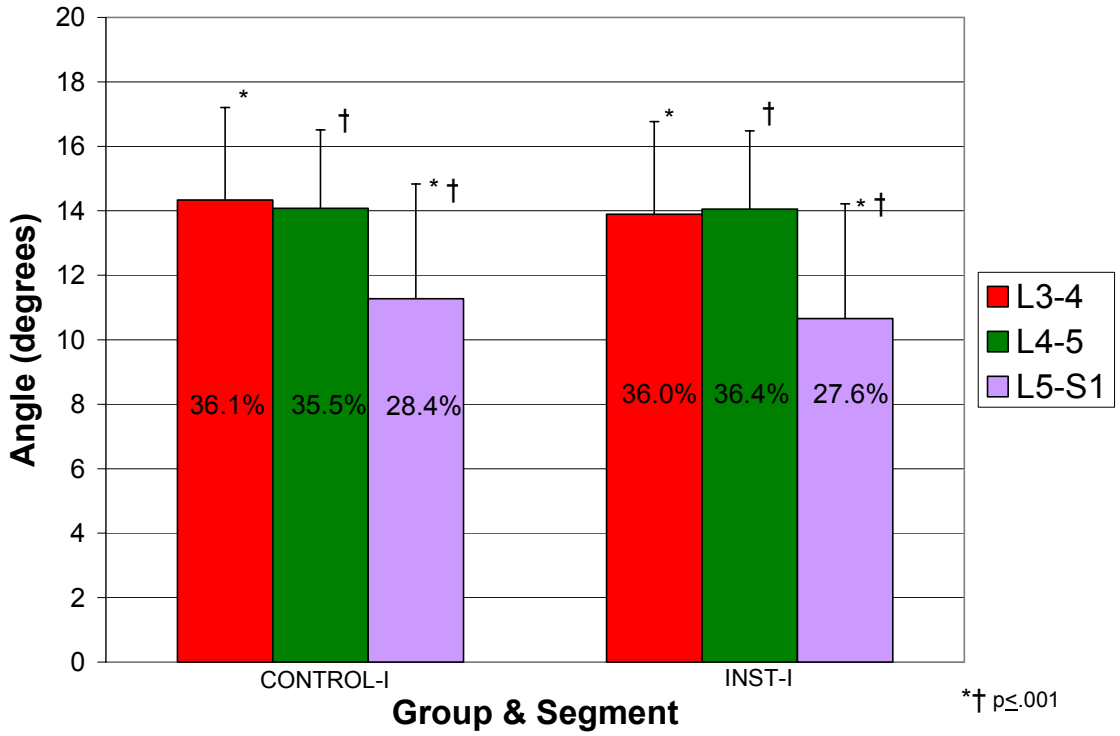


Table 4.5: Segmental angle range as a ratio of total angle range

	CONTROL-I (n=20)	INST-I (n=20)	p-value
Total Angle Range	39.7 ± 5.6°	38.6 ± 5.7°	.538
Percent at L3/4	36.1 ± 6.5%	36.0 ± 6.3%	.944
Percent at L4/5	35.5 ± 3.8%	36.4 ± 4.1%	.467
Percent at L5/S1	28.4 ± 7.1%	27.6 ± 6.0%	.713

Figure 4.6: Segmental angular range during flexion, n=40 (*,† p ≤.001)



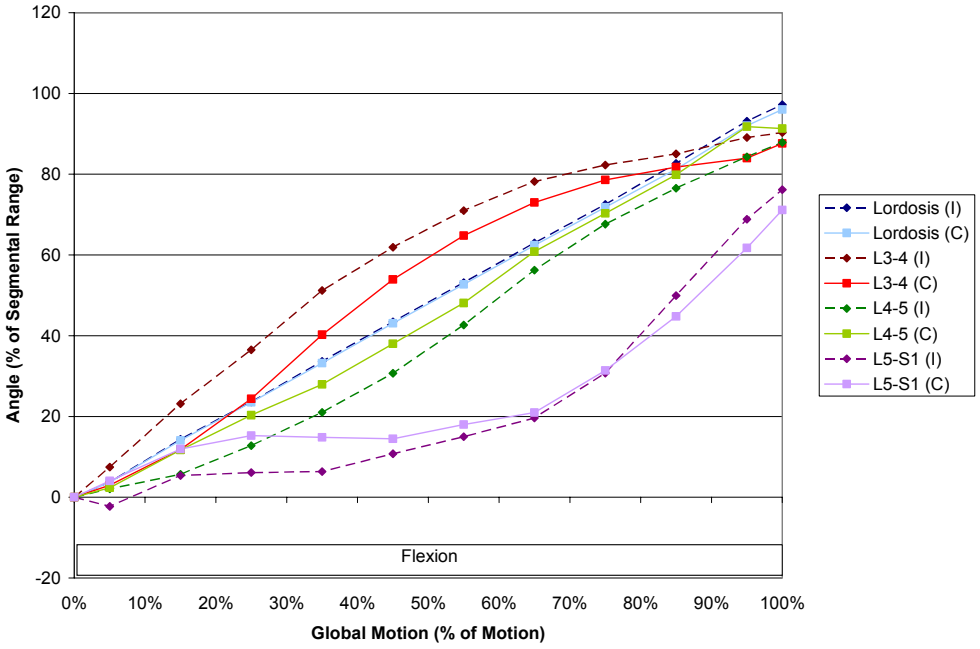
Angle Timing

Flexion: Within-Group Analysis

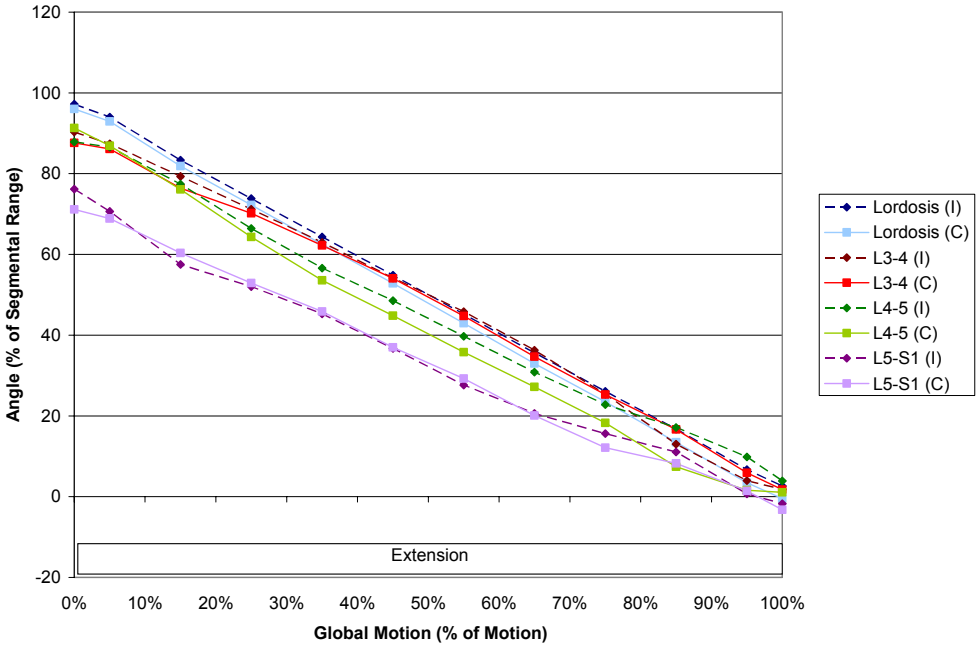
The rate of attainment of segmental angular range as a function of global angular motion (L3-S1 lordosis) was calculated as a measure of timing for angular motion. A trend of sequential motion during flexion can be appreciated while observing the normalized motion graph (Figure 4.7A). The rate of attainment (slope) of the percent of

Figure 4.7: Normalized segmental angle trajectory (%) per global angle (%) during flexion (A) and extension (B).

A



B



angular range of L3-4 as a function of percent of global flexion was at a maximum during the start of flexion, L4-5 was at a maximum during the mid-range of global flexion, and the slope of L5-S1 was at a maximum during the end-range of global flexion, regardless of group (Figure 4.8A-C). A within-group analysis, 3 × 4 ANOVA (Table 4.6), revealed a significant interaction effect ($p < .001$) between the segmental level (L3-4, L4-5, and L5-S1) and percent of motion (0-25%, 25-55%, 55-75%, 75-100%). Post-hoc analysis with Bonferroni correction revealed a significantly greater slope of L3-4 during the first half of global flexion (0-25% and 25-55%) compared to the last half of global flexion (55-75% and 75-100%; $p < .001$). Further, L4-5 had a significantly greater slope ($p = .005$) between 25-55% compared to 0-25% of flexion. Finally, the L5-S1 slope in the last 25% of flexion (75-100% of flexion) was significantly greater ($p \leq .002$) compared to the slope at 0-25%, 25-55%, and 55-75% of flexion. The motion by level post-hoc analysis with a Bonferroni correction was provided in Table 4.7 and Figure 4.9. The slope of L3-4 was greater during the first 0-25% of motion compared to L4-5 ($p = .011$) and L5-S1 ($p = .010$). The slope between L4-5 and L5-S1 did not differ during the first 25% of flexion ($p = 1.000$). During 25-55% of flexion, L3-4 motion was greater than L4-5 ($p = .015$) and L5-S1 ($p < .001$), while L4-5 was greater than L5-S1 ($p < .001$). During 55-75% of flexion the slope of L4-5 was greater than L3-4 ($p = .001$) and L5-S1 ($p = .012$), but the slope between L3-4 and L5-S1 did not differ ($p = 1.000$). During the last 25% of flexion the slope of L5-S1 was greater than L3-4 ($p < .001$) and L4-5 ($p = .004$); the average slope of L4-5 continued to be greater than L3-4 ($p < .001$).

Figure 4.8A-C. Rate of attainment (slope) of normalized angle range (%) as a function of global motion (%) of L3-4 (A), L4-5 (B), and L5-S1 (C)

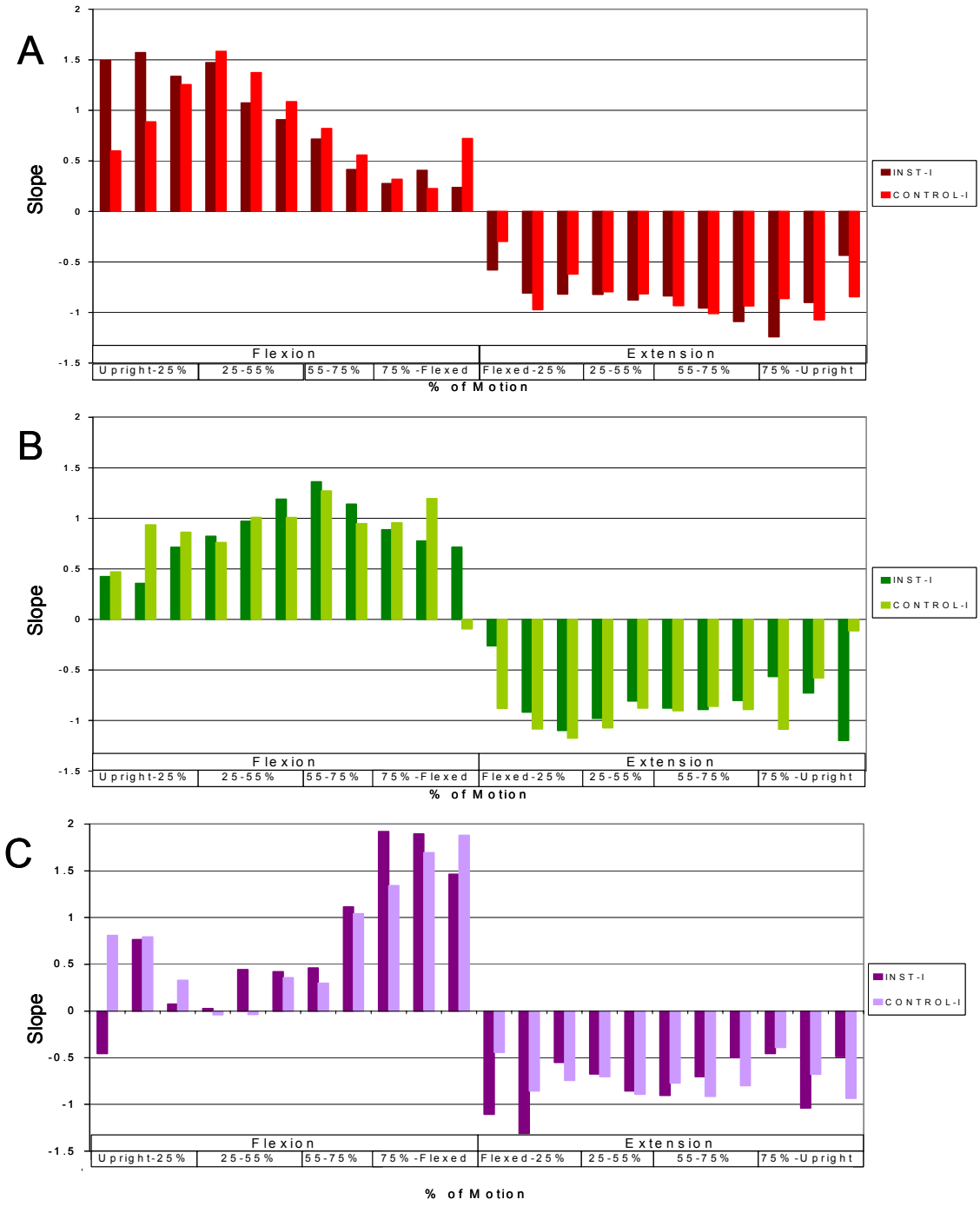
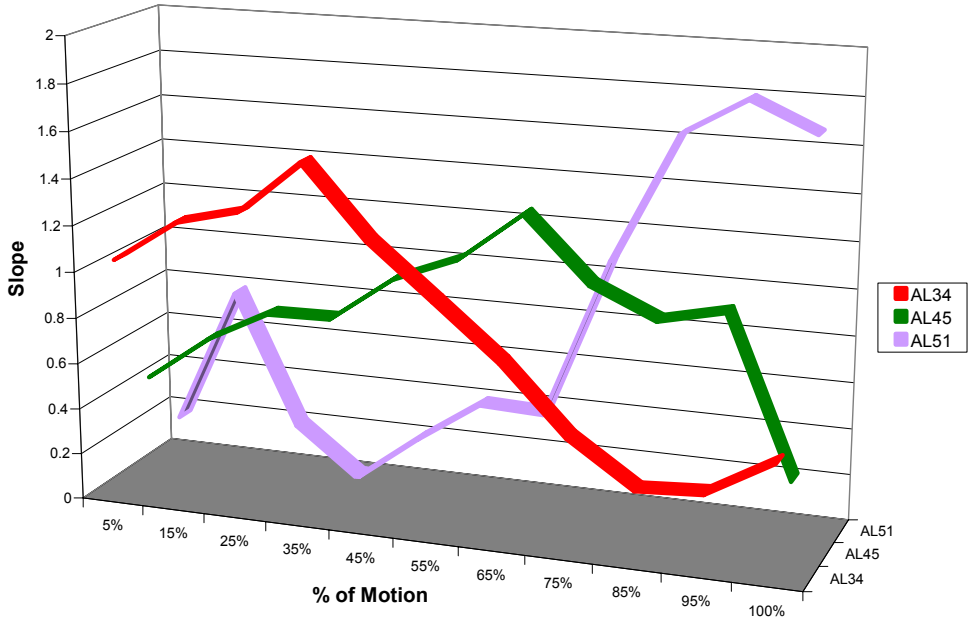


Figure 4.9: Rate of attainment (slope) of the normalized angle range (%) as a function of global motion (%) during flexion (A) and extension (B), n=40

A



B

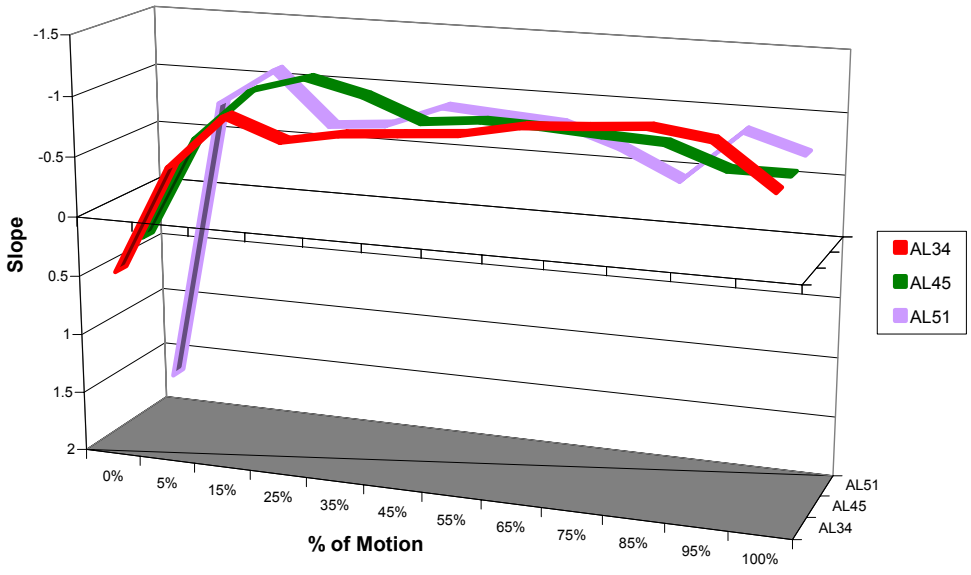


Table 4.6: Analysis of within-group difference across levels (L3-4, L4-5, and L5-S1) and motion (0-25%, 25-55%, 55-75%, and 75-100%) during flexion (n=40)

Source	df†	SS	MS	F	p-value
Level (3)	1.320	2.606	1.974	8.384	.003
Motion (4)	2.159	7.230	3.349	25.752	<.001
Level × Motion	3.052	87.417	28.641	17.910	<.001
Level × Motion × Group	3.052	6.268	2.054	1.284	.283

*df = degrees of freedom, SS = Type III Sum of Squares, MS = Mean Square, and F = F-value

† Sphericity assumption was not met (significant Mauchly's test of sphericity), therefore the df were adjusted using the Greenhouse-Geisser formula.

Table 4.7: Post-hoc analysis with Bonferroni correction for level (3) by motion (4) comparisons during flexion

Motion	0-25%	25-55%	55-75%	75-100%
L3-4 to L4-5	> (p = .011)	> (p = .015)	< (p = .001)	< (p < .001)
L4-5 to L5-S1	- (p = 1.000)	> (p < .001)	> (p =.012)	< (p = .004)
L3-4 to L5-S1	> (p = .010)	> (p < .001)	- (p = 1.000)	< (p < .001)

Flexion: Between-Group Analysis

During the initiation of flexion, the rate of attainment of percent of angular range as a function of percent of global motion differed between groups when analyzed in 5-10% increments of motion (Table 4.8, Figure 4.7A). There was a trend towards greater angular slope of L3-4 from 0-5% of motion in the INST-I group ($p = .086$), with a trend towards a lower slope at L5-S1 in the INST-I group ($p = .061$). From 5-15% of motion, the INST-I group had a greater slope at L3-4 (1.570 ± 0.934) compared to the CONTROL-I group (0.885 ± 0.895; $p = .023$). A trend towards a smaller slope of L4-5 in the INST-I group during 5-15% of motion was also noted ($p = .079$). During the 35-45% of flexion, the CONTROL-I group slope of L3-4 was greater than that of the INST-I group ($p = .034$) and at L5-S1 the slope was greater in the INST-I group ($p = .038$).

Extension: Within-Group Analysis

A sequential motion pattern was not noted during extension (Figure 4.7B). During the return to upright, within-group analysis revealed a significant main effect ($p = .040$) for level (L3-4, L4-5, and L5-S1) and a significant main effect ($p < .001$) for motion (0-25%, 25-55%, 55-75%, 75-100%), but the interaction effect between level and motion was not significant ($p = .546$) and the interaction between level, motion, and group, was not significant ($p = .890$; Table 4.9). Post-hoc analysis with a Bonferroni correction revealed that the greatest rate of attainment of extension angular range (absolute slope) occurred during 55-75% of the extension motion, compared to the absolute slope during 0-25%, 25-55%, and 75-100% of extension ($p < .001$). Additionally, the absolute rate of attainment of angle range during the start of extension (0-25%) was significantly greater ($p < .001$) than the absolute slope from 25-55% of extension (Figure 4.9B). The absolute slope between 25-55% was significantly lower ($p = .047$) than the absolute slope between 75-100% of extension.

Table 4.8: Slope of angular change (%) as a function of global motion (%) during the initiation of flexion

	CONTROL-I (n=20)	INST-I (n=20)	p-value	p < 0.20	p < .05
L3-4 Motion					
0-5%	0.599 ± 1.865	1.492 ± 1.292	.086	*	
5-15%	0.885 ± 0.895	1.570 ± 0.934	.023	*	*
15-25%	1.255 ± 1.093	1.335 ± 0.848	.799		
25-35%	1.584 ± 1.014	1.471 ± 0.649	.677		
35-45%	1.371 ± 0.503	1.072 ± 0.333	.034†	*	*
45-55%	1.086 ± 0.588	0.906 ± 0.463	.288		
L4-5 Motion					
0-5%	0.472 ± 1.186	0.423 ± 1.643	.913		
5-15%	0.935 ± 0.845	0.358 ± 1.154	.079	*	
15-25%	0.862 ± 0.851	0.711 ± 0.864	.583		
25-35%	0.761 ± 0.632	0.822 ± 0.896	.806		
35-45%	1.010 ± 0.587	0.970 ± 0.389	.801		
45-55%	1.008 ± 0.564	1.191 ± 0.462	.269		
L5-S1 Motion					
0-5%	0.810 ± 2.253	-0.454 ± 1.866	.061	*	
5-15%	0.793 ± 1.652	0.763 ± 1.205	.949		
15-25%	0.328 ± 1.206	0.075 ± 1.040	.481		
25-35%	-0.041 ± 1.784	0.026 ± 0.903	.882		
35-45%	-0.038 ± 0.829	0.442 ± 0.557	.038	*	*
45-55%	0.356 ± 0.588	0.422 ± 0.717	.753		

†Equal variance not assumed secondary to a significant Levene's test for equality of variances

Although the ANOVA found a significant difference among the vertebral levels, post-hoc analysis with a Bonferroni correction did not reveal any pair-wise differences, this can be visualized in Figure 4.7B. A possible trend towards a slower rate of attainment (slope) of L5-S1 compared to L3-4 (p = .144) and L4-5 (p = .111) was noted.

Table 4.9: Analysis of within-group difference across levels (L3-4, L4-5, and L5-S1) and motion (0-25%, 25-55%, 55-75%, and 75-100%) during extension

Source	df†	SS	MS	F	p-value
Level (3)	1.549	1.297	0.837	3.723	.040
Level × Group	1.549	0.234	0.151	0.672	.478
Motion (4)	1.870	8.404	4.493	38.686	<.001
Motion × Group	1.870	0.233	0.119	1.027	.359
Level × Motion	3.663	3.074	0.839	0.754	.546
Level ×Motion × Group	3.663	1.052	0.287	0.258	.890

*df = degrees of freedom, SS = Type III Sum of Squares, MS = Mean Square, and F = F-value

† Sphericity assumption was not met (significant Mauchly's test of sphericity), therefore the df were adjusted using the Greenhouse-Geisser formula.

Extension: Between-Group Analysis

During the last half of the return to the upright posture, differences between groups were noted in L4-5, but not in L3-4 and L5-S1 (Table 4.10). Specifically, the absolute slope was greater during the last 5% of extension (95-100% of Extension) in the INST-I group (p = .023). A trend was noted during the 75-85% of extension, with a greater absolute slope in the CONTROL-I group (p = .090).

Table 4.10: Slope of angular change (%) as a function of global motion (%) during the return to upright

	CONTROL-I (n=20)	INST-I (n=20)	p-value	p < .20	p < .05
L3-4 Motion					
45-55%	-0.933 ± 0.499	-0.835 ± 0.614	.585		
55-65%	-1.010 ± 0.614	-0.955 ± 0.337	.725†		
65-75%	-0.936 ± 0.729	-1.089 ± 0.559	.462		
75-85%	-0.862 ± 1.039	-1.240 ± 0.863	.219		
85-95%	-1.072 ± 0.955	-0.902 ± 0.677	.521		
95-100%	-0.843 ± 0.917	-0.436 ± 1.075	.206		
L4-5 Motion					
45-55%	-0.903 ± 0.353	-0.878 ± 0.872	.907		
55-65%	-0.859 ± 0.423	-0.892 ± 0.705	.857		
65-75%	-0.891 ± 0.677	-0.802 ± 0.547	.650		
75-85%	-1.085 ± 1.108	-0.565 ± 0.740	.090†	*	
85-95%	-0.579 ± 0.794	-0.728 ± 0.890	.581		
95-100%	-0.112 ± 1.444	-1.198 ± 1.448	.023	*	*
L5-S1 Motion					
45-55%	-0.773 ± 0.957	-0.904 ± 0.548	.596		
55-65%	-0.914 ± 0.782	-0.702 ± 1.132	.495		
65-75%	-0.798 ± 1.238	-0.500 ± 0.895	.390		
75-85%	-0.390 ± 1.866	-0.454 ± 1.430	.904		
85-95%	-0.677 ± 1.462	-1.038 ± 1.538	.452		
95-100%	-0.934 ± 1.708	-0.488 ± 2.046	.460		

† Equal variance not assumed secondary to a significant Levene's test for equality of variance

Displacement Range (Flexion and Extension)

Segmental displacement (ratio: difference between the perpendicular projections of adjacent vertebral bodies to the bisectrix / mean depth of the cephalad vertebral body) was analyzed to describe and compare the translational kinematic patterns of these groups. Segmental displacement range decreased from the cephalad to caudal segments (Figure 4.10), regardless of group membership. Graphical representation of segmental displacement was provided in Figures 4.11-4.14. As a percentage of total displacement, L3-4 represented approximately 38-39%, L4-5 represented approximately 32-33%, and L5-S1 represented about 28-30%, of total displacement across segments (Table 4.11). An ANOVA revealed a main effect for level (L3-4, L4-5, L5-S1; $p < .001$) without a level by group interaction ($p = .675$). Post-hoc analysis with a Bonferroni correction revealed the percent of segmental displacement at L3-4 was greater than that at L4-5 ($p = .018$), and was greater than that at L5-S1 ($p = .003$). There was no difference in the percent of motion occurring at L4-5 and L5-S1 ($p = .322$).

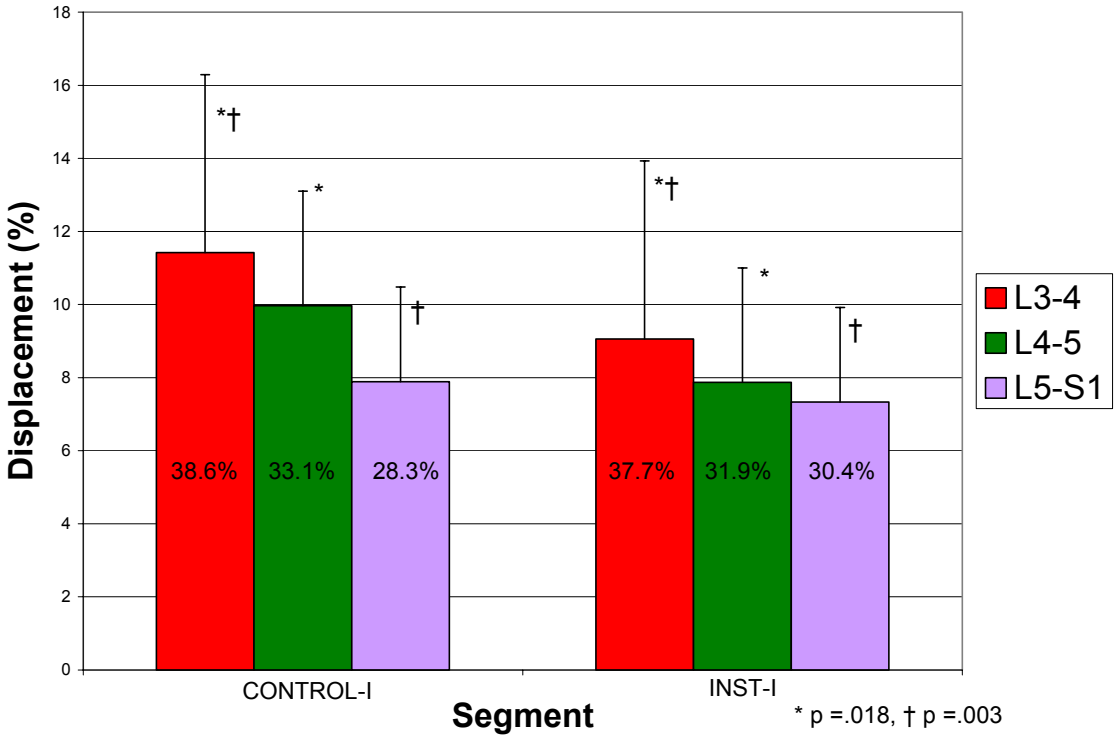
Table 4.11: Segmental displacement range as a ratio of total displacement range

	CONTROL-I (n=20)	**INST-I (n=20)**
Total Displacement Range*,†	33.5 ± 9.2%	27.9 ± 7.4%
Percent at L3-4	38.6 ± 8.2%	37.7 ± 8.8%
Percent at L4-5	33.1 ± 5.9%	31.9 ± 6.5%
Percent at L5-S1	28.3 ± 8.3%	30.4 ± 8.6%

*Total displacement range is the summation of the displacement range at L3-4, L4-5, L5-S1, which is expressed as a percentage.

† $p = .039$

Figure 4.10: Segmental displacement range during flexion, n=40



Overall, total displacement range across segments measured in the INST-I group was lower than in the CONTROL-I group ($p = .039$; Table 4.11; Figure 4.10). Independent t-tests revealed less displacement range during flexion ($p = .043$) and extension ($p = .028$) at L4-5 in the INST-I group than in the CONTROL-I group (Table 4.12).

Figure 4.11A-C: 4.11A: Trajectory of the L3-4 segmental displacement (change from the upright posture in the direction of flexion) with respect to time. Subjects were standardized across time by plotting the maximal value for L3-S1 lordosis angle at 3.96 seconds for all subjects. 4.11B: Trajectory of the average change in the L3-4 segmental displacement with respect to percentage of global motion of L3-S1 lordosis angle. 4.11C: Trajectory of the normalized L3-4 displacement (/Range*100) with respect to percentage of global motion.

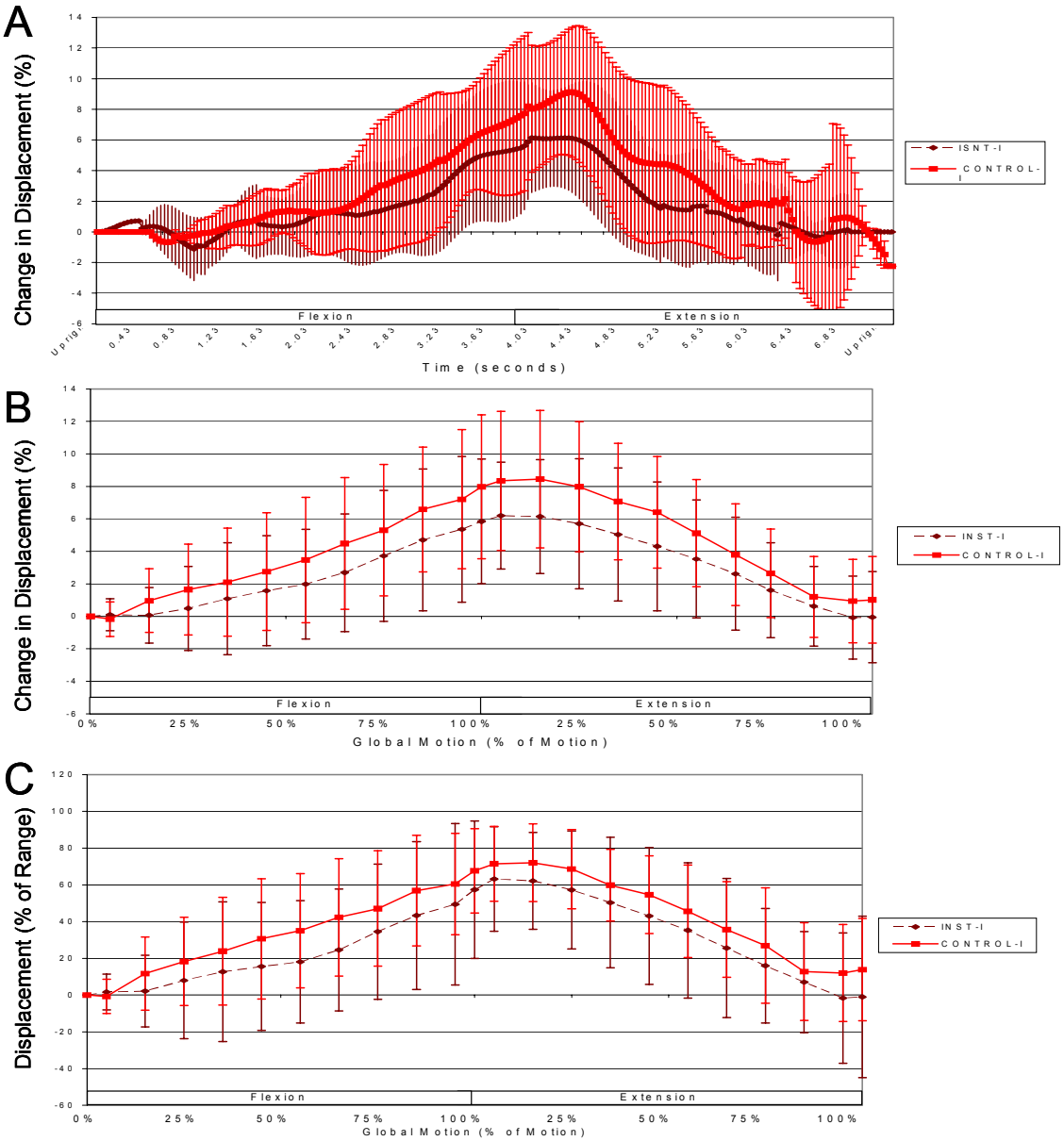


Figure 4.12A-C: 4.12A: Trajectory of the L4-5 segmental displacement (change from the upright posture in the direction of flexion) with respect to time. Subjects were standardized across time by plotting the maximal value for L3-S1 lordosis angle at 3.96 seconds for all subjects. 4.12B: Trajectory of the average change in the L4-5 segmental displacement with respect to percentage of global motion of L3-S1 lordosis angle. 4.12C: Trajectory of the normalized L4-5 displacement (/Range*100) with respect to percentage of global motion.

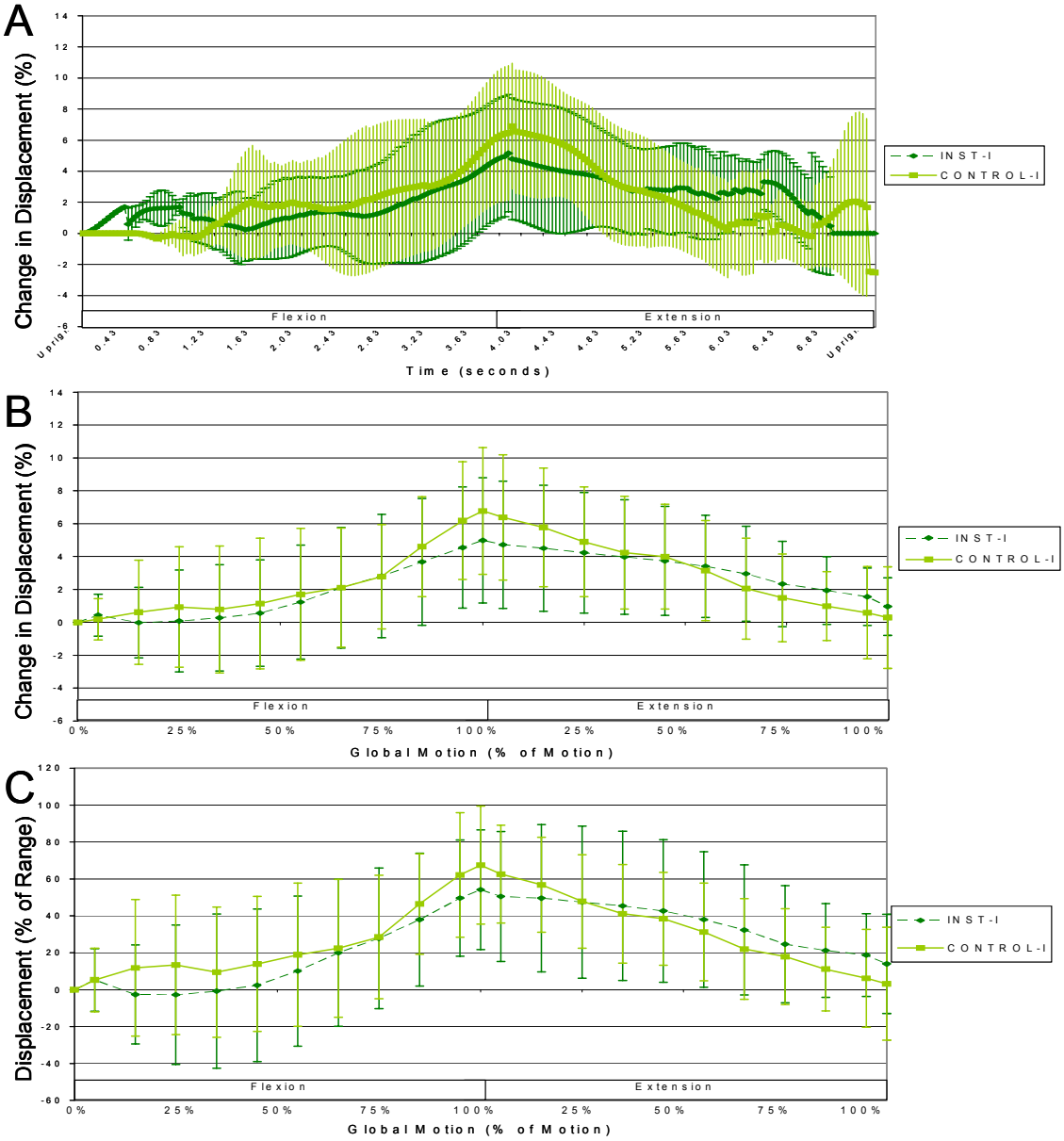


Figure 4.13A-C: 4.13A: Trajectory of the L5-S1 segmental displacement (change from the upright posture in the direction of flexion) with respect to time. Subjects were standardized across time by plotting the maximal value for L3-S1 lordosis angle at 3.96 seconds for all subjects. 4.13B: Trajectory of the average change in the L5-S1 segmental displacement with respect to percentage of global motion of L3-S1 lordosis angle. 4.13C: Trajectory of the normalized L5-S1 displacement (/Range*100) with respect to percentage of global motion.

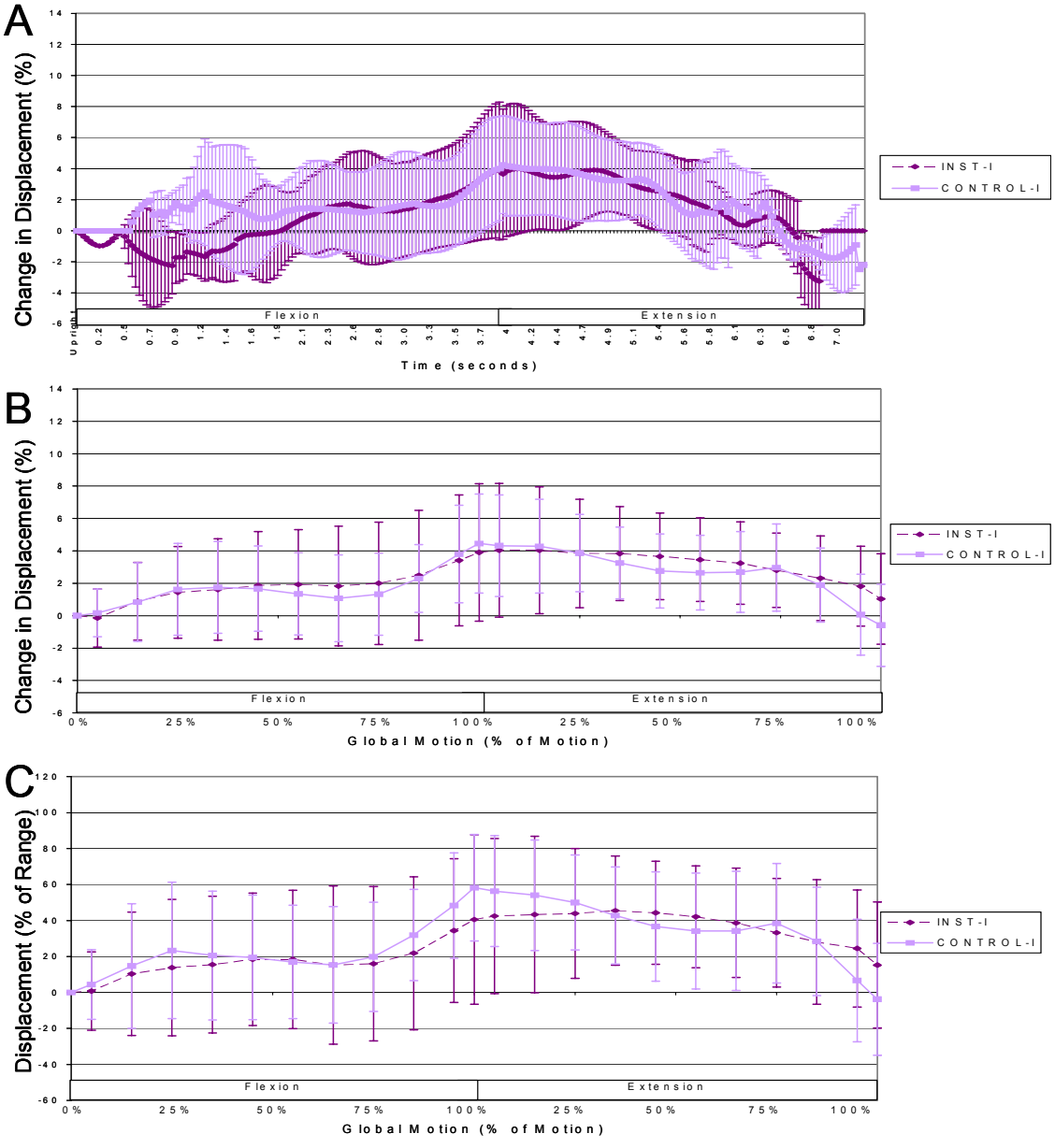


Figure 4.14A-C: Comparison of displacement trajectory of segmental displacement range (4.5A) with respect to time, (4.5B) with respect to global angular motion, and (4.5C), and normalized displacement with respect to global angular motion.

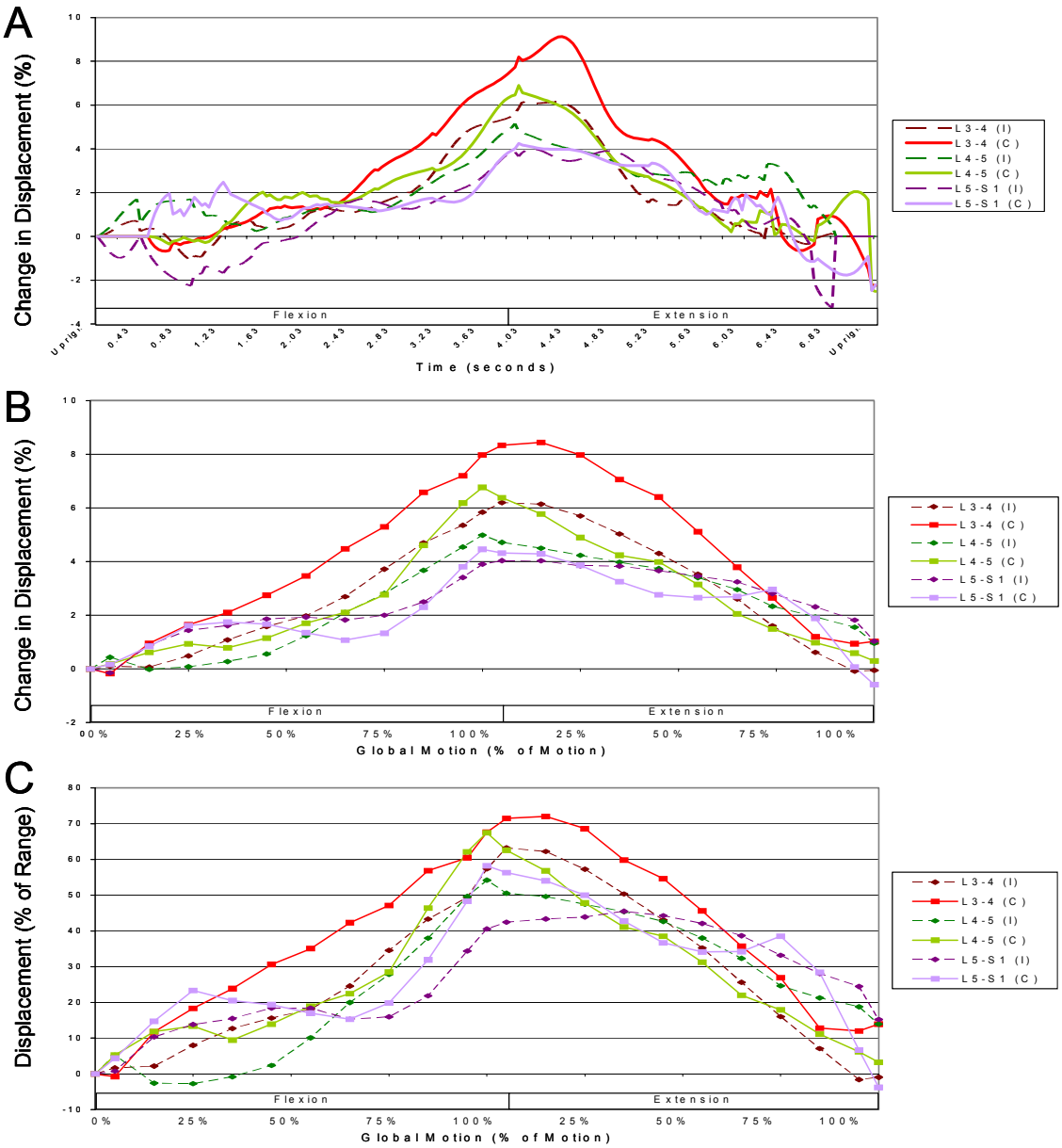


Table 4.12: Descriptive statistics for segmental displacement data

Level	Value	Flexion (%)			Extension (%)		
		CONTROL-I (n=20)	INST-I (n=20)	p-value	CONTROL-I (n=20)	INST-I (n=20)	p-value
L3-4	**Mean**	-.7.05 ± 2.52	-7.75 ± 3.69	.490	-6.14 ± 3.36	-7.13 ± 3.75	.386
	Maximum	-1.09 ± 4.81	-3.00 ± 4.76	.215	-0.50 ± 5.19	-2.81 ± 4.74	.150
	Minimum	-12.52 ± 2.84	-12.07 ± 3.05	.631	-11.53 ± 3.09	-11.77 ± 3.19	.809
	Range	11.42 ± .4.87	9.06 ± 3.44	.086	11.02 ± 5.30	8.96 ± 3.08	.142
L4-5	**Mean**	-8.58 ± 4.60	-8.57 ± 3.34	.994	-8.40 ± 4.59	-7.56 ± 3.43	.517
	Maximum	-3.56 ± 4.69	-4.47 ± 3.73	.502	-3.76 ± 5.42	-4.24 ± 3.66	.741
	Minimum	-13.54 ± 5.07	-12.34 ± 3.60	.395	-12.77 ± 4.38	-10.97 ± 3.74	.170
	Range	9.97 ± 3.13	7.87 ± 3.21	.043	9.02 ± 3.64	6.73 ± 2.58	.028
L5-S1	**Mean**	-6.59 ± 5.54	-7.41 ± 4.94	.625	-5.67 ± 5.47	-6.45 ± 4.44	.622
	Maximum	-2.47 ± 5.99	-4.04 ± 5.47	.392	-2.13 ± 6.10	-3.30 ± 4.98	.511
	Minimum	-10.36 ± 4.94	-11.37 ± 4.15	.489	-9.89 ± 4.87	-9.74 ± 4.77	.922
	Range	7.89 ± 2.59	7.33 ± 3.77	.585	7.76 ± 3.28	6.44 ± 3.27	.211
All	**Instability ratio***	1.26 ± 0.155	1.36 ± .203	.096	1.35 ± 0.202	1.34 ± 0.186	.911

*Maximum range of a single segment across all segments/ mean range of all segments

Displacement Timing

Flexion: Within-Group Analysis

The rate of attainment of segmental displacement range as a function of global angular motion (L3-S1 lordosis) was calculated as a measure of timing for the displacement motion. Unlike angular motion, rate of attainment of segmental displacement during flexion does not appear to occur in a sequential manner. A trend towards a greater slope was seen both during the initiation and final stages of flexion (Figure 4.15). A within-group analysis, 3 × 4 ANOVA (Table 4.13), revealed a significant interaction effect ($p = .028$), between segmental level (L3-4, L4-5, and L5-S1) and percent of motion (0-25%, 25-55%, 55-75%, 75-100%). Segmental level, percent of motion, and group did not interact ($p = .536$). Post-hoc analysis with a Bonferroni correction of segmental level across flexion revealed a greater rate of attainment of percent of displacement range (slope) of L4-5 during the last part of global flexion (75-100%) compared with 0-25% ($p = .010$), with 25-55% ($p = .025$), and with 55-75% ($p = .034$) of global flexion. A greater value of slope was also found in the L5-S1 segment during 75-100% of global flexion compared with 25-55% ($p = .003$) and 55-75% of global flexion ($p < .001$). There was no difference between the rate of attainment of displacement range during flexion of L3-4 ($p = 1.000$) throughout flexion. The rate of attainment of displacement range did not differ among the levels during 0-25%, 25-55%, and 75-100% of global flexion. However, during 55-75% of global flexion the rate of attainment of displacement range of L3-4 was greater than L5-S1 ($p = .050$) and L4-5 was greater than L5-S1 ($p = .011$), Figure 4.16.

Figure 4.15A-C. Rate of attainment (slope) of normalized displacement range (%) as a function of global motion (%) of L3-4 (A), L4-5 (B), and L5-S1 (C)

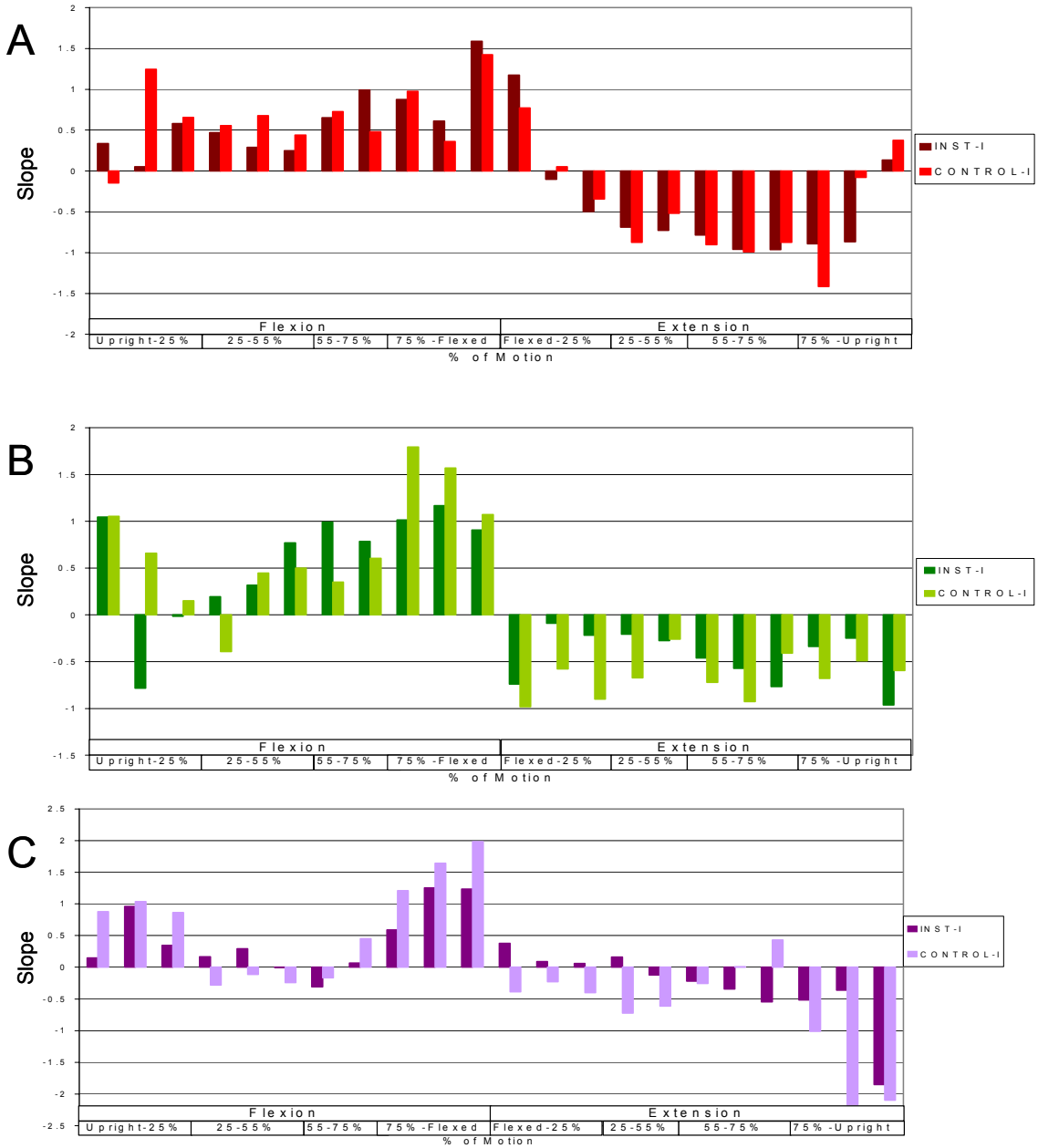


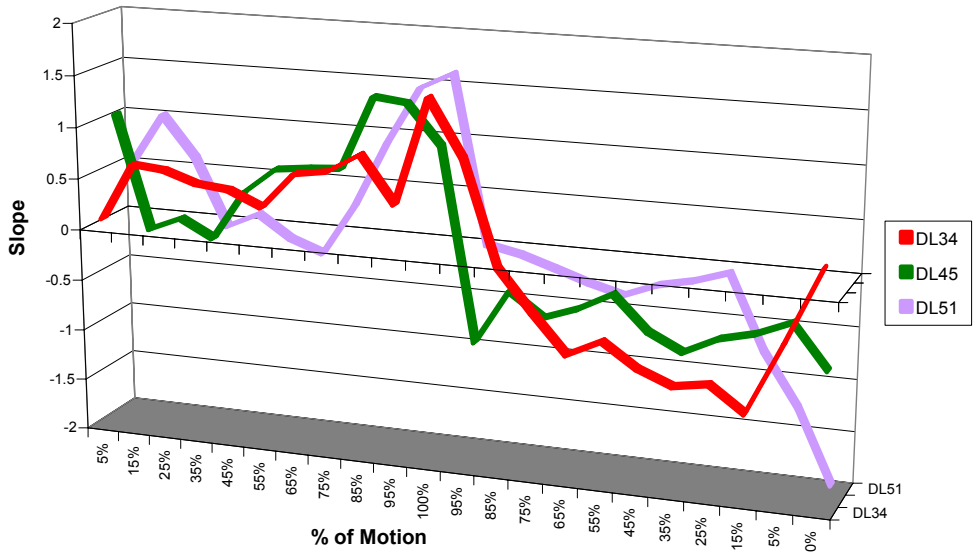
Table 4.13: Analysis of within-group difference of displacement across levels (L3-4, L4-5, and L5-S1) and motion (0-25%, 25-55%, 55-75%, and 75-100%) during flexion (n=40)

Source	df†	SS	MS	F	Sig.
Level (3)	1.685	1.629	0.967	2.318	.115
Motion (4)	2.499	54.212	21.692	8.319	<.001
Level × Motion	4.545	23.715	5.218	2.665	.028
Level × Motion × Group	4.545	7.181	1.580	0.807	.536

*df = degrees of freedom, SS = Type III Sum of Squares, MS = Mean Square, F = F-value, Sig. = level of significance

† Sphericity assumption was not met (significant Mauchly's test of sphericity), therefore the df were adjusted using the Greenhouse-Geisser formula.

Figure 4.16: Rate of attainment (slope) of normalized displacement range (%) as a function of global motion (%)



Flexion: Between-Group Analysis

Qualitative analysis of displacement during the initiation of flexion revealed a difference during 5-15% of flexion (Figure 4.17). In the CONTROL-I group; the rate of attainment of displacement range was both positive and increasing. The INST-I group displayed a different pattern, the mean slope of L3-4 was approximately zero (0.051 $\pm$ 1.376) and the mean slope of L4-5 was negative (-0.784 $\pm$ 1.963) in contrast to a positive slope of L5-S1 (0.962 $\pm$ 2.545). Independent t-tests were used to analyze between-group differences during flexion in 5-10% increments (Table 4.17). The CONTROL-I group slope during 5-15% of flexion was greater than that of the ISNT-I group at L3-4 ($p = .018$). A trend was noted at L4-5 in which the CONTROL-I group had a greater slope during 5-15% of flexion ($p = .087$) while the INST-I had a greater slope during 55-65% of flexion ($p = .136$). No differences were noted in L5-S1 during the initiation of flexion.

Figure 4.17: Normalized segmental displacement trajectory (%) during the start of flexion as a function of global motion (%)

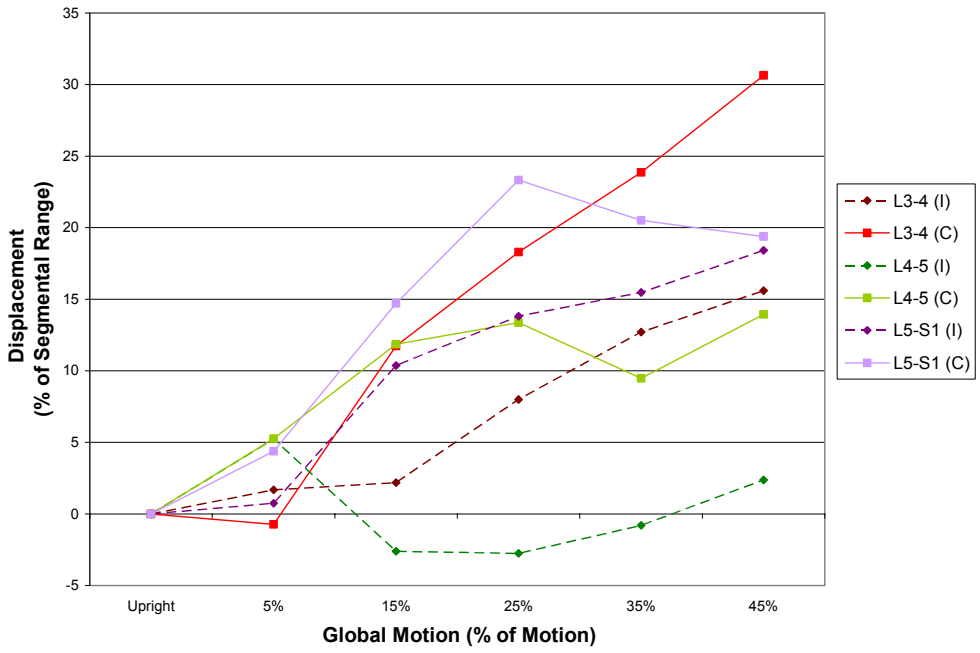


Table 4.14: Slope of displacement change (%) as a function of global motion (%) during the initiation of flexion

	CONTROL-I (n=20)	INST-I (n=20)	p-value	p < .20	p< .05
L3-4 Motion					
0-5%	-0.145 ± 1.873	0.335 ± 1.944	.431		
5-15%	1.246 ± 1.659	0.051 ± 1.376	.018	*	*
15-25%	0.656 ± 1.027	0.581 ± 1.775	.871†		
25-35%	0.558 ± 1.451	0.471 ± 1.412	.850		
35-45%	0.677 ± 1.078	0.289 ± 1.660	.386		
45-55%	0.440 ± 1.308	0.250 ± 1.299	.647		
L4-5 Motion					
0-5%	1.053 ± 3.445	1.045 ± 3.372	.994		
5-15%	0.659 ± 3.111	-0.784 ± 1.963	.087	*	
15-25%	0.151 ± 2.077	-0.014 ± 1.572	.778		
25-35%	-0.390 ± 1.890	0.195 ± 1.326	.264		
35-45%	0.446 ± 1.419	0.317 ± 1.069	.748		
45-55%	0.500 ± 1.167	0.769 ± 0.766	.394		
55-65%	0.350 ± 1.413	0.990 ± 1.240	.136	*	
L5-S1 Motion					
0-5%	0.876 ± 3.872	0.149 ± 4.369	.581		
5-15%	1.033 ± 2.170	0.962 ± 2.545	.925		
15-25%	0.862 ± 2.036	0.344 ± 2.677	.496		
25-35%	-0.281 ± 2.361	0.166 ± 1.242	.457		
35-45%	-0.112 ± 0.953	0.294 ± 1.102	.220		
45-55%	-0.241 ± 1.480	-0.003 ± 1.296	.593		

† Equal variance not assumed secondary to a significant Levene's test for equality of variances

Extension: Within-Group Analysis

Qualitative analysis of extension (Figure 4.15 - 4.16) demonstrated a non-sequential attainment of displacement range. A within-groups analysis, 3 × 4 ANOVA, revealed a significant interaction effect ($p < .001$) between the segmental level (L3-4, L4-5, and L5-S1) and percent of motion (0-25%, 25-55%, 55-75%, 75-100% upright), without a significant interaction ($p = .263$) between segmental level, percent of motion, and group (Table 4.15). Post-hoc analysis with a Bonferroni correction revealed a significantly greater absolute slope of L3-4 during the 55-75% return to upright compared to the initiation of motion (first 25% of extension from the flexed posture). At L5-S1 the absolute rate of attainment of displacement range from during the last 25% of returning to upright (75-100%) was greater than the absolute rate of attainment during 0-25% ($p = .007$), 25-55% ($p = .001$), and 55-75% ($p = .008$) of extension. The rate of attainment of angular range at L4-5 did not differ across the motion pattern. During the first 25% of extension, L4-5 had a greater absolute rate of attainment of displacement range than L3-4 ($p = .038$). From 55-75% of returning to upright the absolute rate of attainment of displacement range of L3-4 was greater than L5-S1 ($p = .001$), and L4-5 was greater than L5-S1 ($p = .032$).

Extension: Between-Group Analysis

During the return to upright the range of displacement attainment at L3-4 and L4-5 did not differ between groups (Table 4.16). At L5-S1 there was a trend ($p = .061$) of a reversal in the slope from 65-75% of return-to-upright in the CONTROL-I group accompanied by a greater absolute slope from 85-95% of motion. Ten of the 20 CONTROL-I subjects demonstrated a reversal of displacement during the 65-75% of return to upright, and nine of those ten demonstrated a greater slope in the direction of

extension during the 85-95% return to upright (p = .008), Figure 4.13C. It should be noted that 7 of the 20 INST-I also demonstrated a positive slope during 65-75% of return to upright and of those seven, four demonstrated a negative slope again at 85-95% of return to upright, however, the values for the INST-I were smaller and had less impact on the group mean values.

Table 4.15: Analysis of within-group difference of displacement across levels (L3-4, L4-5, and L5-S1) and motion (0-25%, 25-55%, 55-75%, and 75-100%) during extension (n=40)

Source	df†	SS	MS	F	Sig.
Level (3)	1.277	1.643	0.778	1.439	.244
Motion (4)	2.432	25.492	10.480	4.578	.008
Level × Motion	4.396	36.137	8.220	5.288	<.001
Level × Motion × Group	4.396	9.002	2.048	1.317	.263

*df = degrees of freedom, SS = Type III Sum of Squares, MS = Mean Square, F = F-value, Sig. = level of significance

† Sphericity assumption was not met (significant Mauchly's test of sphericity), therefore the df were adjusted using the Greenhouse-Geisser formula.

Table 4.16: Slope of displacement change (%) as a function of global motion (%) during the return to upright

	CONTROL-I (n=20)	INST-I (n=20)	p-value	p < .20	p < .05
L3-4 Motion					
45-55%	-0.903 ± 1.183	-0.784 ± 0.953	.728		
55-65%	-0.990 ± 0.999	-0.959 ± 1.505	.940		
65-75%	-0.875 ± 2.254	-0.964 ± 1.520	.885		
75-85%	-1.414 ± 1.167	-0.892 ± 1.868	.296		
85-95%	-0.077 ± 2.009	-0.868 ± 2.476	.275		
95-100%	0.374 ± 1.972	0.134 ± 3.389	.785		
L4-5 Motion					
45-55%	-0.721 ± 1.194	-0.459 ± 1.072	.471		
55-65%	-0.928 ± 0.993	-0.572 ± 1.291	.334		
65-75%	-0.410 ± 2.128	-0.767 ± 1.355	.531		
75-85%	-0.678 ± 1.588	-0.338 ± 1.019	.425		
85-95%	-0.491 ± 1.940	-0.248 ± 1.794	.684		
95-100%	-0.593 ± 2.822	-0.964 ± 3.403	.710		
L5-S1 Motion					
45-55%	-0.253 ± 1.168	-0.219 ± 1.131	.926		
55-65%	0.008 ± 1.157	-0.342 ± 1.445	.403		
65-75%	0.429 ± 1.689	-0.547 ± 1.497	.061	*	
75-85%	-1.009 ± 2.020	-0.514 ± 1.858	.425		
85-95%	-2.172 ± 1.864	-0.359 ± 2.194	.008	*	*
95-100%	-2.097 ± 3.949	-1.850 ± 2.792	.820		

Translational Speed

The change in displacement over time, translational speed, was measured for each vertebral body. Maximum vertebral body translational speed during flexion revealed that each cephalad segment moved faster than its caudal segment regardless of group membership (Figure 4.18). The mean speed during flexion of L3 (56.64 $\pm$ 19.65 mm/s), L4 (46.22 $\pm$ 18.76 mm/s), L5 (39.71 $\pm$ 19.40 mm/s), and S1 (37.24 $\pm$ 19.77 mm/s) were all significantly different. The within-group analysis (ANOVA) of vertebral body speed across vertebral body levels (L3, L4, L5, and S1) during flexion was significant ($p \leq .001$), without an interaction effect of level by group membership ($p = .925$). Mauchly's test of sphericity was significant; therefore a Greenhouse-Geisser correction was used. All pair-wise relationships of vertebral body speed were significant ($p < .01$) using paired t-tests with a Bonferroni adjustment. Specifically, 29 of the 40 subjects followed this pattern with 7 subjects in the instability group and 4 subjects in the control group following different patterns. The different patterns consisted of a reversal of the trend (S1 > L5 > L4 > L3), a single segment moving faster than its cephalad counterpart (i.e. L4 > L3), or no pattern or difference between the levels.

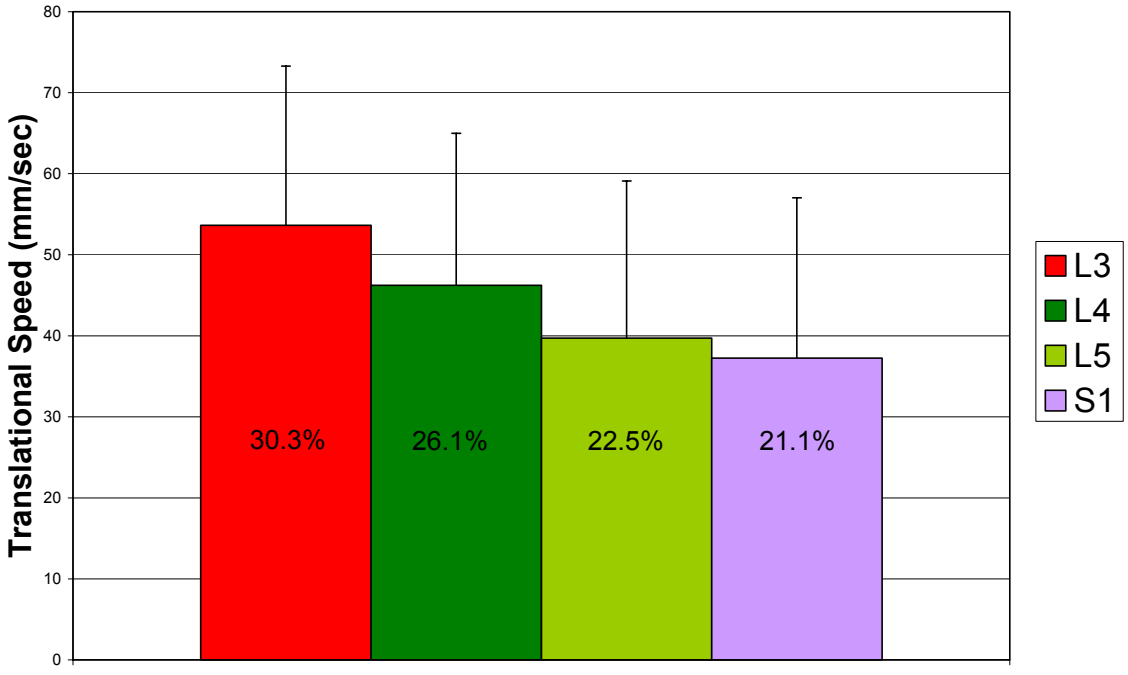
Group comparisons using independent t-tests of the descriptive data related to translation speed were not different. Specifically, the groups were not different at maximum translational speed during flexion ($p \geq .90$; Table 4.20). Further, the ratio of maximum speed of a vertebral body compared to the mean speed of all vertebral bodies during flexion and extension was not different between groups ($p = .53$ & $.74$; Table 4.17). The time interval of maximum speed of the first segment's maximum speed to the last segment's maximum speed during flexion revealed no difference between groups (p

= .70), with the average timing for the CONTROL-I group of 0.020 ± 0.162 seconds and the INST-I group of 0.035 ± 0.064 seconds.

Table 4.17: Vertebral body translational speed comparison between groups

Measure (mm/sec)	CONTROL-I (n=20)	INST-I (n=20)	p-value
Maximum speed during flexion			
L3	53.41 ± 18.04	53.87 ± 21.61	.94
L4	45.83 ± 17.78	46.61 ± 20.14	.90
L5	39.66 ± 17.90	39.76 ± 21.27	.99
S1	36.82 ± 18.14	37.66 ± 21.74	.90
Ratio: Maximum speed of a single segment/ Mean speed of all segments			
Flexion	2.81 ± 0.57	2.92 ± 0.57	.53
Extension	2.95 ± 0.54	3.04 ± 0.97	.74

Figure 4.18: Vertebral body maximal translational speed during flexion (n=40), all pair-wise comparisons are significant (p<.01) with Bonferroni correction, regardless of group membership.



QUALITATIVE DFV ANALYSIS

The expert review of the DFV by the three spine surgeons resulted in 119 complete analyses; an incomplete data set from one reviewer (OS1) resulted in one subject only having two complete reviews. Agreement among the three reviewers based on their assessment of normality of the global movement pattern among the segments (5-point scale: 0 = definitely normal motion, 2 = indeterminate, 4 = definitely abnormal motion) was determined using percent agreement. Agreement was calculated with two definitions. The first definition required that all three raters were in agreement [for which one score of indeterminate (value = 2) was not considered to represent disagreement]. For example, a score set of 0, 1, and 2 was considered to constitute an agreement for normal motion; while a score set of 2, 3, and 4 was considered to constitute an agreement for abnormal motion. Regardless of initial group membership, agreement among all three reviewers resulted in 22 of 40 reviews (55%) being rated as in agreement (16 were viewed as normal and 6 were viewed as abnormal). The other 18 assessments had scores on both sides of the indeterminate value. To analyze those 18 subjects that had scores on each side of the indeterminate value, agreement among two of the three surgeons was analyzed. For example, a score set of 3, 3, and 0 was labeled abnormal motion; while a score set of 1, 1 and 4 was labeled as normal motion. Using this definition the percent agreement increased to 90% (36/40). The four scores of disagreement consisted of scores with a combination of normal, indeterminate and abnormal values (i.e. 1, 2 and 3).

Final group membership was based on the results of the surgeons' analyses of normality of motion. To compare homogenous groups, subjects in the initial control group that were viewed as having normal motion (average score < 2.0, or agreement among two reviewers as normal motion) remained in the final control group, and the same is true with the instability group. Subjects were excluded from the final analysis if

their qualitative score was different from their original group status or if there was disagreement among the reviewers about the motion quality. Ultimately, there were 14 subjects without LBP that were viewed as having normal motion and 11 subjects with instability that were viewed as having abnormal motion based on this qualitative assessment (Figure 3.1).

The qualitative review of stability on a five-point scale (0 = completely stable, 2 = indeterminate, 4 = unstable) yielded agreement across the surgeons that 26 out of 40 subjects (65%) were stable, none were viewed as unstable, and 14 subjects yielded scores on both sides of the indeterminate value, or more than one indeterminate score. Only three subjects in the symptom-based instability group (INST-I) were viewed as being unstable based on a mean score > 2.0, or agreement among two reviewers (Table 4.18). Using the two-reviewer definition of agreement, described above, the percent agreement increased to 85% (34/40).

Table 4.18: Review of average instability scores based on the qualitative assessment of instability by the three expert reviewers.

Average Scores	**Initial Groupings**	
	CONTROL-I (n=20)	**INST-I (n=20)**
<2.0 (viewed as stable)	17	15
>2.0 (viewed as unstable)	2	2
=2.0	1*	3† (1 viewed as abnormal)
Summary	17 viewed as normal	3 viewed as unstable

* Score was (1, 2, 3) and was excluded because it was indeterminate.

† One had surgeon agreement (3, 3, 0) for instability and two were indeterminate (1, 2, 3).

To compare the definitions used by the three reviewers for defining abnormal motion and instability the frequency distribution (Table 4.19) and a correlation matrix

(Table 4.20) were calculated. Overall, reviewer OS1 had an 89.7% agreement between his ordinal responses for both the quality of motion and stability among the subjects, while reviewer OS2 had a 40% agreement and reviewer NS had a 72.5% agreement.

Table 4.19: Frequency distribution of the reviewers results for global motion and stability characteristics

Reviewer	Definite Normal or Stable	Probably	Indeterminate	Probably	Definite Abnormal or Unstable
OS1*	19	6	0	12	2
Motion	48.7%	15.4%	0%	30.8%	5.1%
OS1*	19	9	0	10	1
Stability	48.7%	23.1%	0%	25.6%	2.6%
OS2*	8	6	9	10	7
Motion	20.0%	15.0%	22.5%	25.0%	17.5%
OS2*	12	18	6	3	1
Stability	30%	45%	15.0%	7.5%	2.5%
NS*	0	27	6	7	0
Motion	0%	67.5%	15.0%	17.5%	0%
NS*	1	31	7	1	0
Stability	2.5%	77.5%	17.5%	2.5%	0%

*n=39 for reviewer OS1 and n=40 for reviewers OS2 and NS

Table 4.20: Correlation matrix comparing the responses of normality and stability of motion among the three reviewers

	OS1 Motion	OS1 Stability	OS2 Motion	OS2 Stability	NS Motion	NS Stability
OS1 Motion	1	.926** p = .000	.328* p = .041	.142 p = .389	.219 p = .181	.369* p = .021
OS1 Stability		1	.322* p = .046	.170 p = .300	.301 p = .063	.422* p = .007
OS2 Motion			1	.606** p = .000	.070 p = .666	-.085 p = .600
OS2 Stability				1	.082 p = .615	-.080 p = .625
NS Motion					1	.570** p = .000
NS Stability						1

In addition to the analysis of global motion, the reviewers were asked to comment on segmental motion as normal, hypomobile, or hypermobile for L3-4, L4-5, and L5-S1. In 52/120 (43.3%) of the segmental analyses there was agreement among all three reviewers. There were 48 agreements of normal segmental motion, 3 agreements of hypomobility, and 1 agreement for a hypermobile segment by all three surgeons. When the standard of agreement was changed to two of the three reviewers in agreement; the value increased to 118/120 (98.3 %) segmental agreement. Using this definition, 95 segments were viewed as normal, 14 segments were viewed as hypomobile, and 9 were viewed as hypermobile. The segments that were viewed as hypomobile were: L3-4: 1, L4-5: 5, L5-S1: 8. The levels of the segments that were viewed as hypermobile were: L3-4: 1, L4-5: 7, and L5-S1: 8. Further, four subjects were viewed as having multiple segments of dysfunction: two subjects were viewed to have an hypermobile L4-5 with an hypomobile L5-S1, and two subjects were viewed as having multiple segments that were

hypomobile. Of the 15 individuals with a motion score > 2.0 or agreement among two surgeons of abnormal motion; 13/15 (86.7%) had at least one segment in which two or more surgeons agreed the segment was either hypomobile or hypermobile. There were five subjects in which segmental problems were noted by two or more surgeons, but global motion was determined to be normal or indeterminate (Table 4.21).

In addition to describing the global and segmental motion, the reviewers were asked to select a possible mechanism associated with any problems observed: translation/displacement, angular positioning, velocity, rhythm, or other with comments. Multiple responses were allowed for each DFV viewed. Twenty-five times the reviewers felt that the motion problem was related to translation or displacement abnormalities. In 11 cases they believed the problem was angular in nature. Velocity and rhythm of the motion received 14 and 13 responses, respectively. Ten responses were received based on the limited or lack of motion (globally: 2, L4-5: 3, and L5-S1: 6 or the addition of hip motion during flexion: 3). Three responses further expanded on the rhythm of the motion; two viewed a delayed onset of movement at L4-5 on separate subjects, and one observed the order of motion for a subject switched from the typical cephalad to caudal motion to L4, L3, and then L5. One reviewer observed that a subject had abnormal translation during the beginning of the motion followed by both hypermobility then hypomobility, and one reviewer believed the L3-4 segment did not fully extend upon return to an upright posture. Associated with the fifteen subjects that were viewed by the surgeons to have abnormal motion, as previously described, 48 abnormalities were noted with an average of 3.27 ± 0.96 abnormal movement patterns noted per subject.

Table 4.21: Disagreement between segmental motion analysis and global motion patterns

Symptom-Based Group	Motion Scores*	Motion-Based Group†	Segmental Motion Agreement‡
Control	1, 2, 3	Indeterminate	L5-S1 Hypomobile
Control	1, 2, 3	Indeterminate	L4-5 Hypomobile
Instability	1, 2, 3	Indeterminate	L5-S1 Hypomobile
Instability	1, 1, 4	Normal Motion	L5-S1 Hypomobile
Instability	1, 1, 1	Normal Motion	L4-5 Hypermobile L5-S1 Hypomobile

*Scores from each surgeon for motion characteristic of the entire motion (0 = normal, 2 = indeterminate, 4 = abnormal)

†Average score < 2.0 = normal motion,

Average score = 2.0 with agreement of 2 surgeons < 2.0 = normal motion,

Average score = 2.0 without agreement = indeterminate

‡Agreement of two or more surgeons of segmental dysfunction

Prior to analysis of the DFV, the reviewers were asked to evaluate the static image of each subject's upright state and assess the image as normal static alignment or abnormal static alignment. Only 8 of the 40 images were viewed as having a static abnormality by two or more reviewers; six received an average abnormal motion score > 2.0, five were from the instability group, and three were originally control subjects without a history of LBP. Of the three subjects without a history of LBP and yet viewed as abnormal on static imaging: one had a transitional vertebrae with disc space narrowing at L5-S1, and the other two were viewed has having a forward flexed or hypolordotic standing postures. For the five subjects in the symptom-based group of instability the comments ranged from flattened lumbar spine with upright posture, disc space narrowing at L4-5 and L5-S1, retrololisthesis of L3-4, and a limbus vertebral body.

Towards the end of the analysis, the reviewers were asked to determine if the DFV provided different information than the initial static image. This question was analyzed based on subjects that were reviewed as having an abnormal static image (Table 4.22) and on subjects that were viewed to have an abnormal global motion pattern (Table 4.23). Both of these reviews included the results based on each single reviewer and group agreement data. Based on the combined analysis of all three reviewers, 87.5% of the time the reviewers believed the DFV provided new information about the dysfunction when the static image was abnormal. Further, 88.9% of the time when the reviewer viewed the image as having an abnormal movement pattern, the movement data were viewed as beneficial because of the additional information provided about the subject's possible dysfunction. When analyzing the entire set of DFV, regardless of movement or stability status, the reviewers found the DFV valuable because of the different information it provided over the static upright image in 72.0% of the cases. In 17.8% they did not feel it provided additional information and in 10.2% of the cases they were unsure about its additional benefit.

Table 4.22: Value of DFV versus the static upright image in providing additional information about the subject's dysfunction based on those viewed with an abnormal static image.

Response	OS1 (n=12)	OS2 (n=10)	NS (n=5)	Agreement* (n: 8x3=24)
Yes	10	10	5	21
No	2	0	0	2
Unsure	0	0	0	1

*Agreement was based on two of the three reviewers determining the static upright image was abnormal. In 7 of the 8 combined cases there was at least one reviewer who viewed the image as normal.

Table 4.23: Value of DFV versus the static upright image in providing additional information about the subject's dysfunction based on those viewed with an abnormal movement.

Response	OS1 (n=14)	OS2 (n=17)	NS (n=7)	Abnormal Motion* (n: 15x3=45)
Yes	14	16	7	40
No	0	0	0	3
Unsure	0	1	0	2

*Abnormal motion was determined by a combined score > 2.0, or agreement of two surgeons of abnormal motion based on viewing the DFV. In 10 of the 15 combined cases there was at least one reviewer who viewed the image as a normal movement pattern.

In addition to being asked if the information provided by the DFV was different from the static image, the reviewers were asked if the DFV would have been helpful to the reviewer. In those that were viewed to have an abnormal static image across reviewers, 83.3% of reviews viewed the information as helpful. Further, in those cases determined by the reviewers to have abnormal motion, 84.4% were viewed as helpful to the reviewer. Detailed results of the individual and combined reviewer's answers based on the determination of an abnormal static image or an abnormal movement pattern are provided in Table 4.24 and 4.25, respectively. When analyzing the entire data set, regardless of the movement or stability status of the subjects, the reviewers felt the DFV would have been helpful in the diagnosis and care of the patient in 68.6% of the cases, in 16.1% of the cases they did not feel the DFV would have been helpful, and in 15.3% of the cases they were unsure.

Table 4.24: Helpfulness of DFV based on those viewed with an abnormal static image.

Response	OS1 (n=12)	OS2 (n=10)	NS (n=5)	Agreement* (n: 8x3=24)
Yes	11	8	5	20
No	1	0	0	2
Unsure	0	2	0	2

*Agreement was based on two of the three reviewers determining the static upright image was abnormal. In 7 of the 8 combined cases there was at least one reviewer who viewed the image as normal.

Table 4.25: Helpfulness of DFV based on those viewed with an abnormal movement.

Response	OS1 (n=14)	OS2 (n=17)	NS (n=7)	Abnormal Motion* (n: 15x3=45)
Yes	14	15	7	38
No	0	0	0	3
Unsure	0	2	0	4

*Abnormal motion was determined by a combined score > 2.0, or agreement of two surgeons of abnormal motion based on viewing the DFV. In 10 of the 15 combined cases there was at least one reviewer who viewed the image as a normal movement pattern.

Throughout the qualitative assessment of the DFV, the reviewers were encouraged to comment on their thoughts about the lumbar kinematics observed and the information they provide. One consistent theme in the responses was an appreciation of the pattern of motion between the upright and flexed postures and the ability to assess delays in motion or disordered movement. For example, in one case it appeared that L4 initiated flexion prior to L3. Further, by observing the motion the reviewers commented on the ability to assess the relative motion between different segments. This type of analysis was viewed as valuable to the reviewers because it allowed them to speculate on the level of dysfunction based on excessive motion at one segment, relative hypomobile segments, and to determine if the motion is centering on a more cephalad segment (i.e. kyphosis at L4-5 during flexion). In addition to interbody motion, all three surgeons

commented on the ability of the DFV to observe the facet motion. Further, they commented that the observation of the relative "uncovering" of the facets among levels was beneficial in determining normal and abnormal motion.

In addition to comments on the ability to observe the motion at the segmental level, comments were also received on the ability to correlate those observations with static abnormalities. For those with a possible spondylolisthesis, one comment was that the DFV allowed the observer to differentiate between a static slip and a mobile dysfunction. For those with disc space narrowing, the observers commented on the ability of the DFV to allow them to determine the amount of motion associated with the narrowing, resulting in comments that some cases appeared to allow normal motion while others appeared to be hypomobile. A few comments were received about the motion observed in those with a "deep seated" L5-S1 relative to the pelvis; the comments stated that subjects with this anatomical variant tended to have decreased motion at L5-S1 and increased hip motion. There was one individual with a limbus vertebra, one observer commented on the ability to appreciate motion at the unfused ring apophysis with motion, in which a fixed deformity would otherwise have been assumed.

The reviewers also commented on both new questions and limitations of the DFV technique. A couple comments centered on the definition of normal motion and the definition of instability. One surgeon suggested that the DFV may lead us to define instability differently, while another was concerned that the concept of "stable" may be viewed differently both among the surgeons (orthopedists and neurosurgeons) and the rehabilitation community. Although the DFV provided the surgeons with information on lumbar motion, a couple comments centered on the need to correlate these findings with more traditional imaging techniques (static radiographs, CT scans, and MRIs).

COMPARATIVE & DESCRIPTIVE STATISTICS FOR MOTION-BASED GROUPS

Angular Range (Flexion and Extension)

Global motion, as measured by segmental lordosis (L3-S1), was equivalent between the INST-F and CONTROL-F groups (Table 4.26, Figure 4.19). The global motion of each group was approximately 40 - 42°. The lordosis angle was 8.06 $\pm$ 7.41° for the flexed posture, and 41.77 $\pm$ 5.77° for the upright posture in the INST-F group. Redefinition of group membership resulted in a shift of the means for the minimum and maximum lordosis angle by 2.28° and 2.63°, respectively, from the INST-I group (Figure 4.20). Those changes occurred with only a 0.35° change in the mean difference in global angular range between the two instability groupings, demonstrating a possible shift in the motion measured in the INST-F group towards a more upright posture without a substantial change in total angular ROM. The mean change in values for the control group was 0.78°.

Figure 4.19A-C: 4.19A: Trajectory of the global L3-S1 lordosis angle (change from the upright posture in the direction of flexion) with respect to time. Maximal value for L3-S1 lordosis angle was plotted at 3.96 seconds for all subjects. 4.19B: Trajectory of the average change in the global L3-S1 lordosis angle with respect to percentage of global motion. 4.19C: Trajectory of the normalized global angle (/Range*100) with respect to percentage of global motion.

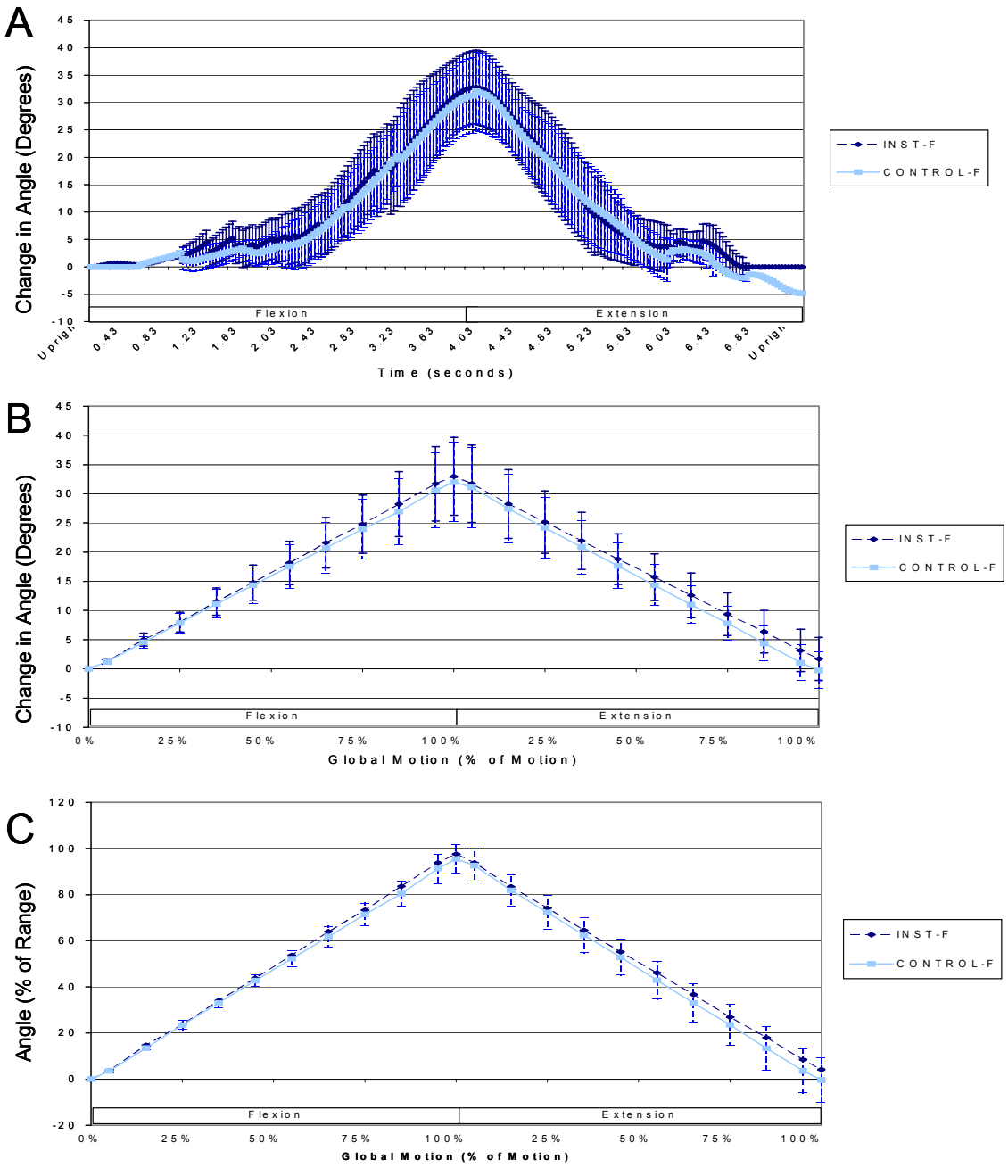
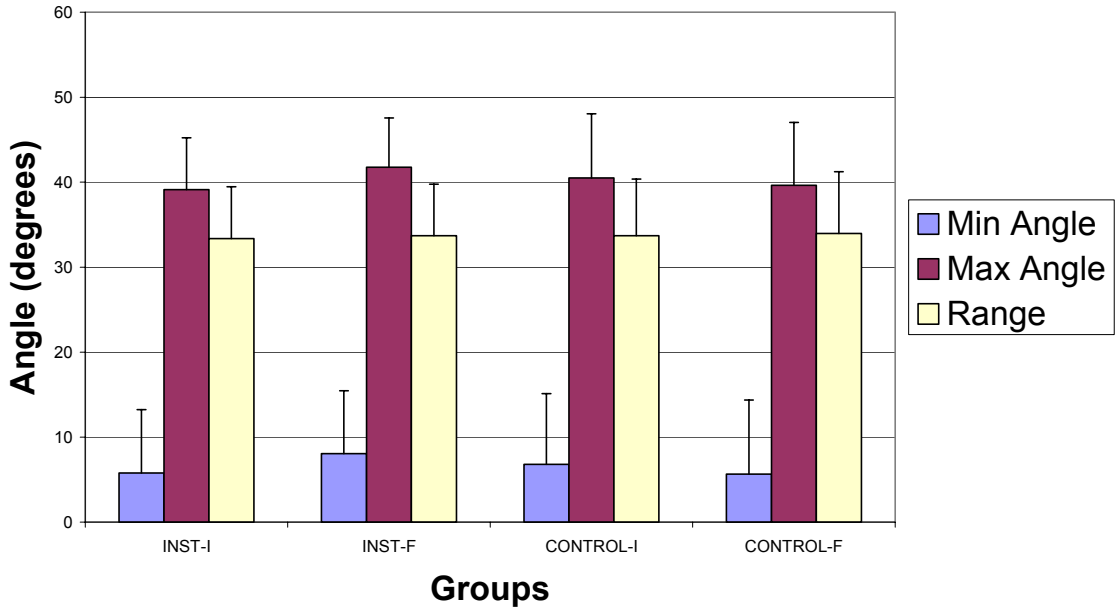


Table 4.26: Global Motion L3-S1 Lordosis Angle

Lordosis Angle (degrees)	CONTROL-F (n=14)	INST-F (n=11)	p-value
Minimum	5.64 ± 8.72	8.06 ± 7.41	.469
Maximum	39.62 ± 7.40	41.77 ± 5.77	.436
Range	33.97 ± 7.27	33.71 ± 6.07	.922

Figure 4.20: Comparison between global motion patterns in both the symptom based groups (INST-I, CONTROL-I) and the final motion-based assessment groups (INST-F, CONTROL-F).



Segmental angular values (range, mean, minimum, and maximum) for each FSU yielded no significant differences between the INST-F and CONTROL-F groups (Table 4.27, Figures 4.21-4.24). However the maximum angular instability ratio was significant ($p = .048$) during extension, demonstrating a mean decrease of 10% from the segment with the maximal angle range compared to the mean range of all segments in the INST-F group. Greater variability of the angular motion at L4-5 was noted in the INST-F group (Figure 4.22A&B).

Segmental angular motion as a percent of total angular motion (From L3-4 to L5-S1) was analyzed using an ANOVA which revealed a main effect for level (L3-4, L4-5, and L5-S1; $p = .002$; Table 4.28), but no interaction between level and group membership ($p = .468$). Post-hoc analysis with a Bonferroni correction revealed the percent of angular motion at L4-5 was greater than that at L5-S1 ($p = .003$) and there was a trend towards increased percent of angular motion at L3-4 compared to L5-S1 ($p = .089$). There were no differences between percent of angular motion at L3-4 compared with L4-5 ($p = 1.000$).

In the initial groupings (INST-I and CONTROL-I) both groups demonstrated approximately 36% of the motion at L3-4 and L4-5, with 28% of the motion occurring at L5-S1. After the expert review, the INST-F grouping had 33.5% of the motion at L3-4, 36.5% at L4-5, and 30% at L5-S1, while the CONTROL-F group continued to display the previous distribution of motion among the levels. The decrease in the mean percent angular range at L3-4 was 2.7%, and the mean increase of angular range at L5-S1 was 2.2% compared to the CONTROL-F group (Table 4.28). Although, the level by group interaction was not significant, these changes help to describe the significant angular instability ratio described previously.

Table 4.27: Descriptive statistics for segmental angle data

Level	Value	Flexion (degrees)			Extension (degrees)		
		CONTROL-F (n=14)	INST-F (n=11)	p-value	CONTROL-F (n=14)	INST-F (n=11)	p-value
L3-4	**Mean**	2.58 ± 3.15	2.97 ± 2.72	.748	3.62 ± 3.01	4.64 ± 2.75	.391
	Maximum	10.07 ± 3.10	10.21 ± 3.01	.907	10.01 ± 4.19	10.12 ± 2.52	.941
	Minimum	-3.01 ± 2.78	-2.04 ± 2.90	.404	-2.72 ± 2.93	-1.33 ± 3.08	.262
	Range	13.08 ± 2.74	12.25 ± 2.64	.455	12.73 ± 3.51	11.44 ± 1.31	.225
L4-5	**Mean**	7.99 ± 4.67	9.33 ± 3.51	.436	9.04 ± 3.53	9.83 ± 4.01	.609
	Maximum	15.44 ± 4.40	16.52 ± 3.86	.527	15.29 ± 4.01	14.97 ± 2.87	.826
	Minimum	1.72 ± 3.60	2.71 ± 3.77	.511	2.01 ± 3.73	2.90 ± 4.09	.575
	Range	13.72 ± 2.62	13.82 ± 3.36	.939	13.28 ± 2.14	12.07 ± 2.91	.242
L5-S1	**Mean**	9.84 ± 2.39	11.59 ± 4.38	.215	9.79 ± 1.73	11.11 ± 3.88	.265
	Maximum	14.88 ± 2.67	16.76 ± 5.26	.257	14.97 ± 3.63	15.84 ± 4.05	.574
	Minimum	4.91 ± 2.83	5.49 ± 4.41	.691	4.47 ± 2.77	5.62 ± 4.27	.424
	Range	9.97 ± 3.62	11.27 ± 3.33	.367	10.49 ± 5.21	10.22 ± 3.30	.882
All	**Instability ratio***	1.24 ± 0.12	1.21 ± 0.10	.552	1.26 ± 0.11	1.16 ± 0.12	.048

*Maximum range of a single segment across all segments/ mean range of all segments

Figure 4.21A-C: Trajectory of the L3-4 segmental angle (change from the upright posture in the direction of flexion) with respect to time. Subjects were standardized across time by plotting the maximal value for L3-S1 lordosis angle at 3.96 seconds for all subjects. 4.21B: Trajectory of the average change in the L3-4 segmental angle with respect to percentage of global motion of L3-S1 lordosis angle. 4.21C: Trajectory of the normalized L3-4 angle (/Range*100) with respect to percentage of global motion.

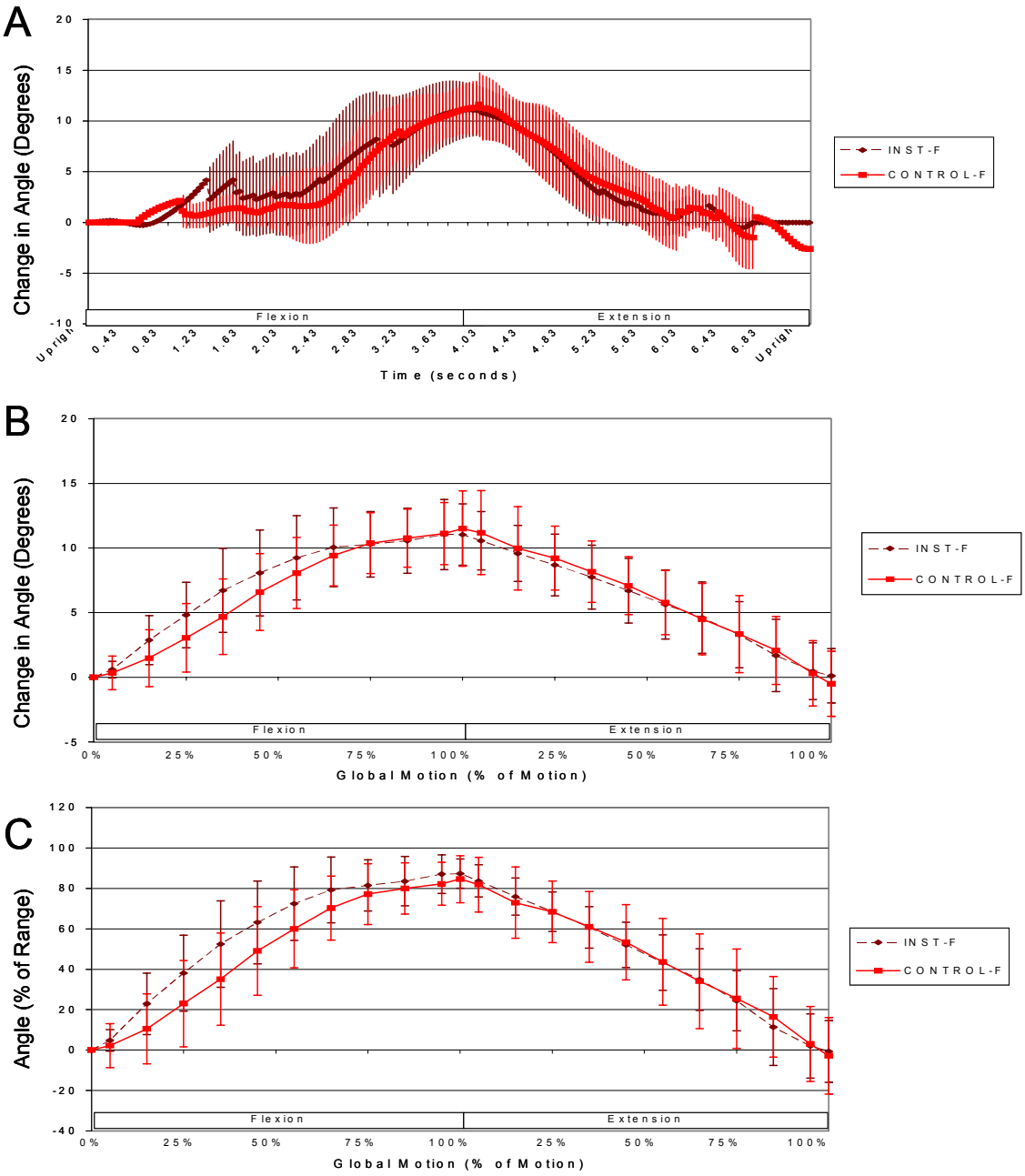


Figure 422A-C: 4.22A: Trajectory of the L4-5 segmental angle (change from the upright posture in the direction of flexion) with respect to time. Subjects were standardized across time by plotting the maximal value for L3-S1 lordosis angle at 3.96 seconds for all subjects. 4.22B: Trajectory of the average change in the L4-5 segmental angle with respect to percentage of global motion of L3-S1 lordosis angle. 4.22C: Trajectory of the normalized L4-5 angle (⁄Range*100) with respect to percentage of global motion.

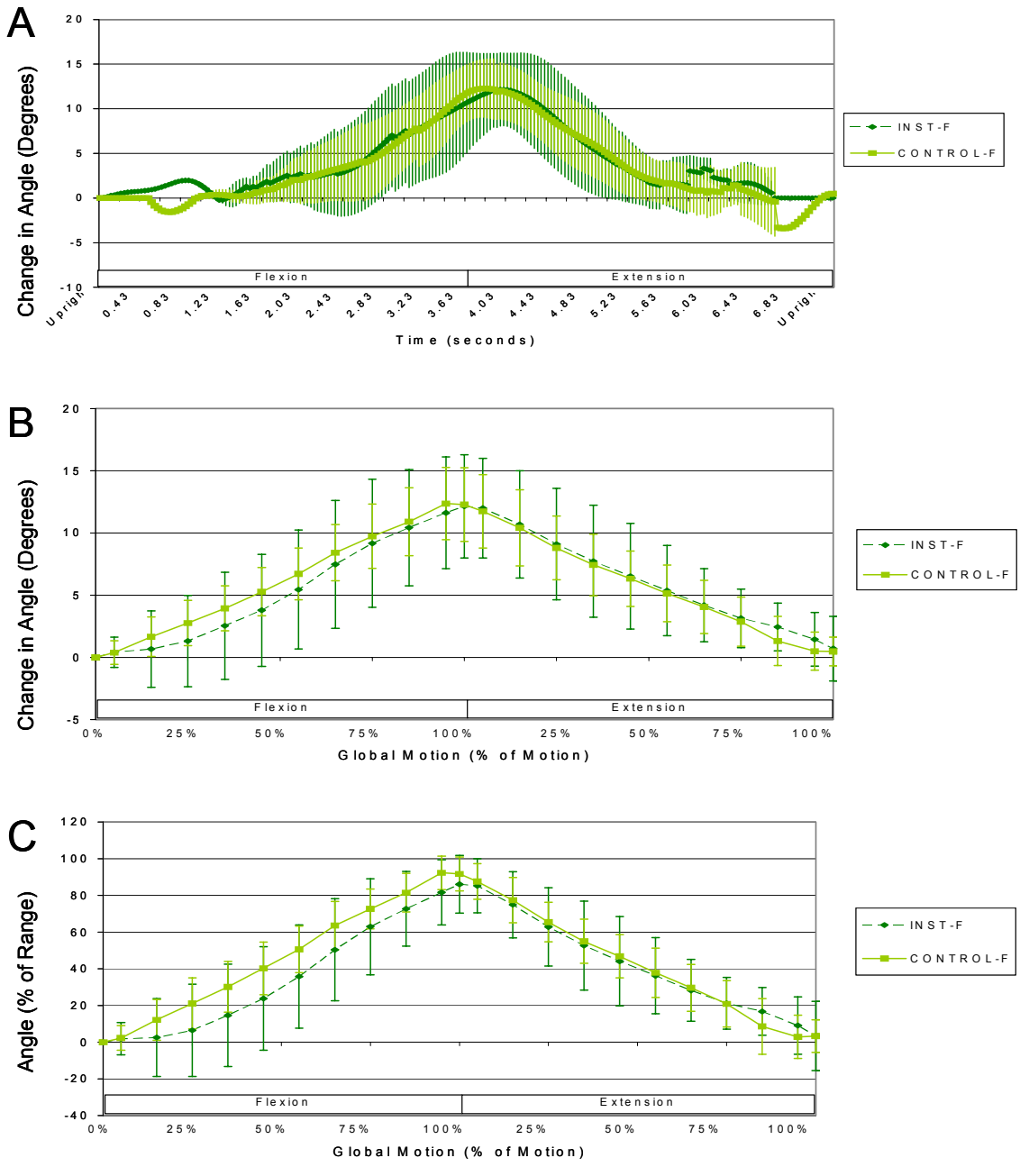


Figure 4.23A-C: 4.23A: Trajectory of the L5-S1 segmental angle (change from the upright posture in the direction of flexion) with respect to time. Subjects were standardized across time by plotting the maximal value for L3-S1 lordosis angle at 3.96 seconds for all subjects. 4.23B: Trajectory of the average change in the L5-S1 segmental angle with respect to percentage of global motion of L3-S1 lordosis angle. 4.23C: Trajectory of the normalized L5-S1 angle (/Range*100) with respect to percentage of global motion.

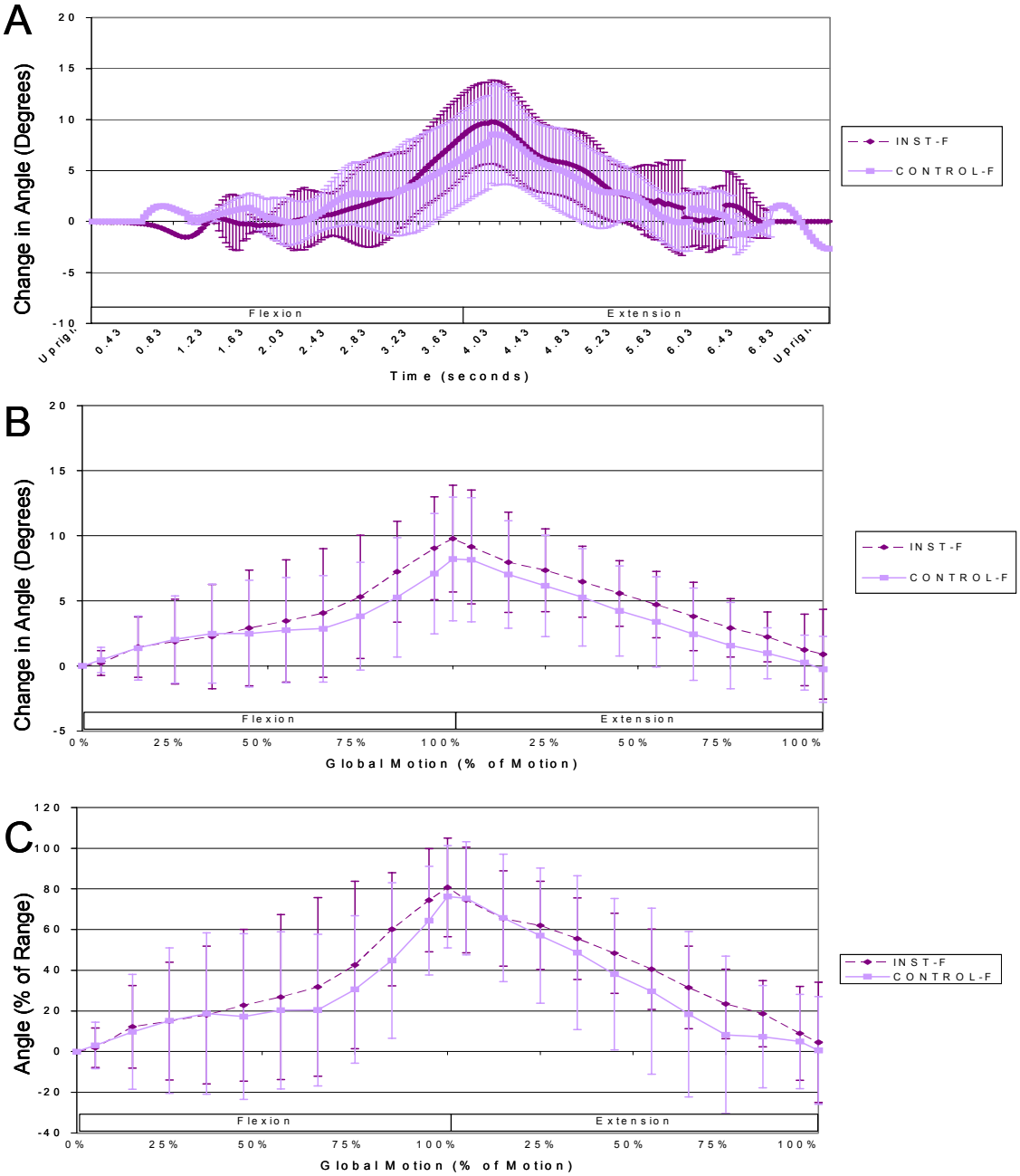


Figure 4.24A-C: Comparison of angle trajectory of lordosis and segmental angle range (4.24A) with respect to time, (4.24B) with respect to global motion, and (4.24C), and normalized angle with respect to global motion.

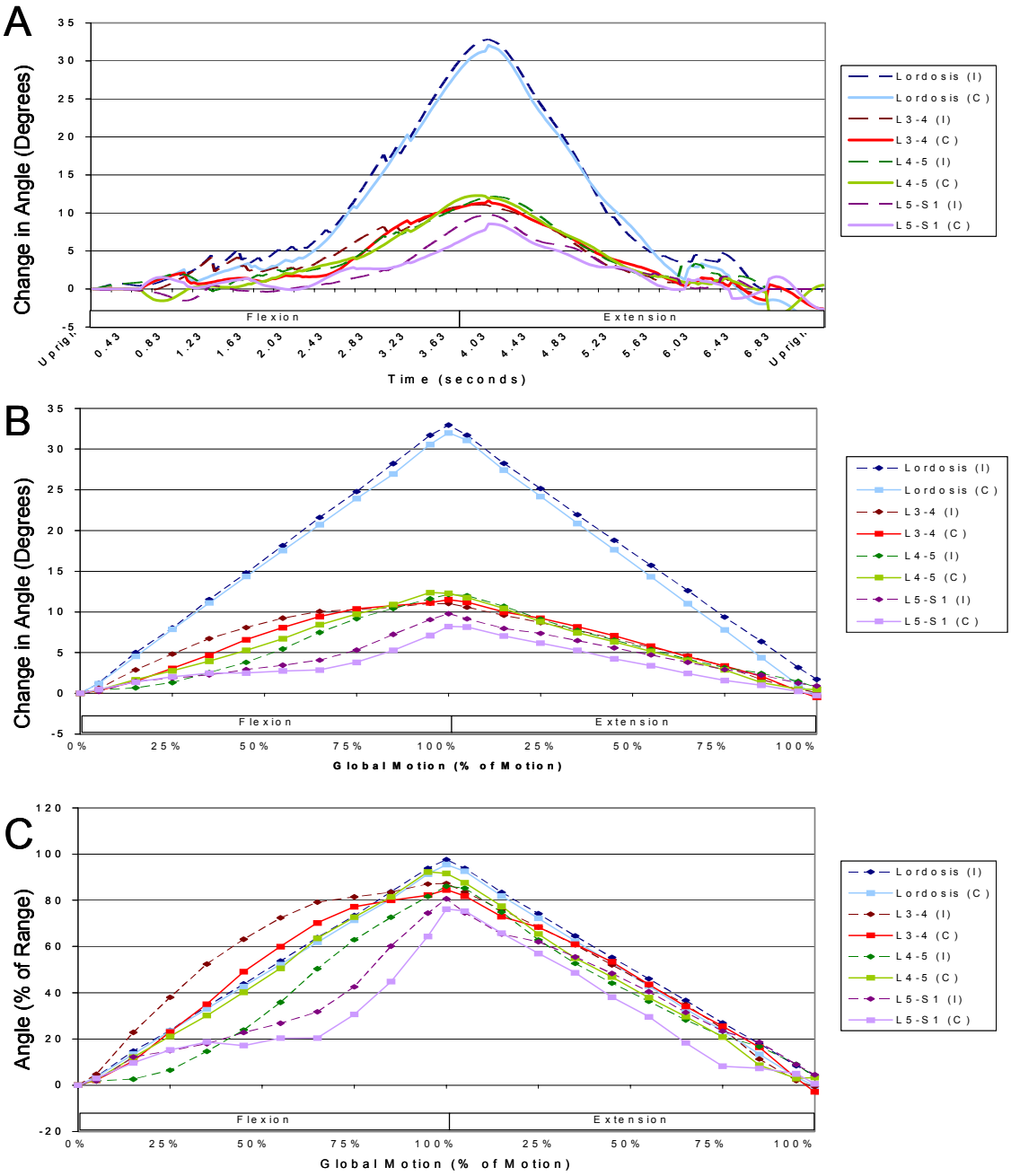


Table 4.28: Segmental angle range as a ratio of total angle range

	CONTROL-F (n=14)	INST-F (n=11)	Mean Difference in INST-F
Total Angle Range	40.06 ± 6.45°	39.38 ± 5.45°	↓ 0.68°
Percent at L3-4	36.1 ± 6.9%	33.4 ± 5.1%	↓ 2.70%
Percent at L4-5	35.9 ± 4.3%	36.4 ± 4.1%	↑ 0.50%
Percent at L5-S1	28.0 ± 7.6%	30.2 ± 4.8%	↑ 2.20%

Angle Timing

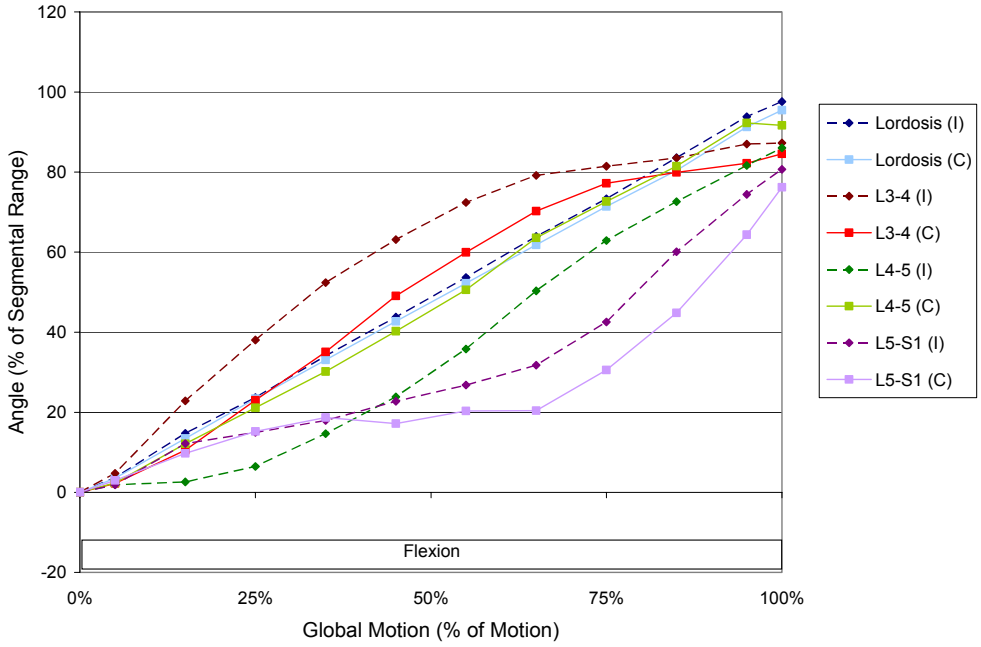
Flexion: Within-Group Analysis

A trend towards sequential motion during flexion can be appreciated while observing the normalized motion graph (Figure 4.25A). The trajectory of L3-4 in the INST-F demonstrates a greater slope during the initiation of flexion than the CONTROL-F group. The rate of attainment of angle range as a function of global motion (slope) of L3-4 is at a maximum at 5-15% of motion for the INST-F group and 35-45% of motion for the CONTROL-F group (Figure 4.26A). The maximum rate of attainment of angular range for L4-5 was at 55-65% of flexion for both groups (Figure 4.26B) and during 75-85% for INST-F and 95-100% for CONTROL-F for L5-S1 (Figure 4.26C).

A within-groups analysis, 3 × 4 ANOVA (Table 4.29), revealed a significant interaction effect ($p < .001$) between the segmental level (L3-4, L4-5, and L5-S1) and percent of motion (0-25%, 25-55%, 55-75%, 75-100%) without a significant interaction between segmental level, percent of motion and group ($p = .316$). Post-hoc analysis with a Bonferroni correction revealed that the attainment of angular range of L3-4 was greater during 0-25% of flexion than 55-75% ($p = .033$) and 75-100% ($p = .002$) of flexion, and was greater during 25-55% of flexion compared with both 55-75% and 75-100% ($p < .001$) of flexion. At L4-5 the attainment of angular range was greater during 25-55% of flexion compared to 0-25% of flexion ($p = .015$), and at L5-S1 the rate of attainment was

Figure 4.25: Normalized segmental angle trajectory (%) per global angle (%) during flexion (A) and extension (B).

A.



B.

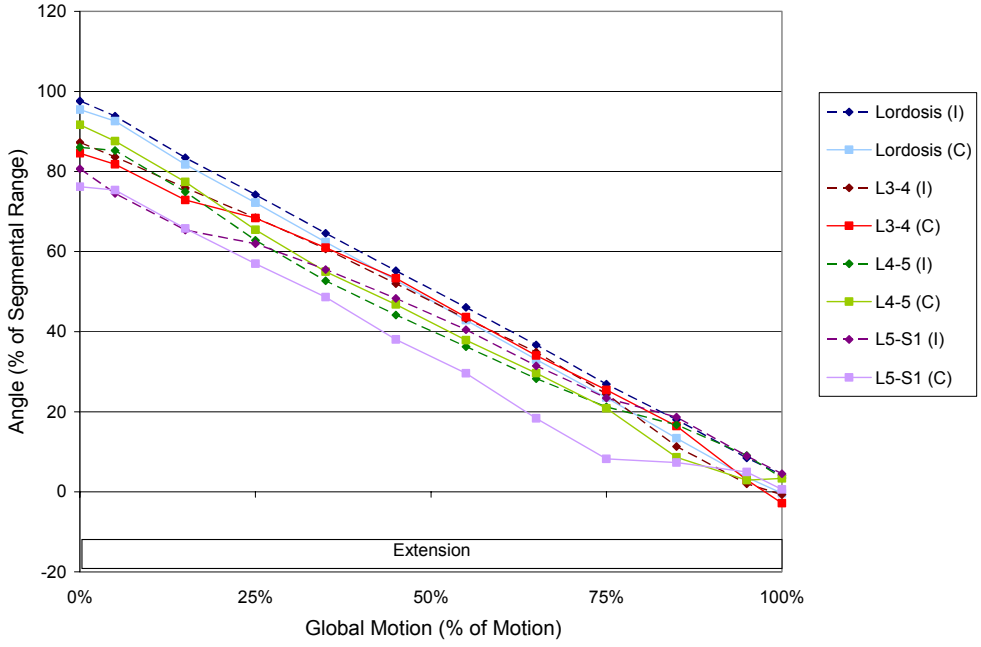


Figure 4.26A-C. Rate of attainment (slope) of normalized angle range (%) as a function of global motion (%) of L3-4 (A), L4-5 (B), and L5-S1 (C)

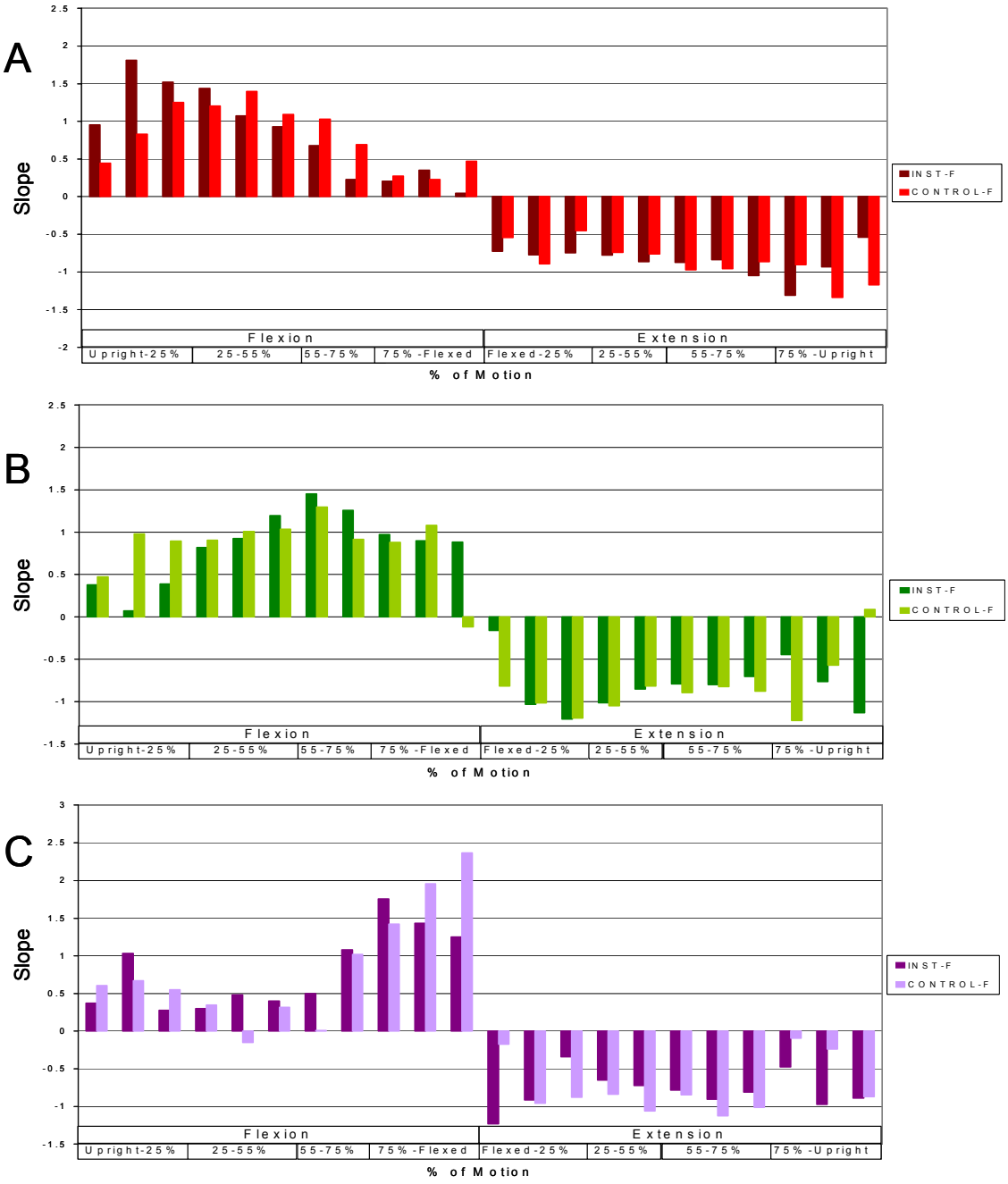


Table 4.29: Analysis of within-group angular difference across levels (L3-4, L4-5, and L5-S1) and motion (0-25%, 25-55%, 55-75%, and 75-100%) during flexion (n=25)

Source	df†	SS	MS	F	p-value
Level (3)	1.567	0.569	0.363	2.462	.111
Motion (4)	1.982	4.143	2.090	14.553	<.001
Level × Motion	2.561	50.557	19.742	9.294	<.001
Level × Motion × Group	2.561	6.504	2.540	1.196	.316

*df = degrees of freedom, SS = Type III Sum of Squares, MS = Mean Square, and F = F-value

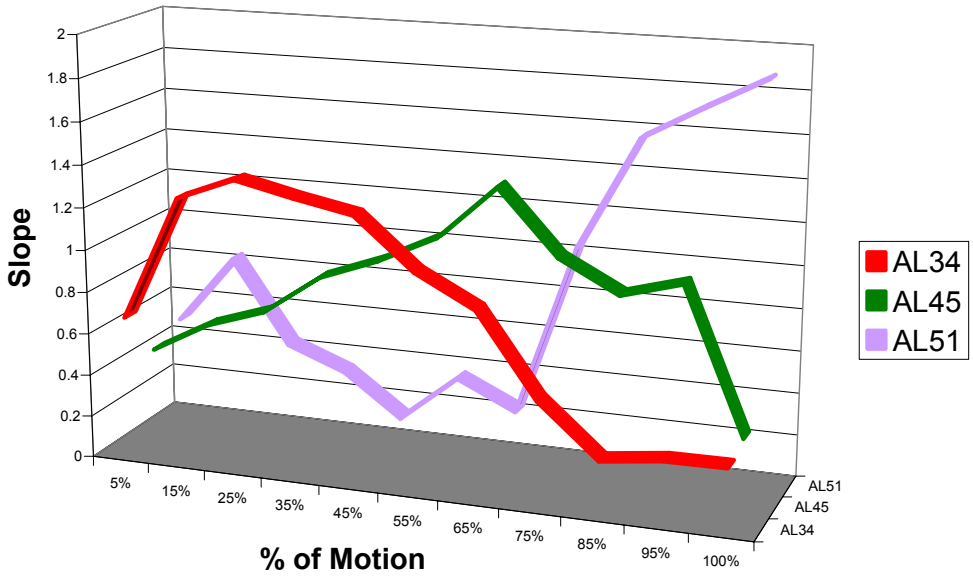
† Sphericity assumption was not met (significant Mauchly's test of sphericity), therefore the df were adjusted using the Greenhouse-Geisser formula.

Table 4.30: Post-hoc analysis with Bonferroni correction for level (3) by motion (4) comparisons during flexion (n=25)

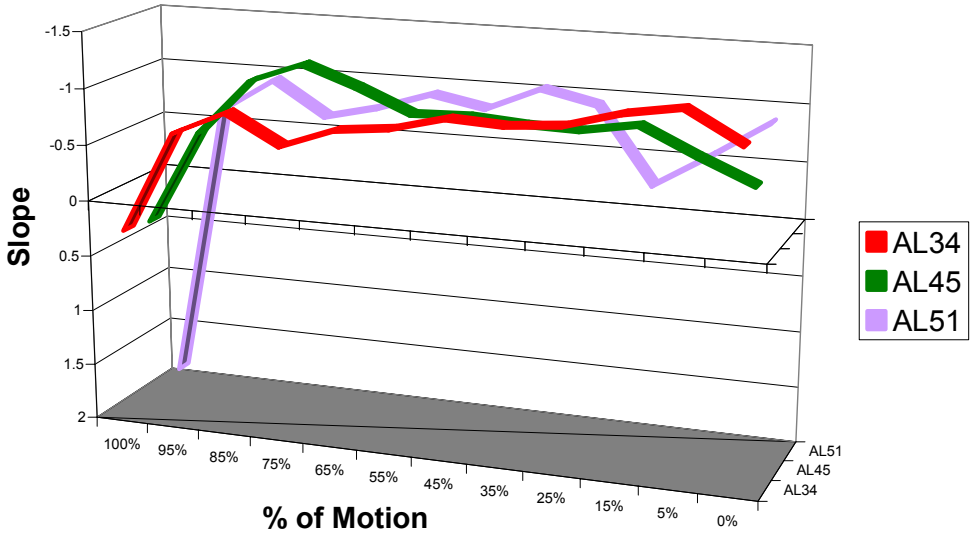
Motion	0-25%	25-55%	55-75%	75-100%
L3-4 to L4-5	> (p = .047)	- (p = .183)	< (p = .008)	< (p = .001)
L4-5 to L5-S1	- (p = 1.000)	> (p < .001)	> (p = .006)	< (p = .059)
L3-4 to L5-S1	- (p = .343)	> (p < .001)	- (p = 1.000)	< (p < .001)

Figure 4.27: Rate of attainment (slope) of the normalized angle range (%) as a function of global motion (%) during flexion (A) and extension (B), n=25

A.



B.



greater during 75-100% of flexion compared to 25-55% ($p = .001$), and from 55-75% ($p < .001$) of flexion. The motion by level post-hoc analysis with a Bonferroni correction was provided in Table 4.30 and Figure 4.27. During the initiation of flexion, the rate of attainment of angular range was greater at L3-4 than at L4-5 ($p = .047$). During 25-55% of flexion both L3-4 and L4-5 were obtaining angular range at a greater rate than L5-S1 ($p < .001$). During 55-75% of flexion L4-5 was obtaining angular range at a greater rate than L3-4 ($p = .008$) and L5-S1 ($p = .006$). During the final stages of flexion (75-100%) L4-5 was obtaining angular range at a greater rate than L3-4 ($p = .001$). Segment L5-S1 was attaining angular range greater than L3-4 ($p < .001$) and a possible trend towards greater attainment compared to L4-5 ($p = .059$).

Flexion: Between-Group Analysis

During the initiation of flexion, the attainment of angular range differed between groups when analyzed in 5-10% increments of motion (Table 4.31, Figures 4.26A and 4.27). During 5-15% of motion, the attainment of angular range at L3-4 was greater in the INST-F group compared to the CONTROL-F group ($p = .019$). This was accompanied by a relative decrease in angular attainment at L4-5 in the INST-F group ($p = .045$), this trend at L4-5 continued during 15-25% of flexion ($p = .106$). During 35-45% of flexion, there was a trend in which the rate of attainment in angular range at L3-4 was greater ($p = .101$) in the CONTROL-F group, while the relative rate of attainment of displacement at L5-S1 was less in the INST-F group ($p = .060$).

Extension: Within-Group Analysis

A sequential motion pattern was not noted during extension (Figure 4.25B). A within-groups analysis, 3×4 ANOVA (Table 4.32) revealed a main effect for motion ($p < .001$) with an interaction effect of motion and group membership ($p = .034$). The

Table 4.31: Slope of angular change (%) as a function of global motion (%) during the initiation of flexion

	CONTROL-F (n=14)	INST-F (n=11)	p-value	p < 0.20	p < .05
L3-4 Motion					
0-5%	0.445 ± 2.175	0.954 ± 1.064	.485		
5-15%	0.829 ± 0.835	1.809 ± 1.118	.019	*	*
15-25%	1.252 ± 1.130	1.519 ± 0.646	.493		
25-35%	1.205 ± 0.630	1.437 ± 0.737	.405		
35-45%	1.397 ± 0.526	1.072 ± 0.392	.101	*	
45-55%	1.091 ± 0.568	0.926 ± 0.474	.447		
L4-5 Motion					
0-5%	0.473 ± 1.327	0.377 ± 1.760	.878		
5-15%	0.980 ± 0.751	0.071 ± 1.365	.045	*	*
15-25%	0.896 ± 0.890	0.387 ± 0.664	.106	*	
25-35%	0.904 ± 0.409	0.817 ± 0.716	.704		
35-45%	1.008 ± 0.397	0.923 ± 0.345	.582		
45-55%	1.033 ± 0.577	1.195 ± 0.278	.404		
L5-S1 Motion					
0-5%	0.604 ± 2.290	0.370 ± 1.945	.789		
5-15%	0.669 ± 1.870	1.034 ± 1.240	.583		
15-25%	0.552 ± 1.268	0.278 ± 1.060	.571		
25-35%	0.345 ± 0.928	0.301 ± 1.114	.914		
35-45%	-0.152 ± 0.916	0.479 ± 0.592	.060	*	
45-55%	0.317 ± 0.612	0.402 ± 0.495	.712		

main effect for segmental level (p = .090), the interaction effect between segmental level and percent of motion (p= .269), and the interaction between segmental level, percent of motion, and group membership (p = .753) were not significant. Post-hoc analysis with a Bonferroni correction revealed the rate of attainment of angular range during extension (absolute mean slope) for the CONTROL-F group was greatest during 55-75% of the return to upright relative to 0-25%, 25-55%, and 75-100% (p < .001). Further the absolute rate of attainment of angular range was greater during the first 25% of extension relative to 25-55% of extension (p = .005). The ISNT-F group displayed a similar pattern. As with the CONTROL-F group, the greatest absolute slope was during 55-75% of the return to upright relative to 0-25% (p = .005), 25-55% (p <.001), and 75-100% (p = .034) and the absolute rate of attainment of angular range was greater during the first 25% of extension relative to 25-55% of extension (p = .001). In addition to those relationships, the INST-F group also demonstrated greater absolute rate of angular attainment during 75-100% of the return to upright relative to 25-55% (p = .011). Graphically, this can be appreciated in Figures 4.26 (A-C) and 4.27B.

Extension: Between-Group Analysis

During the last half of the return to the upright posture differences between groups were noted in L3-4 and L4-5 but not in L5-S1 (Table 4.33). Specifically, the absolute rate of attainment of angular range tended to be less during the last 5% of extension (95-100%) at L3-4 in the INST-F group (p = .099). At L4-5, the absolute rate of attainment of angular range was less in the INST-F group during 75-85% of extension (p = .043), while it was greater during the last 5% of motion (95-100%; p = .041).

Table 4.32: Analysis of within-group angular difference across levels (L3-4, L4-5, and L5-S1) and motion (0-25%, 25-55%, 55-75%, and 75-100%) during extension for the motion-based groups

Source	df	SS	MS	F	p-value
Level (3)	2.000	0.772	0.386	2.540	.090
Motion (4)	2.109†	6.007	2.848	44.521	<.001
Motion × Group	2.109†	0.478	0.227	3.545	.034
Level × Motion	3.707†	4.522	1.220	1.324	.269
Level × Motion × Group	3.707	1.560	0.421	0.457	.753

*df = degrees of freedom, SS = Type III Sum of Squares, MS = Mean Square, and F = F-value

† Sphericity assumption was not met (significant Mauchly's test of sphericity), therefore the df were adjusted using the Greenhouse-Geisser formula.

Table 4.33: Slope of angular change (%) as a function of global motion (%) during the return to upright

	CONTROL-F (n=14)	INST-F (n=11)	p-value	p < .20	p < .05
L3-4 Motion					
45-55%	-0.972 ± 0.436	-0.876 ± 0.394	.574		
55-65%	-0.957 ± 0.578	-0.837 ± 0.242	.490†		
65-75%	-0.862 ± 0.795	-1.048 ± 0.511	.507		
75-85%	-0.902 ± 1.093	-1.308 ± 0.978	.344		
85-95%	-1.341 ± 0.940	-0.932 ± 0.761	.254		
95-100%	-1.173 ± 0.844	-0.539 ± 1.004	.099	*	
L4-5 Motion					
45-55%	-0.894 ± 0.359	-0.791 ± 0.569	.588		
55-65%	-0.823 ± 0.347	-0.801 ± 0.613	.908		
65-75%	-0.877 ± 0.668	-0.703 ± 0.485	.407		
75-85%	-1.225 ± 1.035	-0.447 ± 0.692	.043	*	*
85-95%	-0.570 ± 0.864	-0.764 ± 0.791	.568		
95-100%	0.086 ± 1.308	-1.132 ± 1.498	.041	*	*
L5-S1 Motion					
45-55%	-0.845 ± 0.983	-0.783 ± 0.316	.827†		
55-65%	-1.125 ± 0.704	-0.902 ± 0.633	.470		
65-75%	-1.011 ± 1.413	-0.808 ± 0.806	.674		
75-85%	-0.093 ± 1.986	-0.474 ± 1.372	.593		
85-95%	-0.238 ± 1.510	-0.970 ± 1.238	.207		
95-100%	-0.871 ± 1.642	-0.888 ± 1.998	.981		

† Equal variance not assumed secondary to a significant Levene's test for equality of variance

Displacement Range

The within-group analysis did not reveal a main effect for level (L3-4, L4-5, and L5-S1; p = .236), nor an interaction between level and group membership (p = .450). However, the observed power was only 0.302 for level and 0.181 for the interaction effect. Descriptive variables are provided to help provide an understanding of the displacement motion that occurred between the segmental levels among these groups. As a percentage of total displacement, L3-4 represented about 38%, L4-5 about 32% and L5-S1 about 30% in the CONTROL-F group (Table 4.34). In the INST-F group the amount of displacement at each segment was equivalent (32-34%). The mean segmental displacement range decreased from the L3-4 to L5-S1 for the CONTROL-F group (11% to 8%), while the range in the INST-F group tended to have less variability among levels (9-7%; Table 4.35). Graphical representation of segmental displacement was provided in Figures 4.28-4.31.

Table 4.34: Segmental displacement range as a ratio of total displacement range

	CONTROL-F (n=14)	**INST-F (n=11)**
Total Displacement Range*†	34.1 ± 9.0%	28.9 ± 7.8%
Percent at L3-4	38.2 ± 9.6%	34.3 ± 9.3%
Percent at L4-5	32.1 ± 6.0%	32.2 ± 7.7%
Percent at L5-S1	29.7 ± 8.9%	33.4 ± 9.0%

*Total displacement range is the summation of the displacement range at L3-4, L4-5, L5-S1, which is expressed as a percentage.

†Total displacement range (p = .144)

Independent t-tests to determine differences among the groups on the descriptive statistics related to displacement values found differences between the groups. Segment L4-5 in the INST-F group displayed less displacement range during extension (p = .036;

Table 4.35: Descriptive statistics for segmental displacement data

Level	Value	Flexion (%)			Extension (%)		
		CONTROL-F (n=14)	INST-F (n=11)	p-value	CONTROL-F (n=14)	INST-F (n=11)	p-value
L3-4	**Mean**	-.7.08 ± 2.36	-8.37 ± 4.41	.394	-5.93 ± 3.32	-8.33 ± 4.44	.136
	Maximum	-1.17 ± 4.61	-4.22 ± 5.94	.162	-0.32 ± 5.07	-4.07 ± 5.83	.099
	Minimum	-12.35 ± 3.25	-12.74 ± 3.29	.770	-11.51 ± 3.29	-12.80 ± 3.67	.365
	Range	11.18 ± 5.15	8.52 ± 4.23	.180	11.20 ± 5.54	8.74 ± 3.52	.213
L4-5	**Mean**	-8.84 ± 5.17	-9.20 ± 3.49	.846	-8.59 ± 5.09	-8.26 ± 3.30	.855
	Maximum	-3.88 ± 5.13	-4.90 ± 3.78	.587	-3.60 ± 5.80	-4.96 ± 3.78	.508
	Minimum	-13.49 ± 5.85	-13.53 ± 3.49	.981	-13.21 ± 4.72	-11.83 ± 3.82	.441
	Range	9.60 ± 3.17	8.63 ± 3.20	.457	9.61 ± 3.23	6.87 ± 2.80	.036
L5-S1	**Mean**	-7.40 ± 5.15	-8.31 ± 4.02	.635	-6.25 ± 5.10	-7.47 ± 2.67	.450
	Maximum	-2.93 ± 5.72	-4.43 ± 4.95	.498	-2.30 ± 5.61	-3.84 ± 3.74	.441
	Minimum	-10.92 ± 4.59	-12.70 ± 3.00	.255	-10.55 ± 4.43	-11.00 ± 3.28	.784
	Range	7.98 ± 2.51	8.26 ± 3.78	.825	8.25 ± 3.30	7.15 ± 3.61	.436
All	**Instability ratio***	1.29 ± 0.17	1.32 ± .23	.716	1.33 ± 0.21	1.34 ± 0.18	.999

*Maximum range of a single segment across all segments/ mean range of all segments

Figure 4.28A-C: 4.28A: Trajectory of the L3-4 segmental displacement (change from the upright posture in the direction of flexion) with respect to time. Subjects were standardized across time by plotting the maximal value for L3-S1 lordosis angle at 3.96 seconds for all subjects. 4.28B: Trajectory of the average change in the L3-4 segmental displacement with respect to percentage of global motion of L3-S1 lordosis angle. 4.28C: Trajectory of the normalized L3-4 displacement (/Range*100) with respect to percentage of global motion.

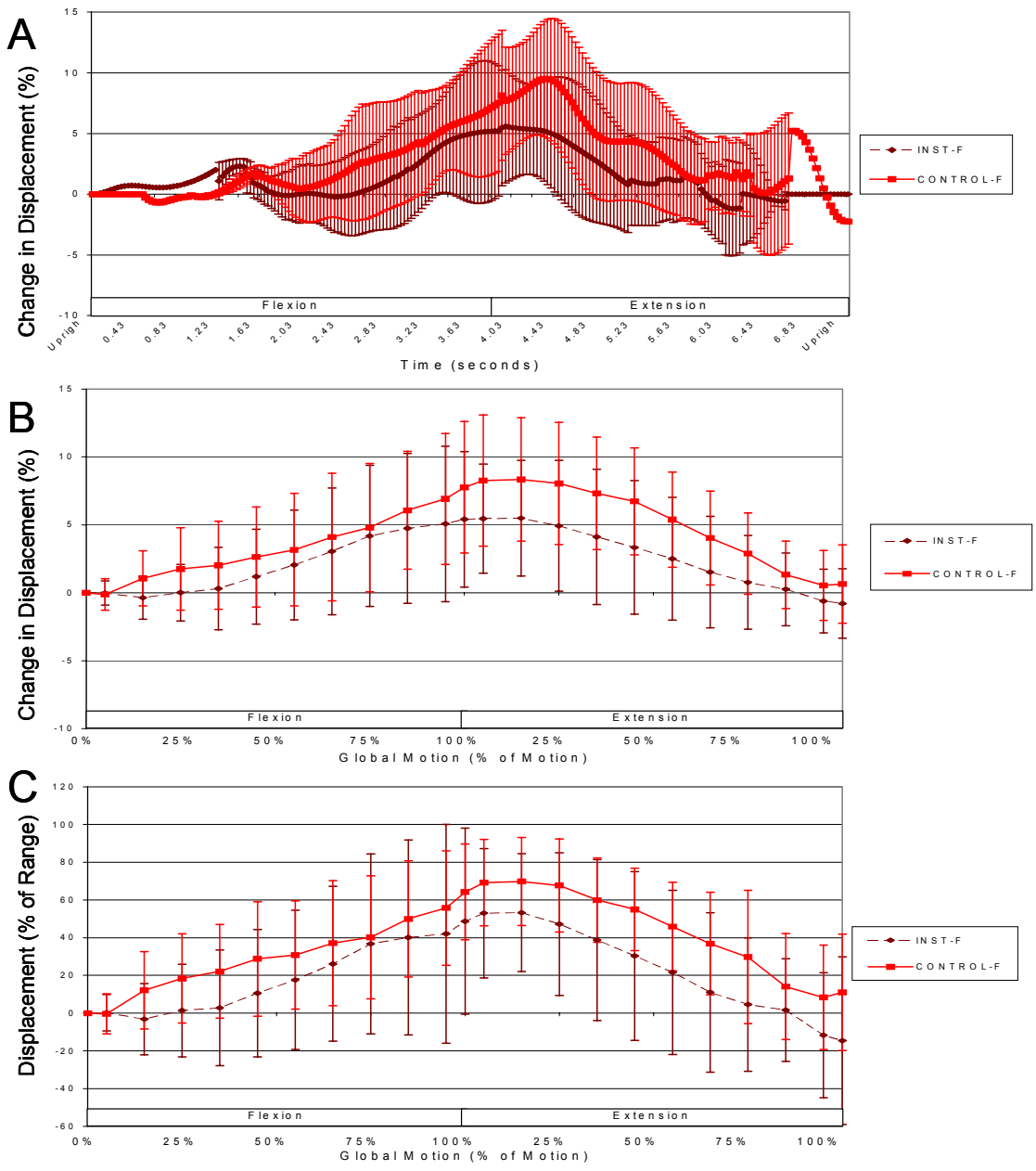


Figure 4.29A-C: Trajectory of the L4-5 segmental displacement (change from the upright posture in the direction of flexion) with respect to time. Subjects were standardized across time by plotting the maximal value for L3-S1 lordosis angle at 3.96 seconds for all subjects. 4.29B: Trajectory of the average change in the L4-5 segmental displacement with respect to percentage of global motion of L3-S1 lordosis angle. 4.29C: Trajectory of the normalized L4-5 displacement (/Range*100) with respect to percentage of global motion.

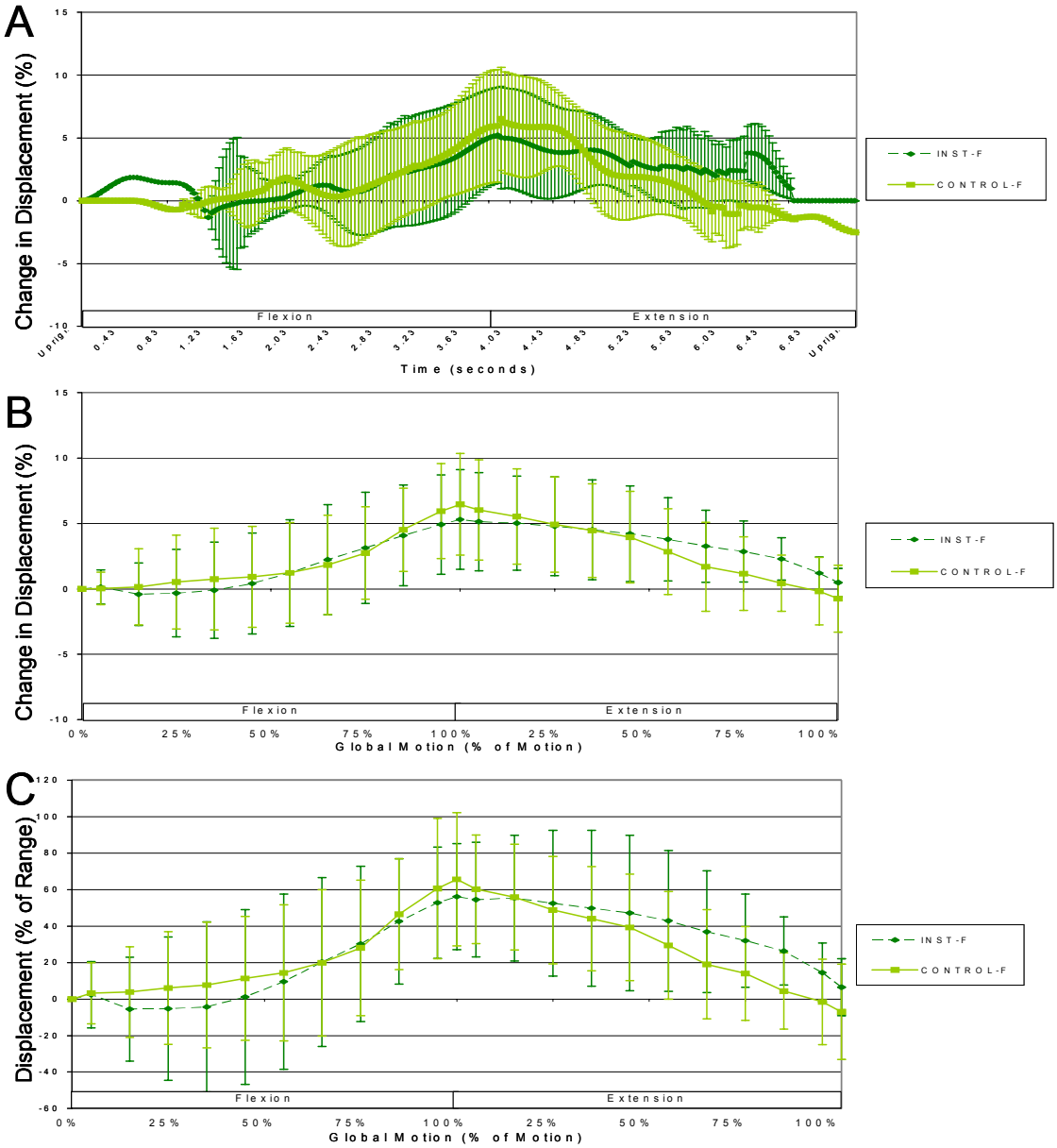


Figure 4.30A-C: 4.30A: Trajectory of the L5-S1 segmental displacement (change from the upright posture in the direction of flexion) with respect to time. Subjects were standardized across time by plotting the maximal value for L3-S1 lordosis angle at 3.96 seconds for all subjects. 4.30B: Trajectory of the average change in the L5-S1 segmental displacement with respect to percentage of global motion of L3-S1 lordosis angle. 4.30C: Trajectory of the normalized L5-S1 displacement (/Range*100) with respect to percentage of global motion.

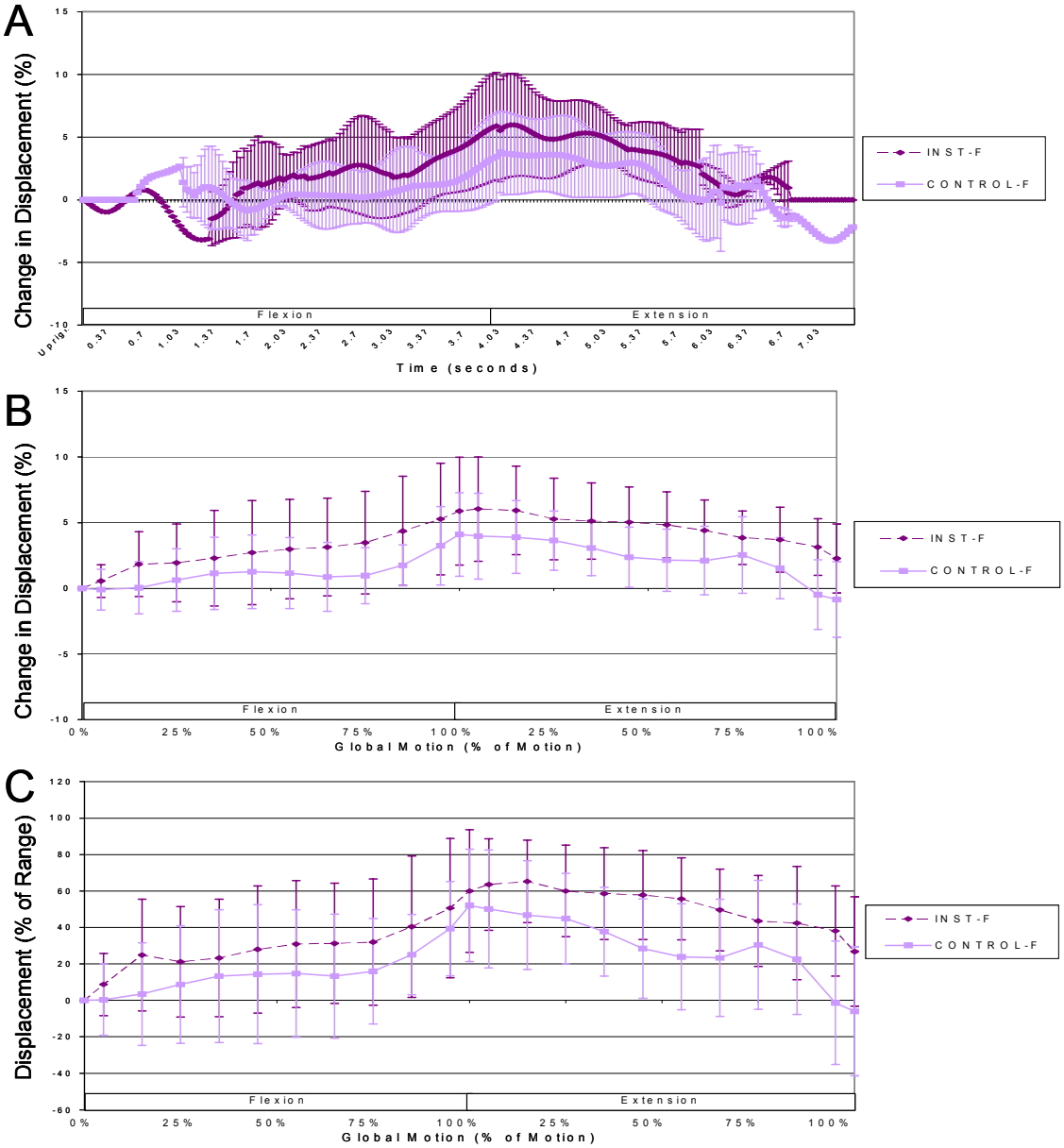


Figure 4.31A-C: Comparison of displacement trajectory of segmental displacement range (4.31A) with respect to time, (4.31B) with respect to global angular motion, and (4.31C), and normalized displacement with respect to global angular motion.

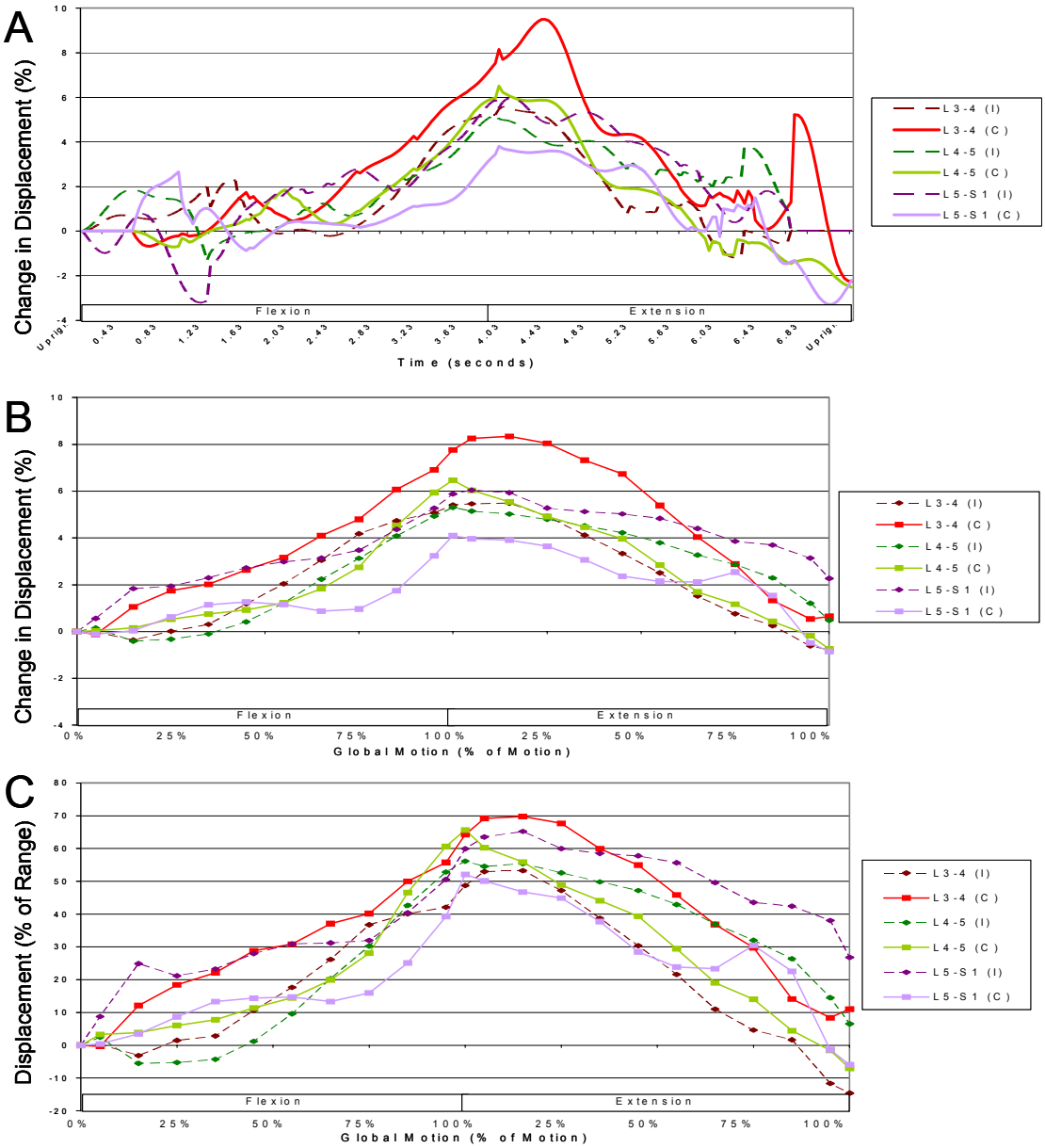


Table 4.35). Further, there was a trend towards different motion variables at L3-4. During flexion, less displacement range in the INST-F group ($p = .180$), with a decrease in maximum anterior displacement of about 3% ($p = .162$) was noted. While, during extension the mean displacement in the INST-F group that was about 2% more displaced in the anterior direction than the CONTROL-F group ($p = .136$), and the INST-F group displayed greater anterior displacement of L3 with respect to L4 (almost 4%; $p = .099$).

Displacement Timing

Flexion: Within-Group Analysis

During flexion, there was a trend towards greater displacement at the end-range of flexion across all levels (Figure 4.32A-C). A within-group analysis, 3 × 4 ANOVA (Table 4.36), revealed a main effect for difference in the rate of attainment of displacement range over the motion pattern ($p = .012$) without a main effect for level ($p = .718$) or an interaction effect for motion pattern by level ($p = .103$) or an interaction between motion pattern by level by group ($p = .682$). A post-hoc analysis with a Bonferroni correction revealed the greatest attainment of slope during the last portion of flexion (75-100%), relative to the 55-75% of flexion ($p = .022$), and a trend towards a greater rate of attainment relative to the first 25% of flexion ($p = .064$; Figure 4.33).

Flexion: Between-Group Analysis

Qualitative analysis of displacement during the initiation of flexion revealed a difference during 5-15% of flexion (Figure 4.34). In the CONTROL-F group, the rate of attainment of displacement range was positive and increasing between 5-15% of flexion for all levels. However, the INST-F group mean slope was decreasing at L3-4 (-0.339 ± 1.407) and L4-5 (-0.796 ± 2.069), while increasing at L5-S1 (1.615 ± 1.792).

Figure 4.32A-C. Rate of attainment (slope) of normalized displacement range (%) as a function of global motion (%) of L3-4 (A), L4-5 (B), and L5-S1 (C)

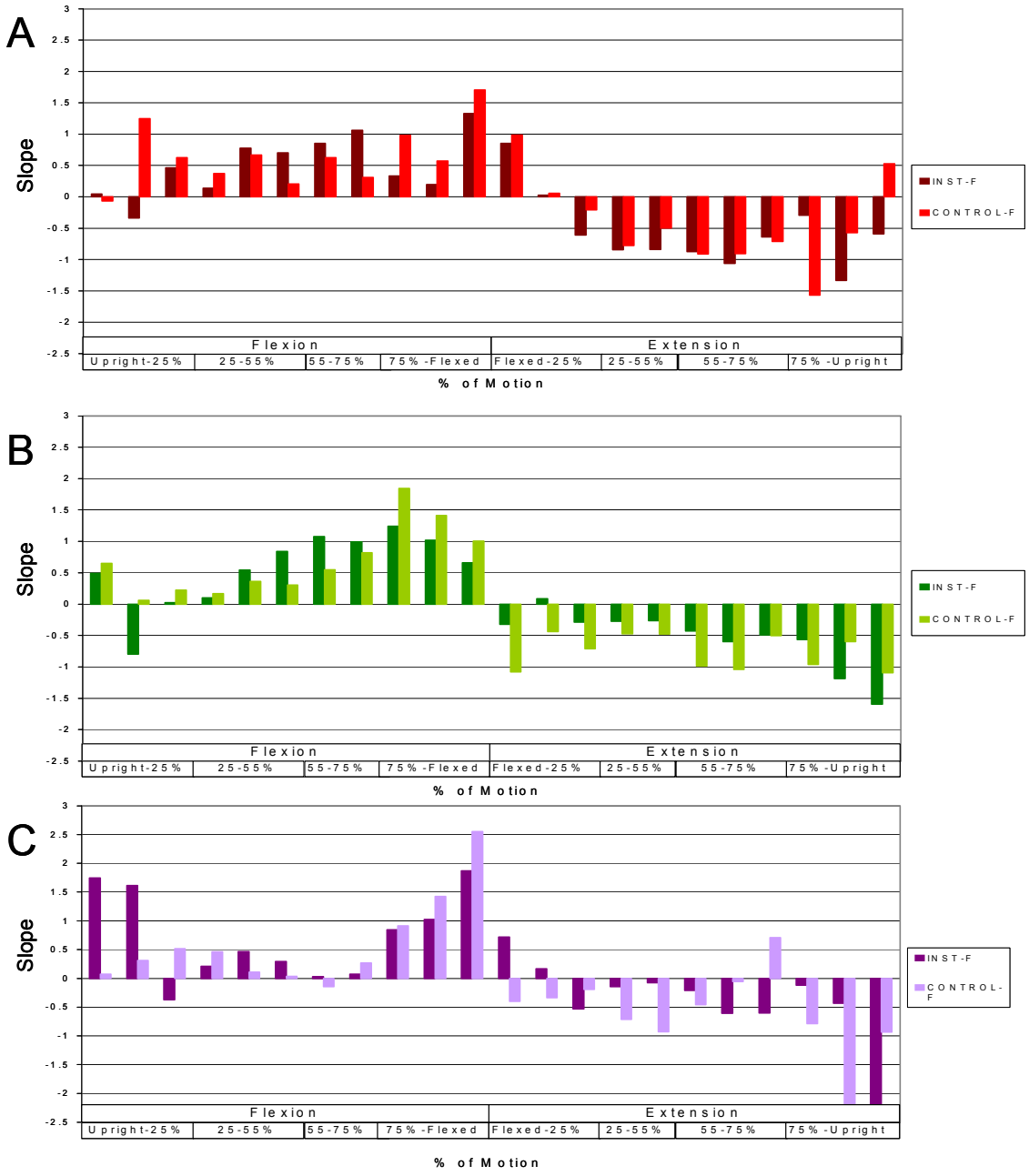


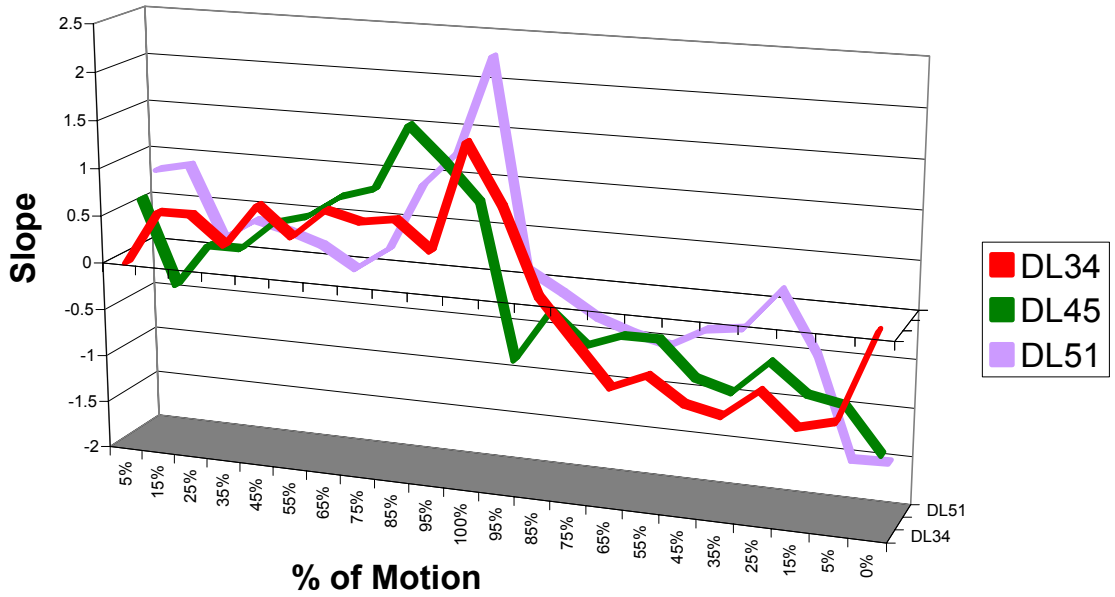
Table 4.36: Analysis of within-group displacement difference across levels (L3-4, L4-5, and L5-S1) and motion (0-25%, 25-55%, 55-75%, and 75-100%) during flexion

Source	df	SS	MS	F	p-value
Level (3)	2.000	0.143	0.071	0.334	.718
Motion (4)	2.187†	26.517	12.127	4.665	.012
Motion × Group	2.187†	5.459	2.496	0.960	.396
Level × Motion	4.267†	15.778	3.698	1.953	.103
Level × Motion × Group	4.267†	4.760	1.116	0.589	.682

*df = degrees of freedom, SS = Type III Sum of Squares, MS = Mean Square, and F = F-value

† Sphericity assumption was not met (significant Mauchly's test of sphericity), therefore the df were adjusted using the Greenhouse-Geisser formula.

Figure 4.33: Rate of attainment (slope) of normalized displacement (%) as a function of global motion (%) during flexion and extension.



Independent t-tests were used to analyze the between group differences during flexion in 5-10% increments (Table 4.37). During 5-15% of motion, the INST-F group's rate of attainment of displacement range at L3-4 was significantly less than the CONTROL-F group ($p = .022$) and the reverse was true at L5-S1 ($p = .086$). Although a visual difference can be seen in L4-5 between 5-15% of flexion (Figure 4.34), this difference was not significant ($p = .408$). The standard deviation at L4-5 during this time period on average between the groups was 2.4% and probably explains the lack of significance at this level. Although the lower slope at L4-5 in the INST-F group during the onset of motion was not found to be significant, the INST-F group trended towards a greater rate of attainment of displacement range (Figure 4.31C) during the 45-55 and 55-65% of motion ($p = .132$, and $p = .181$, respectively) relative to the CONTROL-F group.

Figure 4.34: Normalized segmental displacement trajectory (start of flexion) per global angle

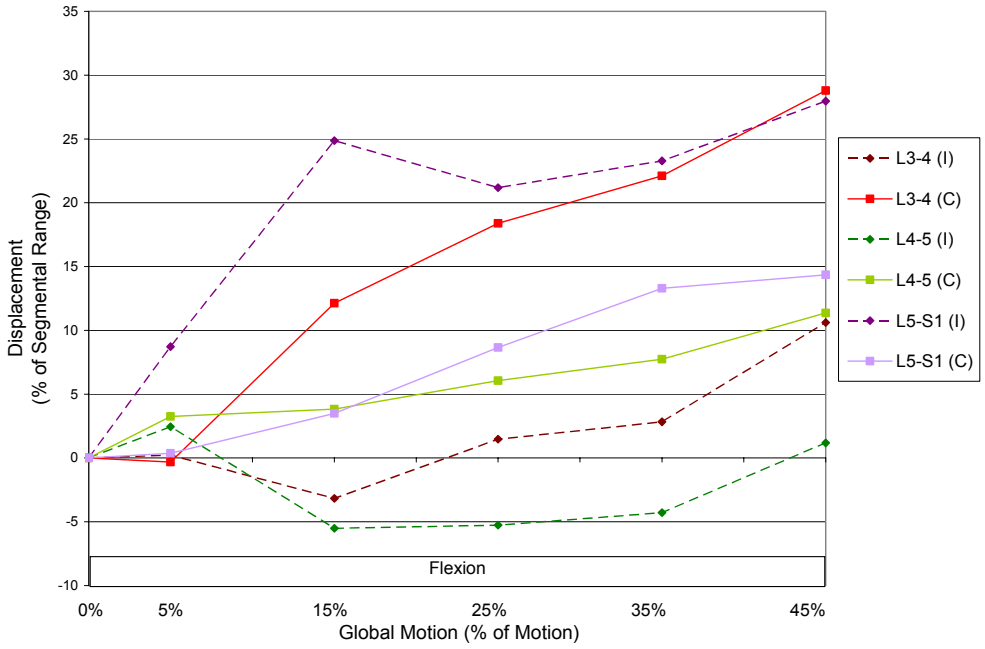


Table 4.37: Slope of displacement change (%) as a function of global motion (%) during the initiation of flexion

	CONTROL-F (n=14)	INST-F (n=11)	p-value	p < .20	p< .05
L3-4 Motion					
0-5%	-0.066 ± 2.121	0.045 ± 1.924	.894		
5-15%	1.246 ± 1.743	-0.339 ± 1.407	.022	*	*
15-25%	0.626 ± 0.933	0.463 ± 1.211	.706		
25-35%	0.372 ± 1.174	0.136 ± 1.320	.641		
35-45%	0.668 ± 1.213	0.778 ± 0.896	.804		
45-55%	0.202 ± 1.385	0.701 ± 0.824	.302		
L4-5 Motion					
0-5%	0.648 ± 3.347	0.489 ± 3.637	.910		
5-15%	0.059 ± 2.808	-0.796 ± 2.069	.408		
15-25%	0.223 ± 1.187	0.024 ± 1.393	.704		
25-35%	0.168 ± 1.037	0.099 ± 1.617	.897		
35-45%	0.363 ± 1.526	0.545 ± 0.471	.706		
45-55%	0.306 ± 0.993	0.841 ± 0.618	.132	*	
55-65%	0.550 ± 0.713	1.076 ± 1.185	.181	*	
L5-S1 Motion					
0-5%	0.072 ± 3.912	1.745 ± 3.412	.274		
5-15%	0.313 ± 1.813	1.615 ± 1.792	.086	*	
15-25%	0.517 ± 1.804	-0.369 ± 2.747	.341		
25-35%	0.463 ± 1.596	0.210 ± 1.532	.693		
35-45%	0.107 ± 0.909	0.468 ± 1.066	.370		
45-55%	0.035 ± 1.303	0.294 ± 0.997	.591		

† Equal variance not assumed secondary to a significant Levene's test for equality of variances

Extension: Within-Group Analysis

Qualitative analysis of the rate of attainment of displacement range during extension (Figure 4.32) demonstrated a greater absolute rate of attainment (slope) during the final stages of the return to upright posture. A within-groups analysis, 3 × 4 ANOVA (Table 4.38), revealed a significant main effect for difference in the rate of attainment of displacement range over the motion pattern ($p = .028$) without a main effect for level ($p = .201$) or an interaction effect between level and motion pattern ($p = .077$). A post-hoc analysis with a Bonferroni correction revealed a trend towards greater absolute rate of attainment for displacement range during the last phase of returning to the upright posture (75-100%), relative to the initiation of extension (0-25%; $p = .086$; Figures 4.33 & 4.34). No other differences were noted.

Table 4.38: Analysis of within-group displacement difference across levels (L3-4, L4-5, and L5-S1) and motion (0-25%, 25-55%, 55-75%, and 75-100%) during extension

Source	df	SS	MS	F	p-value
Level (3)	2.000	1.346	0.673	1.661	.201
Motion (4)	2.447†	23.315	9.527	3.531	.028
Motion × Group	2.447†	1.132	0.462	0.171	.882
Level × Motion	6.000	11.367	1.894	1.951	.077

*df = degrees of freedom, SS = Type III Sum of Squares, MS = Mean Square, and F = F-value

† Sphericity assumption was not met (significant Mauchly's test of sphericity), therefore the df were adjusted using the Greenhouse-Geisser formula.

Extension: Between-Group Analysis

Unlike the symptom-based group analysis, the motion-based groups displayed different rates of attainment of displacement range at L3-4 and L5-S1 during the final stages of returning to upright (Table 4.39). In the last 75-85% of return to upright, the INST-F group displayed a lower absolute rate of attainment of displacement range ($p = .029$) at L3-4, while in the last 85-95% of return to upright, the INST-F group displayed a lower absolute rate of attainment of displacement range ($p = .045$) at L5-S1. A similar trend was noted in L4-5 during the 45-55% portion of the movement pattern ($p = .110$). The trend of a reversal of slope during 65-75% of extension discussed in the symptom-based group continued in the motion-based group in the CONTROL-F subjects ($p = .082$).

Translational Speed

A decrease in translational speed from cephalad to caudal segments was observed. As with the symptom-based group, the motion-based groups demonstrated a significant main effect for level (L3, L4, L5, and S1) with an ANOVA for translation speed, without an interaction effect of level by group membership ($p = .529$). Post-hoc analysis with Bonferroni correction revealed that all pair wise comparisons were significant ($p < .01$).

Group comparison of maximum translational speed during flexion revealed no difference between groups (Table 4.40). Further the ratio of maximum speed of a vertebral body compared to the mean speed of all vertebral bodies during flexion and extension revealed no differences between groups (Table 4.40). The time interval of maximum speed of the first segment's maximum speed to the last segment's maximum speed during flexion revealed no difference between groups ($p = 0.72$), with the average timing for the CONTROL-F group of 0.026 ± 0.194 seconds and the INST-F group of $0.048 \pm .066$ seconds.

Table 4.39: Slope of displacement change (%) as a function of global motion (%) during the return to upright

	CONTROL-F (n=14)	INST-F (n=14)	p-value	p < .20	p< .05
L3-4 Motion					
45-55%	-0.911 ± 1.226	-0.874 ± 0.693	.930		
55-65%	-0.905 ± 1.007	-1.060 ± 1.310	.740		
65-75%	-0.708 ± 2.408	-0.640 ± 1.092	.932		
75-85%	-1.567 ± 1.208	-0.294 ± 1.523	.029	*	*
85-95%	-0.572 ± 2.054	-1.333 ± 2.679	.429		
95-100%	0.531 ± 2.121	-0.591 ± 3.898	.367		
L4-5 Motion					
45-55%	-0.987 ± 0.886	-0.430 ± 0.755	.110	*	
55-65%	-1.041 ± 0.952	-0.597 ± 0.990	.267		
65-75%	-0.502 ± 2.256	-0.493 ± 1.004	.990		
75-85%	-0.961 ± 1.701	-0.564 ± 0.958	.497		
85-95%	-0.595 ± 1.887	-1.186 ± 1.403	.395		
95-100%	-1.092 ± 2.956	-1.596 ± 2.386	.650		
L5-S1 Motion					
45-55%	-0.457 ± 1.209	-0.211 ± 0.854	.574		
55-65%	-0.057 ± 1.266	-0.606 ± 1.142	.273		
65-75%	0.711 ± 1.874	-0.604 ± 1.681	.082	*	
75-85%	-0.787 ± 2.297	-0.116 ± 1.672	.425		
85-95%	-2.388 ± 2.064	-0.435 ± 2.558	.045	*	*
95-100%	-0.932 ± 3.011	-2.258 ± 2.890	.278		

† Equal variance not assumed secondary to a significant Levene's test for equality of variances

Table 4.40: Vertebral body translational speed comparison between groups

Measure (mm/sec)	CONTROL-F (n=14)	INST-F (n=11)	p-value
Maximum speed during flexion			
L3	54.88 ± 20.11	58.12 ± 22.33	.71
L4	46.54 ± 20.12	47.57 ± 16.93	.89
L5	40.10 ± 20.28	38.01 ± 16.37	.78
S1	37.27 ± 20.60	34.97 ± 17.03	.77
Ratio: Maximum speed of a single segment/ Mean speed of all segments			
Flexion	2.88 ± 0.64	2.71 ± 0.48	.48
Extension	3.03 ± 0.45	3.02 ± 0.92	.97

DISTINGUISHING GROUP MEMBERSHIP BASED ON KINEMATIC VARIABLES

Average area under the ROC curve

The symptom-based groups had 22 variables that were considered possible kinematic variables ($p < .20$) from the previous analysis. Nine of those variables were based on descriptive statistics of the displacement and range variables, while 13 of those variables were based on the timing of the angular or displacement variables. The average area under the curve was 0.664 ± 0.038 for the symptom-based group's variables.

The motion-based group had 23 variables that were considered possible criteria for the model (seven descriptive variables of displacement and angle and 16 timing variables of displacement and timing). The average area under the curve was 0.704 ± 0.050 for the motion-based group's variables.

For this analysis, a third classification of the subjects was determined based on the qualitative review of motion by the expert-reviewers regardless of original group membership (22 with normal motion, 15 with abnormal motion, and three with

indeterminate motion). The average area under the curve using this classification was 0.626 ± 0.056.

Distinguishing group membership of subjects in the symptom-based group based on kinematic variables

Of the initial 22 variables that were determined to be potential variables that could distinguish group membership, 15 (four descriptive variables of displacement and angle and 11 timing variables of displacement and angle) had an ROC curve in which an identifiable cut-off value was found. A list of these variables and the associated Sn, Sp, +LR, and –LR are provided in Table 4.41. Of these variables, 10 had a +LR >2.0. These 10 variables were used to identify clusters of motion variables that maximized the ability to distinguish group membership (Table 4.42-4.43). The greatest accuracy ((true positive + true negative)/total) was achieved when 4 of the 10 variables were present (87.5%); in which one subject from INST-I would be classified as CONTROL-I and four CONTROL-I subjects would have been classified as INST-I. The remaining subjects would not have changed classification. The +LR was six when six or more variables were present. The + LR approached infinity after that point because there was no one in the CONTROL-I group that had more than six of the ten variables present. The –LR was .063 when four or more of the variables were present. When three or fewer variables were present, the –LR approached zero because none of those in the ISNT-I group had less than four variables present.

Table 4.41: Accuracy statistics (95% confidence interval) for potential motion variables for distinguishing the symptom-based groups. Variables are coded (a-o) to demonstrate descending order of +LR values, +LR < 2.0 are shaded gray

	Sn	Sp	+LR	-LR
Descriptive Variables: Displacement				
Range Extension L4-5[b]	.550 (.342 - .742)	.850 (.640 - .948)	3.667 (1.347 - 11.088)	0.529 (0.297 - 0.846)
Total Displacement Range[f]	.550 (.342 - .742)	.750 (.531 - .888)	2.200 (0.991 - 5.278)	0.600 (0.331 - 1.006)
Range Flexion L4-5[g]	.550 (.342 - .742)	.750 (.531 - .888)	2.200 (0.991 - 5.278)	0.600 (0.331 - 1.006)
Minimum Extension L4-5[k]	.750 (.531 - .888)	.600 (.387 - .781)	1.875 (1.080 - 3.559)	0.417 (0.176 - 0.903)
Timing (Slope) Variables: Angle				
5-15% Flexion L3-4[c]	.700 (.481 - .855)	.750 (.531 - .888)	2.800 (1.346 - 6.500)	0.400 (0.188 - 0.763)
5-15% Flexion L4-5[e]	.700 (.481 - .855)	.700 (.481 - .855)	2.333 (1.198 – 5.016)	0.429 (0.199 - 0.835)
0-5% Flexion L5-S1[h]	.650 (.433 - .819)	.700 (.481 - .855)	2.167 (1.089 - 4.706)	0.500 (0.247 - 0.925)
95-100% Extension L4-5[i]	.600 (.387 - .781)	.700 (.481 - .855)	2.000 (0.982 - 4.396)	0.571 (0.298 - 1.015)
75-85% Extension L4-5[l]	.700 (.481 - .855)	.600 (.387 - .781)	1.750 (0.985 - 3.356)	0.500 (0.227 - 1.019)
0-5% Flexion L3-4[n]	.750 (.531 - .888)	.550 (.342 - .742)	1.667 (0.994 - 3.023)	0.455 (0.189 - 1.009)
Timing (Slope) Variables: Displacement				
65-75% Extension L5-S1[a]	.600 (.387 - .781)	.900 (.699 - .972)	6.000 (1.834 - 22.302)	0.444 (0.240 - 0.720)
5-15% Flexion L3-4[d]	.600 (.387 - .781)	.750 (.531 - .888)	2.400 (1.107 - 5.686)	0.533 (0.281 - 0.926)
5-15% Flexion L4-5[j]	.600 (.387 - .781)	.700 (.481 - .855)	2.000 (0.982 - 4.396)	0.571 (0.298 - 1.015)
85-95% Extension L5-S1[m]	.700 (.481 - .855)	.600 (.387 - .781)	1.750 (0.985 - 3.356)	0.500 (0.227 - 1.019)
55-65% Flexion L4-5[o]	.700 (.481 - .855)	.550 (.342 - .742)	1.556 (0.905 - 2.852)	0.545 (0.245 - 1.140)

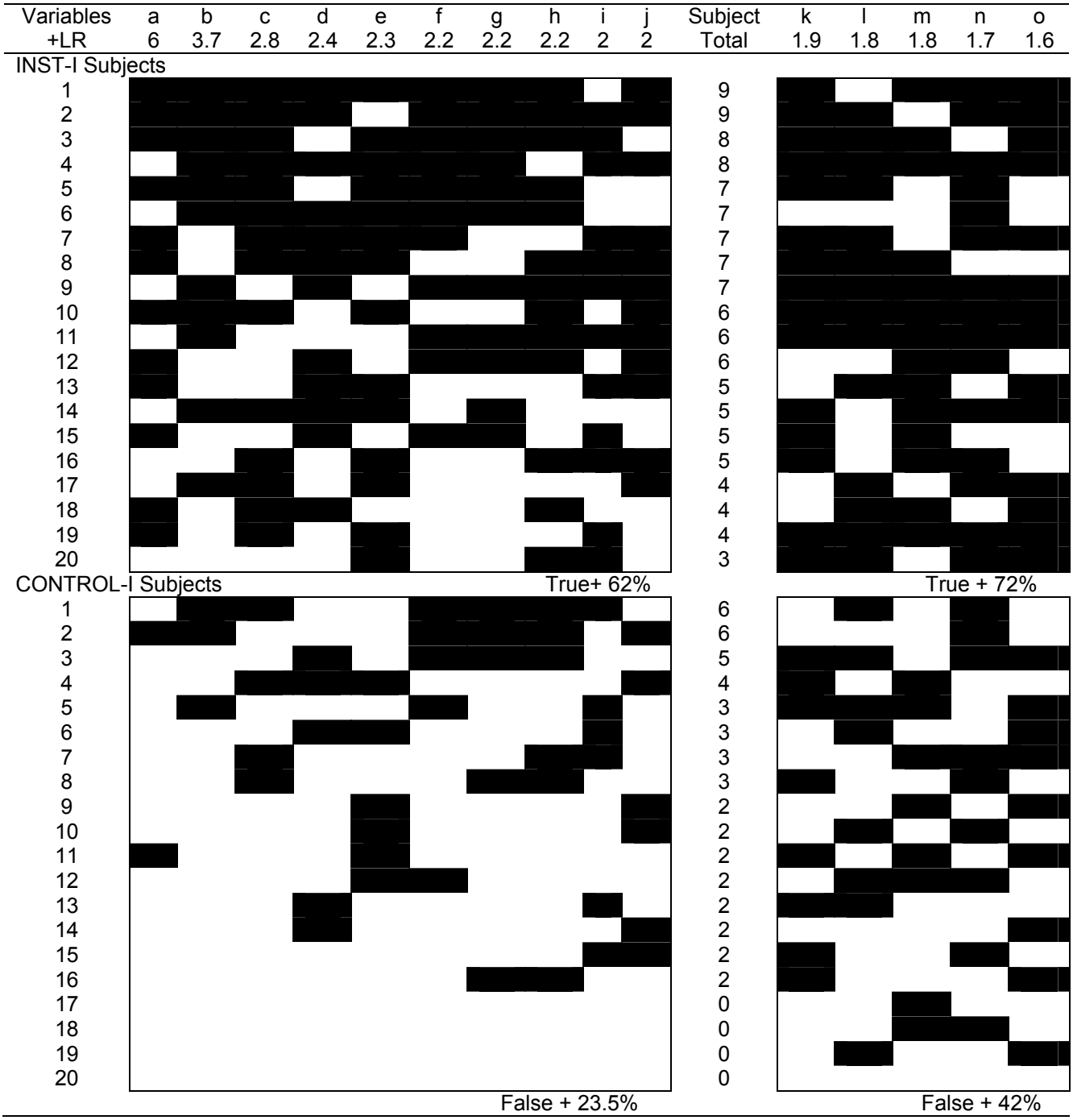
Sensitivity (Sn), Specificity (Sp), Positive Likelihood Ratio (+LR), Negative Likelihood ratio (-LR)

Table 4.42: Accuracy at each level of the model to distinguish group membership for the symptom-based groups. Values represent accuracy statistics with 95% confidence intervals (CI).

Number of Predictor Variables Present	Sn	Sp	+LR	-LR
All ten present (none)	NA	NA	NA	NA
Nine or more present	.100 (.028 - .301)	1.000 (.839 - 1.000)	Approaches Infinite (0.555 – Infinite)	0.900 (0.699 – 1.083)
Eight or more present	.200 (.081 - .416)	1.000 (.839 - 1.000)	Approaches Infinite (1.148 – Infinite)	0.800 (0.584 – 0.973)
Seven or more present	.450 (.258 - .658)	1.000 (.839 - 1.000)	Approaches Infinite (2.694 – Infinite)	0.550 (0.342 – 0.742)
Six or more present	.600 (.387 - .781)	.900 (.699 - .972)	6.000 (1.833 - 22.286)	0.444 (0.240 - 0.720)
Five or more present	.800 (.584 - .919)	.850 (.640 - .948)	5.332 (2.120 - 15.531)	0.235 (0.094 - 0.510)
Four or more present	.950 (.764 - .991)	.800 (.584 - .919)	4.750 (2.252 - 11.825)	0.063 (0.011 - 0.302)
Three or more present	1.000 (.839 - 1.000)	.600 (.387 - .781)	2.500 (1.630 – 4.570)	Approaches Zero (0.000 – 0.274)
Two or more present	1.000 (.839 - 1.000)	.200 (.081 - .416)	1.250 (1.028 – 1.712)	Approaches Zero (0.000 – 0.871)
One or more present	1.000 (.839 - 1.000)	.200 (.081 - .416)	1.250 (1.028 – 1.712)	Approaches Zero (0.000 – 0.871)

Sensitivity (Sn), Specificity (Sp), Positive Likelihood Ratio (+LR), Negative Likelihood Ratio (-LR)

Table 4.43: Representation of distribution of positive tests among the variables with + LR > 2.0 (a-j), and those that had a +LR < 2.0 (k-o). Variable codes provided in Table 4.45.



Distinguishing group membership of subjects in the motion-based group based on kinematic variables

Of the initial 23 movement variables that were determined to be variables that could possibly distinguish group membership among the motion-based groups, 19 (six descriptive variables of displacement and angle and 13 timing variables of displacement and angle) had an ROC curve in which an identifiable cut-off value was found. A list of these variables and the associated Sn, Sp, +LR, and –LR are provided in Table 4.44. Of these variables, 16 had a +LR > 2.0 and eight had a +LR > 2.5. These 16 variables were used to identify clusters of motion variables that maximized the ability to distinguish group membership (Table 4.45 - 4.46). The greatest accuracy ((true positive + true negative)/total) was achieved if seven, eight, or nine variables were present (92.0%); in which two subjects would be misclassified. If eight or nine variables were present, then one subject from each group was misclassified, if seven variables were present, two subjects from the CONTROL-F group would have been classified as INST-F. The +LR ratio was 12.727 and the –LR was .098 when eight or more, or nine or more variables were present. The + LR approached infinity after that point because there was no one in the CONTROL-F group that had more than nine of the sixteen variables present. The – LR approached zero when seven or less variable were present because none of those in the ISNT-F group had seven or fewer variables present.

A more concise model of eight variables was calculated using a +LR > 2.5 for the cut-off value (Table 4.44). These eight variables were used to identify clusters of motion variables that maximized the ability to distinguish group membership (Table 447 - 4.48). The greatest accuracy was achieved if four variables were present (96.0%); in which one subject from the CONTROL-F group would be misclassified as INST-F. The +LR ratio was 13.987 and the –LR was approaching zero when four or more variables were present.

The + LR approached infinity after that point because there was no one in the CONTROL-F group that had more than four of the eight variables present. The –LR approached zero when four or fewer variables were present because none of those in the ISNT-F group had more than four variables present.

Table 4.44: Accuracy statistics (95% confidence interval) for potential motion variables (descriptive variables) for distinguishing the motion-based groups. Variables are coded (a-s) to demonstrate descending order of +LR values, +LR < 2.0 are shaded gray

	Sn	Sp	+LR	-LR
Descriptive Variables: Angle				
Ratio Extension[b]	.636 (.354 - .848)	.857 (.601 - .960)	4.455 (1.352 - 16.713)	0.424 (0.174 - 0.830)
Descriptive Variables: Displacement				
Range Extension L4-5[f]	.636 (.354 - .848)	.786 (.524 - .924)	2.970 (1.088 - 8.962)	0.463 (0.187 - 0.942)
Maximum Flexion L3-4[j]	.636 (.354 - .848)	.714 (.454 - .883)	2.227 (0.912 - 5.845)	0.509 (0.203 - 1.077)
Range Flexion L3-4[k]	.636 (.354 - .848)	.714 (.454 - .883)	2.227 (0.912 - 5.845)	0.509 (0.203 - 1.077)
Mean Extension L3-4[l]	.636 (.354 - .848)	.714 (.454 - .883)	2.227 (0.912 - 5.845)	0.509 (0.203 - 1.077)
Maximum Extension L3-4[m]	.636 (.354 - .848)	.714 (.454 - .883)	2.227 (0.912 - 5.845)	0.509 (0.203 - 1.077)
Slope Variables: Angle				
5-15% Flexion L3-4[c]	.818 (.523 - .949)	.786 (.524 - .924)	3.818 (1.541 - 11.086)	0.231 (0.064 - 0.658)
5-15% Flexion L4-5[d]	.727 (.434 - .903)	.786 (.524 - .924)	3.394 (1.307 - 10.024)	0.347 (0.121 - 0.802)
15-25% Flexion L4-5[g]	.727 (.434 - .903)	.714 (.454 - .883)	2.545 (1.102 - 6.518)	0.382 (0.131-0.913)
95-100% Extension L3-4[h]	.727 (.434 - .903)	.714 (.454 - .883)	2.545 (1.102 - 6.518)	0.382 (0.131-0.913)
95-100% Extension L4-5[n]	.636 (.354 - .848)	.714 (.454 - .883)	2.227 (0.912 - 5.845)	0.509 (0.203 -1.077)
75-85% Extension L4-5[o]	.727 (.434 - .903)	.643 (.388 - .837)	2.036 (0.954 - 4.699)	0.424 (0.144 - 1.052)
Slope Variables: Displacement				
65-75% Extension L5-S1[a]	.636 (.354 - .848)	.929 (.685 - .987)	8.909 (1.803 - 51.724)	0.392 (0.162 - 0.735)
5-15% Flexion L3-4[e]	.727 (.434 - .903)	.786 (.524 - .924)	3.394 (1.307 - 10.024)	0.347 (0.121 - .802)
55-65% Flexion L4-5[i]	.818 (.523 - .949)	.643 (.388 - .837)	2.291 (1.136 - 5.173)	0.283 (0.077 - 0.853)
5-15% Flexion L5-S1[p]	.727 (.434 - .903)	.643 (.388 - .837)	2.036 (0.954 - 4.699)	0.424 (0.144 - 1.052)
75-85% Extension L3-4[r]	.818 (.523 - .949)	.571 (.326 - .786)	1.909 (1.005 - 3.965)	0.318 (0.085 - 0.993)
45-55% Flexion L4-5[q]	.818 (.523 - .949)	.571 (.326 - .786)	1.909 (1.005 - 3.965)	0.318 (0.085 - 0.993)
45-55% Extension L4-5[s]	.727 (.434 - .903)	.571 (.326 - .786)	1.697 (0.841 - 3.609)	0.477 (0.159 - 1.231)

Table 4.45: Accuracy at each level of the model to distinguish group membership for the motion-based groups. Values represent accuracy statistics with 95% confidence intervals.

Number of Predictor Variables Present	Sn	Sp	+LR	-LR
All sixteen present (none)	NA	NA	NA	NA
Fifteen or more present	.091 (.016 - .377)	1.000 (.785 - 1.000)	Approaches Infinite (0.350 – Infinite)	0.909 (0.622 – 1.173)
Fourteen or more present	.182 (.051 - .477)	1.000 (.785 - 1.000)	Approaches Infinite (0.727 – Infinite)	0.818 (0.523 – 1.071)
Thirteen or more present	.273 (.097 - .566)	1.000 (.785 - 1.000)	Approaches Infinite (1.122 – Infinite)	0.727 (0.434 – 0.969)
Twelve or more present	.455 (.213 - .720)	1.000 (.785 - 1.000)	Approaches Infinite (1.950 – Infinite)	0.545 (0.280 – 0.788)
Eleven or more present	.636 (.354 - .848)	1.000 (.785 - 1.000)	Approaches Infinite (2.817 – Infinite)	0.364 (0.152 – 0.646)
Ten or more present	.636 (.354 - .848)	1.000 (.785 - 1.000)	Approaches Infinite (2.817 – Infinite)	0.364 (0.152 – 0.646)
Nine or more present	.909 (.623 - .984)	.929 (.685 - .987)	12.715 (2.811 - 71.767)	0.098 (0.017 - 0.413)
Eight or more present	.909 (.623 - .984)	.929 (.685 - .987)	12.715 (2.811 – 71.767)	0.098 (0.017 - 0.413)
Seven or more present	1.000 (.741 - 1.000)	.857 (.601 - .960)	6.997 (2.503 – 24.924)	Approaches Zero (0.000 – 0.306)
Six or more present	1.000 (.741 - 1.000)	.643 (.388 - .837)	2.800 (1.632 – 6.117)	Approaches Zero (0.000 – 0.421)
Five or more present	1.000 (.741 - 1.000)	.643 (.388 - .837)	2.800 (1.632 – 6.117)	Approaches Zero (0.000 – 0.421)
Four or more present	1.000 (.741 - 1.000)	.500 (.268 - .732)	2.000 (1.330 – 3.731)	Approaches Zero (0.000 – 0.555)
Three or more present	1.000 (.741 – 1.000)	.214 (.076 - .476)	1.273 (0.915 – 1.908)	Approaches Zero (0.000 – 1.403)
Two or more present	1.000 (.741 - 1.000)	.143 (.040 - .399)	1.167 (0.848 – 1.665)	Approaches Zero (0.000 2.176)
One or more present	1.000 (.741 - 1.000)	.000 (.000 - .215)	1.000 (0.739 – 1.274)	Approaches Zero (0.000 – Infinite)

Table 4.46: Representation of distribution of positive tests among the variables with + LR > 2.0 (a-p), and those that had a +LR < 2.0 (q-s). Variable codes provided in Table 4.48.

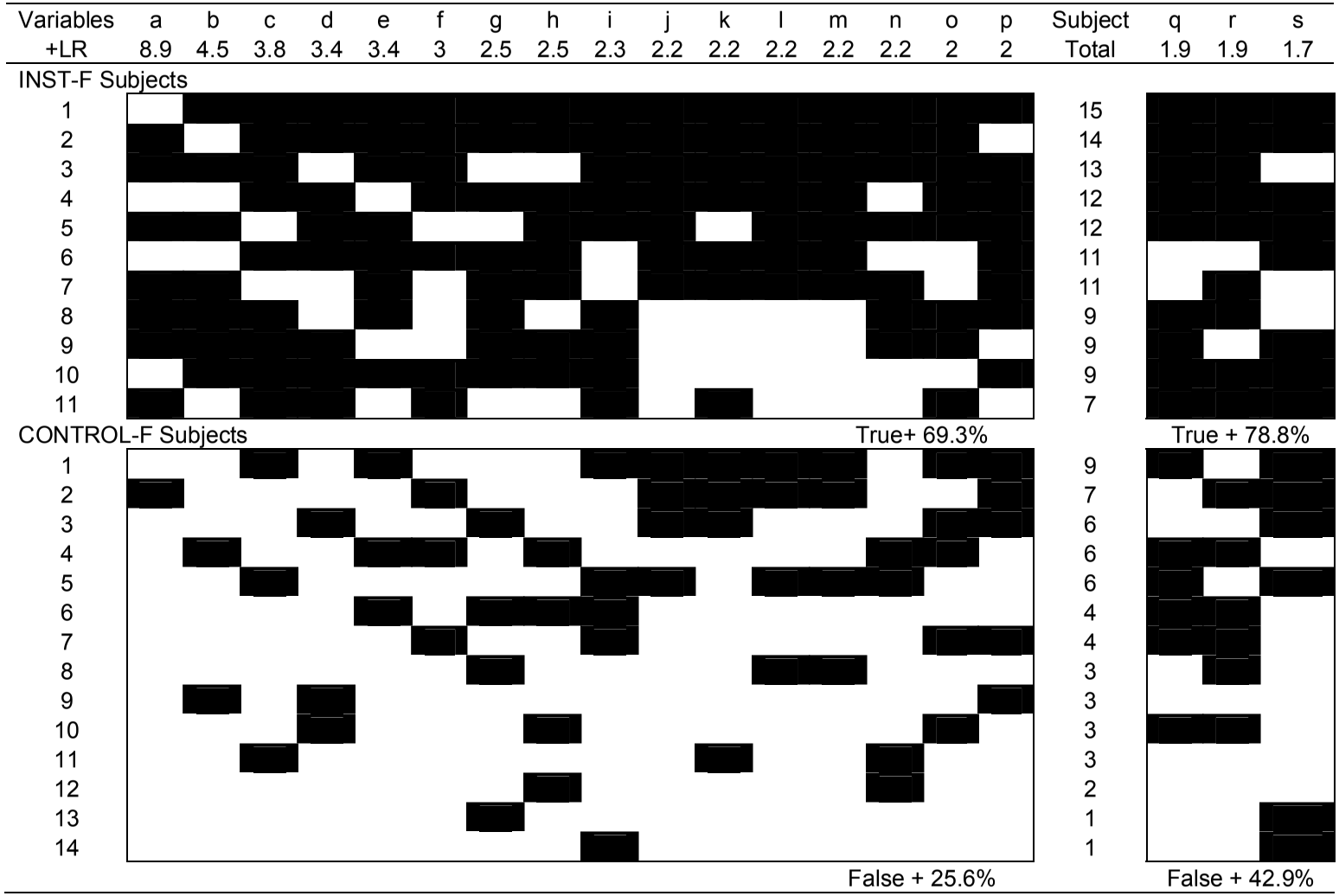
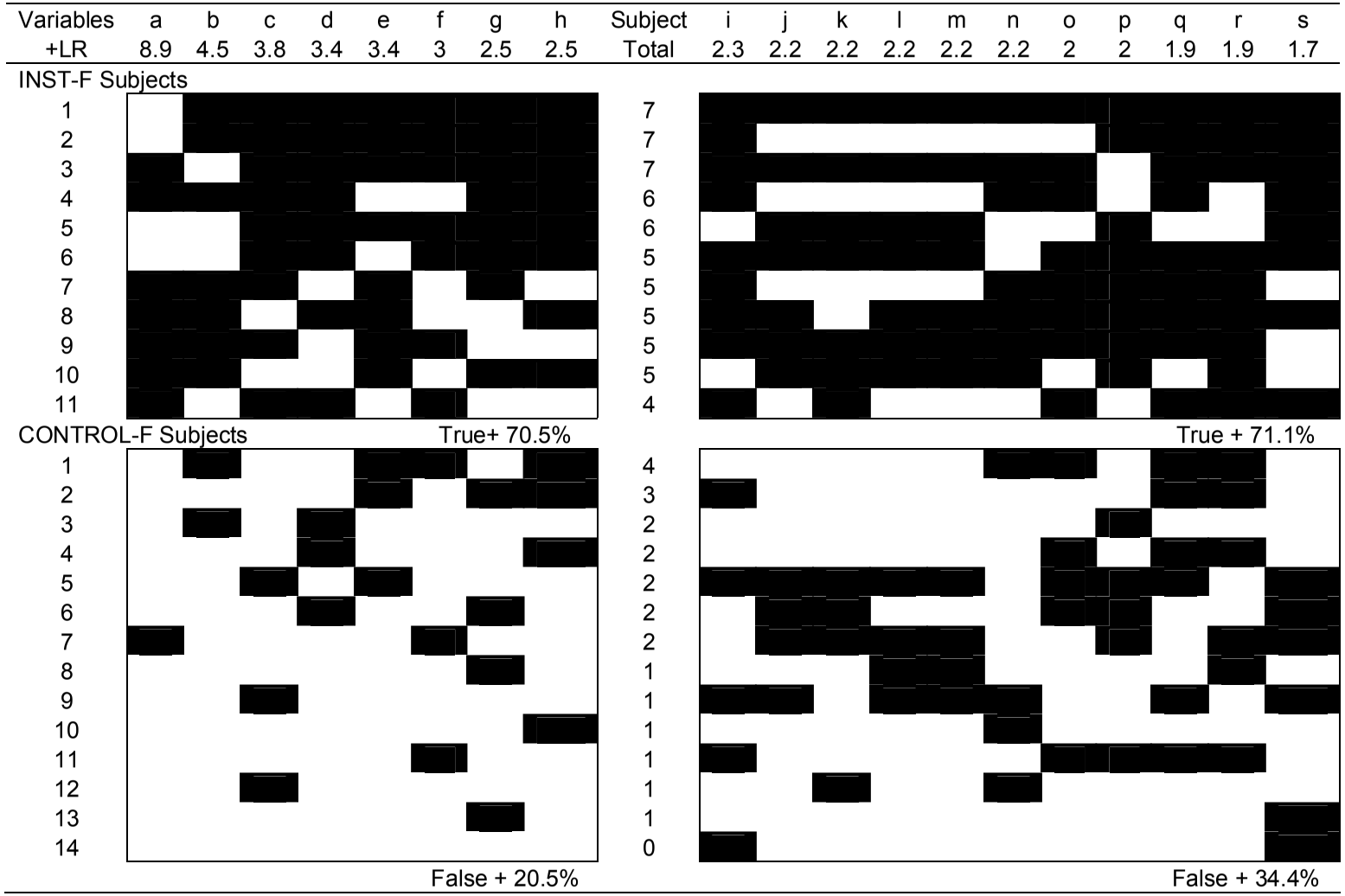


Table 4.47: Accuracy at each level of the model to distinguish group membership for the motion-based groups. Values represent accuracy statistics with 95% confidence intervals.

Number of Predictor Variables Present	Sn	Sp	+LR	-LR
All eight present (none)	NA	NA	NA	NA
Seven or more present	.273 (.097 - .566)	1.000 (.785 - 1.000)	Approaches Infinite (1.122 – Infinite)	0.727 (0.434 – 0.969)
Six or more present	.455 (.213 - .720)	1.000 (.785 - 1.000)	Approaches Infinite (1.950 – Infinite)	0.545 (0.280 – 0.788)
Five or more present	.909 (.623 - .984)	1.000 (.785 - 1.000)	Approaches Infinite (4.175 – Infinite)	0.091 (0.016 – 0.377)
Four or more present	1.000 (.741 - 1.000)	.929 (.685 - .987)	13.987 (3.177 – 78.475)	Approaches Zero (0.000 – 0.281)
Three or more present	1.000 (.741 - 1.000)	.857 (.601 - .960)	6.997 (2.503 – 24.924)	Approaches Zero (0.000 – 0.307)
Two or more present	1.000 (.741 - 1.000)	.500 (.268 - .732)	2.000 (1.330 – 3.731)	Approaches Zero (0.000 – 0.555)
One or more present	1.000 (.741 - 1.000)	.071 (.013 - .315)	1.077 (0.791 – 1.459)	Approaches Zero (0.000 – 4.559)

Sensitivity (Sn), Specificity (Sp), Positive Likelihood Ratio (+LR), Negative Likelihood Ratio (-LR)

Table 4.48: Representation of distribution of positive tests among the variables with + LR ≥2.5 (a-h), and those that had a +L.R < 2.5 (i-s). Variable codes provided in Table 4.48.



Chapter 5: Discussion

This chapter focuses on the relationships, impacts, clinical implications, and limitations of the conducted research. It starts with a review of the reliability of the measurement technique developed. This will be followed by a discussion about the developed models using both the symptom-based and motion-based groups as the reference criterion. During the discussion of each model, the individual hypotheses about the descriptive and timing variables will be reviewed. After all of the hypotheses have been addressed, the clinical importance, limitations, and suggestions for future research will be discussed.

RELIABILITY

Intra-rater reliability was measured both by repeated measurements of sagittal plane flexion from the same movement (intra-image reliability) and by measurements obtained on two separate movements (inter-image reliability). The intra-image reliability study was designed to test the reliability of the measurement technique and the rater, while the inter-image reliability was designed to address the impact of variation of movement patterns between trials and the effects of repositioning a subject within the FOV.

Intra-Image Reliability

The intra-image reliability values, ICC (2, 12), were all > .96 and were interpreted as good, and were greater than the .90 standard outlined by Portney and Watkins to ensure reasonable validity.[125] The measurement errors (SEM) were minimal, 0.2-0.3 mm and 0.4-0.7° across segments. These error values were less than prior published error

reports of 0.5 to 0.8 mm and 0.8 to 1.6° that used similar measurement techniques but a different statistical technique (standard deviation instead of SEM) to measure error (Table 5.1).[46] Although the error measurements provided by Frobin et al[46] were obtained *in vitro* (therefore less scatter of the DFV beam) with the specimen imaged at different orientations and were determined by different statistical techniques, the comparison reveals that the digital adaptation of the technique may have been better or at least comparable to their findings (Table 5.1). Therefore, the adapted version of the DCRA technique for edge enhanced DFV developed and used in this study was reliable and the repeated measures of the same DFV would be within 0.6 mm and 1.45° based on a 95% confidence interval.

Table 5.1: Comparison of intra-image SEM of the current study with the results published by Frobin et al.[46]

	Current Study*		**Frobin et al.** †	
	n*	**Error (SEM)** ‡	**n**†	**Error (SD)** ‡
		Intersegmental (Midplane) Angle		
L3-4	40	0.40°	54	0.85°
L4-5	40	0.72°	52	1.32°
L5-S1	40	0.58°	11	1.64°
		Intersegmental Displacement		
L3-4	40	0.200 mm	54	0.518 mm
L4-5	40	0.314 mm	52	0.546 mm
L5-S1	40	0.271 mm	11	0.840 mm

* 3 Segments measured representing 20 subjects and 40 images (flexion and upright)

†For L3-4 and L4-5: 6 cadaver specimens, 9 radiographs taken in different 0, +5, -5 degrees of rotation or tilt, For L5-S1 11 images of a bony phantom taken at different distances from the image intensifier.

‡Example based on a 35 mm vertebral body (SEM*35 mm or SD*35 mm). Note this is 68% CI and was done to compare with the published data from Frobin et al[46] which was only $\pm$ 1 SD

As discussed above an exact comparison to a prior study was not possible because of differences in how the images were obtained and the statistical measurement techniques. However, one of the closest comparisons possible to the work of Frobin et al[46] was with a step prior to the establishment of their error measurements. Prior to reporting error measurements, Frobin et al[46] provided the mean difference and the standard deviation of the difference of intra-rater assessment of images using the DCRA technique as assessed over repeated measurements (Table 5.2). The standard deviation of the difference only varied 0.06% for displacement and 0.19° for angle evaluation, demonstrating only minimal differences between the static technique using hand-drawn then digitized vertebral body outlines from static radiographs used by Frobin et al[46] and the current technique which used a more automated process with edge-enhanced DFV that measured these properties directly on the video images.

Table 5.2: Comparison of intra-rater reliability data of the current study with the results published by Frobin et al.[46]

	Current Study	**Frobin et al.[46]**
Number of Images	40 (2 sets of 20)	16 (1 set of 16)
Number of Segments	120	78
Intersegmental Midplane Angle		
Mean Difference*	0.089°	0.015°
Standard Deviation†	1.178°	0.992°
Intersegmental Displacement		
Mean Difference*	0.00083 (0.083 %)	0.0005 (0.05 %)
Standard Deviation†	0.0154 (1.54 %)	0.0148 (1.48 %)

*Mean difference of the paired measurements from the segments

†Standard deviation of the difference

One of the problems previously noted by Frobin et al[46] was the higher error rates associated with the S1 segment and the adaptations their algorithm required; which relied heavily on manual point placements to locate the landmarks on S1 compared to the other vertebral bodies. These alterations were required because the locations of the caudal borders of S1 were difficult to visualize and standardize when obtained with standard radiographs by Frobin et al.[46] Therefore, the decreased image quality associated with DFV relative to standard radiographs required a different approach. This protocol adapted the DCRA for S1 by only digitizing the cephalad border of S1. This adaptation was similar to the measurement algorithm established for the C2 vertebral body as outlined in a more recent research report by Frobin et al.[47] As noted in Tables 4.1 and 5.1, the reliability and response stability values for L5-S1 were no longer the values demonstrating the greatest amount of error. Therefore, the measurement of the cephalad border of S1 was a reliable alteration to the original DCRA protocol that did not require the rater to attempt to locate the poorly visualized caudal borders subjectively.

Inter-Image Reliability

As expected with the inter-image reliability, the reliability coefficients decreased with the increased variability in human movement and patient positioning expected between imaging separate movement trials. The inter-image reliability ICC (2, 4) for midplane angle were all > 0.82, and these were interpreted as good based on the Portney & Watkins[125] classification system. Further, five of the six midplane angle measurements tested were > 0.9 level to ensure reasonable validity. The ICC (2, 4) values for displacement ranged from 0.64 to 0.93 and were interpreted as moderate to good,[125] with four of these six measurements being > 0.9 level.

Only the reliability coefficients associated with the L3-4 segment were below the value of .90. This was unexpected. It was the opinion of the rater that L3-4 was the easiest segment for the subjective point placements of the vertebral corners, this was corroborated by the lowest SEM (0.4° and 0.2 mm; Table 4.1) at L3-4 during the intra-image reliability study. Possible explanations of the lower reliability coefficients at L3-4 for inter-image reliability can be based on both limitations in the analysis protocol and variations in human movement. Based on a review of the data it appeared that the standardization of the movement pattern by global lordosis may have been inadequate to assess the L3-4 at the upright position. After re-standardizing the L3-4 data by flexed posture only, the ICC (2, 4) values increased from 0.82 to 0.93 for maximum (upright) midplane angle. However that change had only a minimal impact on the lower reliability coefficient for the minimum intersegmental displacement. A second possible explanation of the decreased inter-image reliability at L3-4 may have been because of variation in the attainment of the maximum L3-S1 lordosis angle between trials which was used to define the movement pattern. Multiple repetitions of the movement pattern to represent the subject's movement may help to reduce this error in future research.

Although the ICC values at L3-4 were lower than expected, the average 95% CI for the SEM across all segments remained low (< 2° and 1.2 mm). Comparisons at the segmental level to the reported error values by Frobin et al[46] are provided in Table 5.3. The comparison reveals the SEM at the 68% CI level measured in this study, relative to the standard deviation reported by Frobin et al[46] were comparable. The continued relative decrease in error at L5-S1 provided further support for the alteration of the algorithm in which only the cephalad border of S1 was used to represent the first sacral body.

Although there are differences in the methods in which these error measurements were obtained, the minimal differences between the two techniques support the claim by Frobin et al[46] in regards to the robustness of the DCRA technique. Future use of this technique should investigate the benefit of using the mean of multiple motion trials (i.e. three repetitions) to represent a subject's motion pattern. By using an average of three separate motion trials to represent the subject's true motion, the fluctuations due to variability of human motion may be minimized. This potentially would improve the ICC and decrease the SEM which would improve the ability of this technique to assess significant kinematic changes over time.

Table 5.3: Comparison of inter-image SEM of the current study with the results published by Frobin et al.[46]

	Current Study*		Frobin et al.[46]†	
	n*	**Error Min:Max (SEM) ‡**	**n†**	**Error (SD) ‡**
		Intersegmental (Midplane) Angle		
L3-4	20	0.68 to 1.42°	54	0.85°
L4-5	20	0.97 to 1.12°	52	1.32°
L5-S1	20	0.80 to 0.99°	11	1.64°
		Intersegmental Displacement		
L3-4	20	0.584 to 0.602 mm	54	0.518 mm
L4-5	20	0.438 to 0.473 mm	52	0.546 mm
L5-S1	20	0.651 to 0.732 mm	11	0.840 mm

* 3 Segments measured representing 20 subjects during the motion from upright to flexion

†For L3-4 and L4-5: 6 cadaver specimens, 9 radiographs taken in different 0, +5, -5 degrees of rotation or tilt, For L5-S1 11 images of a bony phantom taken at different distances from the image intensifier.

‡Example based on a 35 mm vertebral body (SEM*35 mm or SD*35 mm). Note this is 68% CI and was done to compare with the published data from Frobin et al[46] which was only $\pm$ 1 SD

In summary, the use of DCRA to measure the kinematic variables of lumbar movement as imaged by DFV was a reliable technique with an average inter-image SEM < 2.0° and 1.2 mm. The ability to enhance the images digitally prior to analyses appears to be a successful strategy that did not require the digitization of hand-drawn outlines of the vertebral bodies to determine the location of the vertebral bodies. Besides allowing direct measurement on the DFV images, this alteration allowed for greater automation of the process which ultimately allowed for the analysis of more frames per second (30 Hz) relative to prior VF studies (3-5 Hz).[55,65,66,106] Further, the alterations to the measurements of S1 appeared to be successful. To improve the ability to measure repeated movement over time, average measurements of multiple movement patterns may be more representative of the individual's movement pattern and therefore reduce the error associated with a test-retest design. Although the error measurements in this study were low, further improvement may be beneficial with regard to the ability of the responsiveness of this technique to detect change pre- and post-treatment (or surgery).

USE OF KINEMATIC VARIABLES TO DISTINGUISH GROUP MEMBERSHIP

Kinematic Variables Were Able to Distinguish Group Membership Between the Symptom-Based Groups

Although a measurement technique may be reliable, its usefulness for the medical community requires that the technique provide both clinically useful and valid information. To help establish the construct validity of this DFV measurement technique and its clinical utility, the current study determined whether this technique could distinguish group membership based on a set of kinematic variables. A cluster of 10 kinematic variables was able to distinguish group membership between those with signs and symptoms of LSI and those without a history of LBP in the last 10 years. The

greatest accuracy (87.5%) and the best combination of Sn, Sp, +LR, and –LR of the model occurred if a subject had four or more of the 10 criteria (Table 4.42). Therefore, the hypothesis that kinematic variables could distinguish group membership of the symptom-based groups was accepted.

The ability to create a model of kinematic variables that collectively were able to distinguish group membership also helps to establish construct validity for the CPR designed by Hicks.[58] The entrance criteria for this study were based on a cluster of signs and symptoms that were selected to assist providers in determining those patients who will succeed with a lumbar stabilization exercise program. The majority (70%) of the criteria in this kinematic model were related to timing (rate of attainment) of angular range and displacement range. One of the basic tenets of physical therapy treatment of LBP, specifically associated with a standard lumbar stabilization exercise program, has been to improve the motor control components related to LBP.[129] Therefore the model developed in this study supports the theoretical concepts underlying the CPR and treatment approach outlined by Hicks.[58] In addition to timing differences between the groups, the INST-I group also demonstrated displacement hypomobility (30% of the variables in the model). Therefore, this model also supports a clinical treatment approach that combines the use of manual therapy with lumbar stabilization training, as suggested by Niemisto et al.[102]

Prior to the discussion of the kinematic variables individually, examination of the types of variables that entered the model provides some insight into the difficulty of using traditional descriptive measures of displacement and angle range in distinguishing group membership. As previously stated fifteen variables met both the statistical criteria ($p < .20$) and had a distinguishable cut-off value on a ROC curve to possibly make them

eligible components of the model. These variables included only four of the more traditional descriptive variables of displacement mobility, of which three were included in the final model (30%). Further, no variables describing angle mobility met the criteria to enter the model. Conversely, eleven timing variables describing both rate of attainment of angle and displacement range as a function of global motion met the entrance criteria for the model, and seven remained in the final model (70%). The lack of angular descriptive variables and the limited number of displacement descriptive variables that were able to distinguish group membership relative to the timing variables supports prior researchers[33,57,78,90,97,103,126,143,145] who have suggested the difficulty of using these types of mobility measures to identify those with LSI. Further, the greater number of timing variables for both angle and displacement that entered the model supports prior researchers[14,15,65,66,78,83,84,95,97,106,160] who have advocated the need for dynamic analysis of lumbar kinematics to describe those with LSI.

A discussion of the variables used in the development of this model follows. First, the limited role of the more traditional descriptive variables of angle, displacement and translational speed to distinguish group membership are discussed. Then the role of the timing variables (rate of attainment) of angular and displacement range to distinguish group membership are discussed.

Limited Influence of Traditional Descriptive Variables (Angle, Displacement, and Translational Speed) in Distinguishing Group Membership

Of the more traditional measurements of lumbar movement, only displacement hypomobility in the INST-I group relative to the CONTROL-I group entered the model. The measurements of L3-S1 global angle, segmental angle, or translational speed did not

differentiate the symptom-based groups. Interpretation of each of these more traditional measurements and their influence on the clinical implications of this study are discussed.

Although the results were different from those hypothesized, there were no differences between the descriptive measurements of angular values or the angle instability ratio between the groups (Tables 4.3-4.4; Figures 4.1-4.5). Both groups moved through approximately 33 $\pm$ 6° ($p = .871$) of L3-S1 motion during flexion and return to upright. The inability to measure differences in group means of the descriptive data (maxima, minima, range, mean) may reflect the difficulty of using such measures based on the wide variation of normal movement and the differences in mobility observed with different stages of a dysfunction.[32,33,71,91,96,103,144]

Another possible reason for the lack of differences among the angular descriptive variables was the entrance criteria for this study. Specifically, prior researchers[31,103] have critiqued research performed on subjects in which pain status may have resulted in altered total volitional movement and hence increased error and underestimation of the measured movement pattern. To limit this possibility, subjects in this study were required to be in a subacute state and were required to be able to perform flexion and the return to upright in a relatively gross normal movement pattern, unobstructed by pain as observed by their referring physical therapist. These entrance criteria probably contributed to the lack of differences between the groups (INST-I and CONTROL-I) in global and segmental angular range. Furthermore, the lack of angular differences between group memberships has provided a beneficial role and foundation to interpret the rest of the findings in this study. Specifically, the differences observed in this study occurred when the group means for the subjects in both groups moved through the same global ROM and same segmental angular motion.

Although both groups (INST-I and CONTROL-I) had the same angular range, they displayed different displacement ranges. However hypomobility was found in the INST-I group, not hypermobility. Therefore the direction of the difference was opposite that of the original hypothesis. Specifically, the combined total displacement range (L3-4 + L4-5+L5-S1) of the CONTROL-I group (33.5 $\pm$ 9.2%) was greater than the INST-I group (27.9 $\pm$ 7.4%; Tables 4.11-4.12; Figures 4.11-4.14). Further, there was also a significant decrease (approximately 2%) in displacement range of L4-5 during flexion and the return to upright in the INST-I group. In addition to these three variables that entered the model, there were other trends of displacement hypomobility at L3-4 and L4-5 that did not enter the model (Table 4.12). These variables may be of interest in future studies. Overall, the greater displacement range noted in the CONTROL-I group may be associated with previous findings of a 'flexion-relaxation' phenomena, in which there is electrical silence of electromyographic (EMG) activity of the lumbar paraspinals at the end range of flexion noted in healthy individuals, that does not occur in those with LBP.[115,138,140] Therefore, continued activity of the lumbar paraspinal muscles at the end range of flexion in those with LBP may limit segmental displacement range. More research is needed.

One limitation of measuring individual segment displacement characteristics (mean, maxima, minima, and range) was that different subjects may have dysfunctions at different segments and therefore the group means of these values would obscure any individual differences. To overcome this obstacle an instability ratio was developed in which the greatest displacement range of any single FSU was divided by the mean of all three FSU displacement range values. During flexion, this ratio demonstrated a possible trend, in which the segment that had the greatest displacement range was 36% greater

than the mean of the three segmental range values in the INST-I group, while only 26% difference between the maximum value and the group mean was measured in the CONTROL-I group during flexion ($p = .096$). There was no difference noted during extension ($p = .911$). Although this met the criteria for a possible trend and the direction of change was as hypothesized, it did not have an identifiable cut-off value on the ROC curve and was not analyzed further. Future researchers should consider using a similar ratio that can address the different levels of dysfunction among subjects.

Descriptive measurements of translational speed (mm/sec) were not different between the groups (Table 4.17). Specifically, the maximum translational speed during flexion was not different between the groups nor was there a difference in the speed ratio comparing the maximum speed of a single vertebral body to the mean of all vertebral bodies. Further, the time delay in attainment of maximum speed of L3 to S1 during flexion was not different between the groups.

The lack of differences in translational speed between the groups was different from prior reports.[84,89] Both Marras and Wongsam[84] and McGregor et al[89] found that those with LBP had a decrease in velocity and that these differences were able to distinguish group membership better than more traditional descriptive positional measurements. Differences in test conditions and patient selection may help to explain this discrepancy. First, the subjects in this study were instructed to complete the global motion of flexion and extension between 4-5 seconds. Although only global motion was controlled, differences in segmental translational speeds obtained by self-selected global movement speeds were not tested and therefore can not be compared. This slower speed of global movement was required to prevent blurring of the image. A second possible explanation was the influence of the entrance criteria on the subjects selected for this

study. As previously stated, the entrance criteria were designed to minimize the effects of pain on measurement error. More acute patients may experience reduction in translational speeds. Although there was not a difference in the maximum translational speeds between the groups, this commonality also provides a foundation to interpret the rest of the findings. Specifically, the angular and displacement timing differences observed occurred without a difference in maximum translational speed of the vertebral bodies.

In summary, there was less displacement range in the INST-I group relative to the CONTROL-I group, even when the global angular range, segmental angle range, and maximum translational speed were equivalent. As discussed above, the hypotheses of greater global angular range, greater segmental angular range, greater angular instability ratio during flexion and extension, maximum translational speed, speed ratio, and timing of maximum speed during flexion were all rejected. Further, the direction of the hypothesis for segmental displacement during flexion and extension was incorrect; as the INST-I group displayed displacement hypomobility. There appears to be some potential value for a measurement variable that takes into account the disparity of the range values over all of the measured segments that may be masked by comparing only segmental differences; more research is required.

Influence of Dynamic Timing Variables (Angle and Displacement) in Distinguishing Group Membership

A theoretical benefit of measuring lumbar kinematics with DFV over static images is the ability to measure how the motion is attained; with specific interest in the motion that occurs within the NZ.[18,73,95,97,110] Of the 10 criteria in the model, seven were categorized as timing variables measured during the mid-range of motion; which has

been theorized to be under neuromuscular control.[109,110] Both angle and displacement timing variables contributed to the model (Table 4.41). During the initiation of flexion (0-15%) there were disruptions with both angular and displacement timing variables in the INST-I group. Although more research is required, these disruptions may be consistent with the "slipping" and/or "catching" sensation felt by these patients during the onset of flexion. These disruptions help to provide face validity to the model because of the consistency between these variables and typical difficulty of these patients during the onset of flexion. The hypotheses regarding a difference between the rate of attainment of angular and displacement range between the INST-I and CONTROL-I groups during the onset of flexion and upon return to upright were accepted. Each of these variables is discussed below.

During flexion, a simultaneous initiation of angular range during the first 15% of movement appeared in the CONTROL-I group. Conversely, the INST-I group exhibited a greater rate of attainment of angular range at L3-4 accompanied by a delay in the rate of attainment of angular range at L4-5 and L5-S1 (Table 4.8, Figure 4.7A). Specifically, at L3-4 the greater rate of attainment of angular range in the INST-I group entered the model with a + LR of 2.8; this was accompanied by a decreased rate of attainment at L4-5 during 5-15% (+ LR 2.3) and at L5-S1 during 0-5% of flexion (+ LR 2.2; Table 4.41). This may represent a compensatory mechanism in which the individuals with LSI initiated angular movement at a theoretically healthier segment (L3-4) while allowing the lower and theoretically more dysfunctional segments to attain their angular range in a more delayed manner. Further, this different rate of attainment of angular range in those with LSI may represent underlying muscle guarding or a pain avoidance movement pattern, more research is required. These differences were in contrast to those without

LBP; which tended to initiate the angular motion during 5-15% of motion in a more uniform manner across all three FSUs.

Similar to rate of attainment of angular range during flexion, the rate of attainment of displacement range for the INST-I group demonstrated a disordered movement pattern during 5-15% of flexion (Table 4.14; Figure 4.17). At L3-4, the INST-I group was basically in a paused state (slope = 0.05) and at L4-5 the INST-I group had a negative slope (-0.8). At the same time, at segment L5-S1 the INST-I group was attaining a positive and increasing rate of attainment of displacement. These differences noted in the INST-I group occurred at the same time the CONTROL-I group experienced positive and increasing rate of attainment of displacement range at all segments. Therefore, the INST-I group was attaining the displacement range at the most caudal segment (L5-S1) during the onset of motion at the same rate as the CONTROL-I group ($p = .925$), while the more cephalad segments of the INST-I group were either in a relative pause or displacing in a negative direction. The differences at L3-4 and L4-5 from 5-15% of flexion contributed as criteria to the final model with a +LR of 2.4 and 2.0, respectively. The delayed attainment of displacement range in those with LSI was similar to the concept of prolonged deflection reported by Okawa et al.[106]

As discussed, the differences during the initiation of flexion between 5-15% of flexion occurred with the rate of attainment of both displacement and angular range. Specifically, the greater rate of angular motion at L3-4 was accompanied by a relative decreased rate of attainment of displacement range in the INST-I group. The lower rate of attainment of angle range at L4-5 was accompanied by a negative rate of attainment of displacement range at L4-5 in the INST-I group. At L5-S1 there was a relative delay in the rate of angular range during 0-5% of flexion in the INST-I group, but the rate of

attainment of displacement range was not different between the groups at 0-15% of flexion. These timing problems, occurring at the onset of flexion, are consistent with the NZ theory outlined by Panjabi[110] in which the dysfunctional movement occurs during the ROM under neuromuscular control and not at the end range of flexion, which has been theorized to be limited by the passive osteoligamentous system. These differences at the onset of flexion may represent the "catching" or "slipping" sensation felt by subjects with LSI. More research is needed to address this question.

There were fewer differences noted in the rate of attainment of angular range during extension (Figure 4.7B). During extension, only variables related to L4-5 met the statistical requirement for further analysis. It appears that the CONTROL-I group attained its angular range at L4-5 earlier during the return to upright (about 75-85% of the motion) and then slows down, while the INST-I group attains its angular range at a higher rate during the last 5% of returning to upright (Table 4.10). Only the difference during the last 5% of extension met the criteria for the model with a + LR of 2.0 (Table 4.41).

During the return to upright there was an unexpected and interesting movement pattern related to the attainment of displacement range in the CONTROL-I group at L5-S1 (Figure 4.14C). During 65-75% of extension, the CONTROL-I group's rate of attainment of displacement range reversed direction and had a positive slope of 0.4 ± 1.7. This unexpected difference in the CONTROL-I group entered into the final model with the highest +LR of 6.0 and a Sp of .90. An interesting note about this paradoxical motion was that examination of the raw data revealed that both groups experienced this phenomenon (7 of the 20 INST-I and 10 of the 20 CONTROL-I subjects), in which a positive slope was observed. However, the amplitude for the CONTROL-I group was larger. This greater variability in the movement pattern resulted in a reversal in the mean

slope value from a negative to a positive slope only in the INST-I group (Table 4.16). Although the meaning of this reversal is not currently understood, it may represent an adjustment to the movement pattern to help slow down the overall motion at L5-S1 as the person returns to upright, or it may demonstrate some type of adjustment during the return to upright as the upper trunk returns to a more vertical position. Further research is required to further understand this pattern of movement and to determine its significance.

During extension, the differences noted were more uni-segmental. This was in contrast to the multi-level differences found during flexion. The different roles of the spinal extensor muscles during these actions (eccentric versus concentric) is one suggested reason to explain the disparity that deserves further analysis. Further research should assess the kinematic movement pattern along with EMG analysis to further understand this disparity.

One interesting finding that did not enter the model was that there appeared to be a "correction" or "catch-up" phenomena experienced by these initial angular timing lags later in the movement pattern. For example, at L3-4 the slope of the INST-I group decreased during 35-45% (Table 4.8). While, at L4-5, the initial delay in rate of angular range at L4-5 did not reach a slope equivalent to the slope of the CONTROL-I group during 5-15% of flexion (> 0.9) until 35-45% of flexion. This phenomenon was also seen at L5-S1, in which the INST-I group had a significantly greater attainment of angular range at 35-45% of flexion accompanied by a negative slope in the CONTROL-I group.

Similar to the pattern noted with the rate of attainment of angular range, there was a "catching-up" phenomenon observed with the rate of attainment of displacement range. At L4-5 during 55-65% of flexion, the increased rate of attainment of displacement range theoretically could represent a period of time in which the INST-I group was making up

for the delay in the rate of attainment of displacement range noted earlier in the motion pattern (Table 4.41). Further, at the final stages of extension (85-95%), the CONTROL-I group displayed an increase in the absolute rate of attainment of displacement range after the reversal discussed above (Table 4.16). Although these trends were noted, none of these differences entered the final model but were discussed in reference to their possible future importance.

In summary, the kinematic variables that entered the model in which the reference criterion represented the symptom-based groups provide construct validity both for the use of DFV to measure lumbar kinematics and in the CPR outlined by Hicks.[58] As noted by the multi-level differences discussed, the influence of LSI was not related to a single segmental dysfunction. Multi-level findings measured in those with LSI was in agreement with the reports by Okawa et al.[106] From a treatment perspective, the disordered movement pattern for timing of the attainment of angular and displacement range and the overall hypomobility of displacement range provide support for the use of lumbar stabilization exercise programs with the possible addition of manipulation to treat these individuals.[58,102,129]

Kinematic Variables Were Able to Distinguish Group Membership Between the Motion-Based Groups

Clinically, the use of imaging to support or help determine a diagnosis is common practice. However, the use of DFV to assess lumbar kinematics has been limited because of the image quality issues previously described. Although the influence of qualitative assessment of the DFV was initially unknown, it was theorized that adding this step to the process would result in more homogenous groupings of subjects; both instability and control (labeled the motion-based groups). Therefore, it was hypothesized that kinematic

variables would also be able to distinguish group membership in the motion-based grouping of subjects (INST-F and CONTROL-F) and that the visual information observed by the expert reviewers would result in a different set of kinematic variables in the model. Both of these hypotheses were supported.

As speculated, the addition of the expert review process resulted in subject groupings that were more distinctive and resulted in an improvement of a kinematic based model to identify group membership (INST-F and CONTROL-F; Tables 4.45 and 4.47). This was supported by the average area under the ROC curve, the number of variables that qualified to enter each model, the values of the +LR that entered the model, and the greatest accuracy attained by each model. Among all the kinematic variables that were tested for the models, the average area under the ROC curve increased from 0.664 $\pm$ 0.038 in the symptom-based groups to 0.704 $\pm$ 0.050 in the motion-based groups. This increased area represents an increase in the ability of a kinematic variable to correctly identify the classification of two individuals (one with and one without LSI) from 66.4% to 70.4% based on an average single variable. The analysis of the variables with a +LR > 2.0 increased from 10 in the symptom-based group to 16 in the motion-based group. Further, in the symptom-based group there were only three variables with a + LR > 2.5, while the motion-based group had eight variables that met this criteria. Finally, the greatest accuracy of each model increased from 87.5% in the symptom-based 10 variable model to 96.0% in an eight variable model from the motion-based groups. Therefore, the model improved with the additional step of expert review of the DFV to determine group membership.

The two models developed for the motion-based groups (16 variable and eight variable models) were similar to the symptom-based models in the general types of

variables used to distinguish group membership. As with the symptom-based groups, more timing variables (62.5 and 75%) were used in the motion-based models compared to the more traditional descriptive variables of angle, displacement, and translational speed (37.5 and 25%). Further, the general patterns of motion (displacement hypomobility, disordered angular and displacement movement patterns during the first 15% of flexion, and the reversal of the rate of attainment of displacement range during extension in the control group) remained as distinguishing characteristics in the motion-based groups. However, some of the individual variables that support these trends varied from the original symptom-based model. Although the eight variable model was more accurate (96%) and was more concise than the 16 variable model (92%), both models were presented in order to describe possible variables of interest for future research.

Comparison of the models between the symptom-based and motion-based groups revealed that the addition of expert review of the DFV to dichotomize the groups not only resulted in a more homogenous grouping of the subjects (as discussed above) but resulted in a different set of specific kinematic variables that were able to distinguish group membership. A comparison among the types of variables that were able to distinguish group membership among the three models is presented in Table 5.4. Although the general trends across the models were consistent, the motion-based 16 variable model had 10 different kinematic variables compared to the symptom-based model. An angle descriptive variable was now in the model along with four different displacement variables, and five new angle and displacement timing variables. Comparison of the models based on lumbar segmental levels that entered the model (Table 5.5) revealed that the expert review of the images resulted in an addition of five variables from L3-4 and an addition of one variable from L4-5 in the 16 variable motion-based group model

compared to the symptom-based model. All models had only one or two variables representing L5-S1 motion or a descriptor describing the overall motion pattern (i.e. total displacement range or angle ratio). The lack of differences at L5-S1 that entered the model was in contrast to the high rate (16/30) of comments by the qualitative reviewers about dysfunction noted at this level relative to the number of comments for both L3-4 and L5-S1 (14/30). The differences between the levels of dysfunction and the measurements of interest in the motion-based models provide some insight into the process of qualitative review; these differences between the observed visual deficiencies and the kinematic assessments should be a topic of future research.

Table 5.4: Comparison of the criteria used to distinguish group membership across the three models

Model (Variables)	Decision Rule + LR	Descriptive Variables		Timing Variables	
		Angle	Displacement	Angle	Displacement
Symptom-Based Group					
10	> 2.0	0	3	4	3
Motion-Based Group					
16	> 2.0	1	5	6	4
8	> 2.5	1	1	4	2
# Shared variables between symptom-based (10) and motion-based (16) models		0	1	3	2

Table 5.5: Comparison of the criteria used to distinguish group membership across segmental levels

Levels	Symptom-Based (10 Variables)	Motion-Based (16 Variables)	Motion-Based (8 Variables)
L3-4	2	7	3
L4-5	5	6	3
L5-S1	2	2	1
Overall Measure	1	1	1

Limited Influence of Traditional Descriptive Variables (Angle, Displacement and Translational Speed) in Distinguishing Group Membership

Of the more traditional measurements of lumbar movement, only the angle instability ratio and displacement hypomobility in the INST-F group relative to the CONTROL-F group entered the model. There continued to be no differences in L3-S1 global angle, segmental angle, or translational speed after the expert review process. As previously stated, the lack of differences in L3-S1 global angle, segmental angle, and translational speed has provided a foundation for the interpretation of the differences that were measured.

Although there were no differences measured in L3-S1 global angle (Table 4.26, Figure 4.19) or segmental angular values (Table 4.27, Figures 4.21-4.24), the expert-reviewers visualized distinctions between the disparities of angular range among the levels, however the direction of the difference was opposite to that of the original hypothesis. Specifically, the motion-based groups displayed a difference in the angle instability ratio (maximum range of a single FSU / mean of the maximum ranges of all FSUs) during extension. The CONTROL-F group displayed a greater amount of variability ($26 \pm 11\%$) between a single segment's maximum range compared to the group mean of all segments, while the INST-F group only had a $16 \pm 12\%$ difference (Table 4.27). This difference was strong enough to have a Sp of .857 and +LR of 4.455 (Table 4.44) and was included in both the 16 variable and eight variable models to distinguish group membership. The greater variation in the angular disparity among the segmental levels in the CONTROL-F group as compared to the INST-F group occurred without any other significant differences in other unisegmental angular descriptive data. As previously stated, future research should continue to investigate the role for kinematic

variables that account for relative differences among the measured levels to help detect dysfunctional movement instead of the more traditional unisegmental descriptive measures which have been controversial and ultimately unsuccessful in distinguishing group membership.[32,33,71,91,103]

Displacement hypomobility at L3-4 and L4-5 were noted in the INST-F group. The measured hypomobility was different from the hypermobility initially hypothesized. The addition of the expert review process resulted in five displacement variables demonstrating displacement hypomobility in the INST-F group (Table 4.44). The four new variables, specific to the motion-based group, were related to hypomobility of L3-4 during flexion and extension in the INST-F group (Figure 4.28). Each of these four variables had a + LR of 2.227 and entered the 16 variable model but did not meet the requirements for the eight variable model. Similar to the differences among the symptom-based groups, the INST-F group displayed less displacement range at L4-5 during extension compared to the CONTROL-F group (Figure 4.29). The displacement range of L4-5 during extension entered both models with a Sp of .786 and +LR of 2.970. Similar to the symptom-based groups, there was a trend towards an overall decrease in displacement range in the INST-F group (Table 4.34), but this trend did not have an observable cut-off score on the ROC curve and was not further analyzed. Further, the decreased range of L4-5 during flexion and the increased displacement instability ratio of the INST-I group were not noted in the INST-F group.

Measurements of translational speed during flexion (mm/sec) continued to display no difference between the groups, did not meet the criteria to be considered for the model, and was different from the original hypothesis. Specifically, there was no difference between the maximum translational speed of each vertebral body during

flexion between the groups nor was there a difference in the speed ratio comparing the maximum speed of a single vertebral body to the mean of all vertebral bodies (Table 4.40). Further, the delay in attainment of maximum speed of L3 to S1 was not different between the groups.

Although not a specific aim of this study, one interesting comparison was the observed differences noted by the expert reviewers and the results of the more traditional measurement techniques on the final kinematic models. Specifically, the reviewers commented 25 times on displacement issues, 11 times on angular issues, 14 times on velocity issues, and 13 times on rhythm issues, and 10 times on overall hypomobility. One interesting comparison was that unlike the symptom-based groups, the reorganization into the motion-based groups resulted with an angular measure (angle instability ratio) that was incorporated in the model to describe group membership. A second interesting difference between the symptom-based and motion-based models was that the overall decrease in L3-S1 displacement hypomobility and the displacement hypomobility at L4-5 during flexion were no longer discriminators and hypomobility at L3-4 was a discriminator after the expert-review of the DFV. Further, there continued to be no differences between the descriptive values of translational speed despite the observed velocity differences in the DFV by the expert reviewers. Therefore, the observations by the expert reviewers, which were based on terms associated with more traditional descriptive measurements, may actually be reflective of the timing differences described below that were better discriminators of group membership or differences that were not measured in this study. Future studies should address the relationship between qualitative assessment and quantitative assessment of DFV to better understand the role of qualitative assessment of DFV in a clinical setting.

Influence of Dynamic Timing Variables (Angle and Displacement) in Distinguishing Group Membership

Similar to the symptom-based groups, the models that represented the motion-based groups had more timing variables that were able to distinguish group membership as compared to the traditional descriptive measures. Specifically, there were more angular timing variables than any other category of variables (Table 5.4). Six angular timing variables entered the 16 variable model, of which four entered the eight variable model (Table 4.44). These variables provided support for the hypothesis that differences in the rate of attainment of angular range would exist between the two groups. There were four displacement timing variables that entered the 16 variable model, of which two entered the eight variable model. These variables provided support for the hypothesis that differences in the rate of attainment of displacement range would exist between the two groups. Five of the angle and displacement timing variables were robust enough to be in both the symptom-based and the 16-varaible motion-based models. The differences noted after the expert review process between the groups will be discussed during flexion and then extension.

Differences in the rate of attainment of angular range during the onset of flexion continued to be able to help differentiate group membership in the motion-based groups. The greater rate of attainment of angular range at L3-4 during 5-15% of flexion and the slower rate of attainment of angular range at L4-5 during 5-15% in the INST-F group remained significant (Table 4.31) and were criteria in both motion-based models (Table 4.44). Further, the subjects selected with abnormal movement patterns by the expert reviewers maintained the slower rate of attainment of angular range at L4-5 in the INST-F group through 15-25% of flexion relative to those viewed as having normal movement

(Figure 4.25A). However, unlike the symptom-based groups, there was no difference at L5-S1 during the onset of flexion. These differences noted in the INST-F group occurred while the CONTROL-F group had similar positive slopes across all three levels during the onset of flexion (Table 4.31). Therefore, the differences in the rate of attainment of angular range measured in the symptom-based groups were also differences observed by the expert reviewers that ultimately composed the motion-based groups.

The expert-reviewers also selected individuals with differences in the rate of attainment of displacement range during the onset of flexion (Table 4.37; Figure 4.34). During 5-15% of flexion the rate of attainment of L5-S1 displacement range demonstrated a trend towards a greater slope in the INST-F group; this criterion entered the 16 variable model. At the same time, the INST-F group displayed a negative slope at L3-4 (-0.3 ± 1.4) compared to the CONTROL-F group (1.2 ± 1.7; $p = .022$). This variable had a + LR of 3.394 and entered both the 16 and eight variable model. At L4-5 (Figure 4.34), the INST-F group displayed a negative rate of attainment of displacement range and it appeared that this was different from the more neutral slope in the CONTROL-F group. However the large standard deviations among the groups resulted in a non-significant difference ($p = .408$).

Displacement timing differences during the onset of flexion between the groups was seen in both the symptom-based and motion-based groups; however there were slight differences in which levels of the spine were significant. The commonality between the analyses of both instability groups was that the L5-S1 segment was attaining a positive rate of attainment of displacement range while the slope was more neutral or negative at L3-4 and L4-5 in the INST-F group. Meanwhile, the CONTROL-F group displayed a cephalad to caudal pattern, with the greatest slope value attained at L3-4 during 5-15% of

flexion than at L4-5 and L5-S1. Not only was this attainment of displacement range different for the INST-F group, it also appears to be opposite of what was occurring during the timing of angular motion in which L3-4 in the instability groups was greatest during 5-15% of flexion. These alterations in how the angular and displacement movement was attained by those in the instability group during the onset of flexion may help to provide a better understanding of the motor control issues related to LSI and, as previously discussed, supports the NZ theory for dysfunctional movement as outlined by Panjabi.[110]

During the return to upright (Table 4.33; Figure 4.25B), the motion-based groups displayed the same differences in the pattern of motion at L4-5 as the symptom-based groups from 75-85% and 95-100% of extension. The pattern consisted of a greater absolute rate of attainment of angular range in the CONTROL-F group from 75-85% of extension followed by a greater rate in the INST-F group from 95-100% of extension. This may demonstrate a delay in the movement pattern of L4-5 in the INST-F group. Both of these variables entered the 16 variable model, but did not meet the criteria (+LR > 2.5) for the eight variable model (Table 4.44). The consistency between these variables in both the symptom-based groups and the motion-based groups demonstrates that these differences may have been observable differences that helped to determine the final group membership by the expert reviewers.

As noted in the symptom-based group, there was a reversal of the rate of attainment of displacement range from 65-75% of return to upright in the CONTROL-F group (Table 4.39). As with the symptom-based group, the finding of the reversal of rate of attainment of displacement range from 65-75% of extension resulted in the largest +

LR of both models (+ LR = 8.909) but, as previously discussed, the reason for this variation in the CONTROL-F group remains unknown.

As discussed with the symptom-based groups, there was a common trend towards a "catch-up" or a "correction" type of phenomena with the differences observed between the groups. This occurred with both the angle and displacement timing variables. The initial delay in attainment of displacement range at L4-5 was accompanied by a greater slope later in the movement pattern (45-55% and 55-65% of flexion). The differences from 55-65% met the criteria to enter the 16 variable model (Table 4.44). The initial greater rate of attainment of angular range at L3-4 in the INST-F group was coupled with a slower rate from 35-45% flexion. Although not all of these variables met the criteria to enter the model, they may be variables of interest for future research because of the consistent trend in these timing variables for some sort of "catch-up" phenomena occurring after an initial delay.

The comparison between the criteria in the symptom-based versus the motion-based models reveals similar trends in the variables that can distinguish group membership. Overall displacement hypomobility, angular and displacement timing differences during the onset of flexion, and angular timing differences during the return to upright, were consistent across the models. These variables in the motion-based groups' models became stronger discriminators of group membership compared to the symptom-based model. The additional step of qualitative review of DFV appears to be beneficial in the process of defining a homogenous group of individuals both with LSI and healthy controls. Future research should consider a similar process when trying to assess homogenous samples.

DESCRIPTION OF LUMBAR MOVEMENT PATTERNS

One of the specific aims of this study was to describe the observed motion pattern among the segmental levels. To accomplish this goal, within-group analyses were performed to describe the angular, displacement, and velocity differences noted across the segmental levels (L3-4, L4-5, L5-S1) and across the movement patterns (0-25%, 25-55%, 55-75%, and 75-100%). These analyses were performed for both the symptom-based and motion-based groups. First the percent of angular and displacement range that occurred at each level will be discussed followed by a discussion of the timing of these variables over the movements of flexion and extension.

Descriptive Variables

The amount of angular motion was greater at L3-4 and L4-5 relative to L5-S1. The angular range at L3-4, L4-5, and L5-S1 can be described roughly by 36%, 36%, and 28% for the CONTROL-I, CONTROL-F, and INST-I groups (Tables 4.5, 4.28, Figure 4.6). This relationship was similar to the percentage of motion suggested by Boyling et al[13] for L3-4, L4-5, and L5-S1 (35%, 35%, and 30%, respectively). However, the INST-F group displayed less variability among the levels with 33.5%, 36.5%, and 30% occurring at L3-4, L4-5, and L5-S1, respectively. Although the relationship between L3-4 and L5-S1 along with L4-5 and L5-S1 were significant in the symptom-based groups ($p < .001$), only the relationship between L4-5 and L5-S1 was significant for the motion-based groups ($p = .003$). The decrease in variation among the INST-F levels was also noted with a significant finding in the angle instability ratio during extension (Table 4.27). Therefore, the robustness of the mean percents of angular motion across the levels with the CONTROL-I, CONTROL-F, and INST-I groups was not observed in the INST-F group. The decreased angular variability noted in the INST-F group possibly

demonstrated one aspect of the motion pattern that the expert reviewers used to select a subgroup of subjects. The decreased variability in the INST-F group was previously masked by the group means in the more heterogeneous INST-I group.

A decrease in the range of displacement from the more cephalad to caudal segments was observed. The displacement range at L3-4 was greater than the range at L4-5 ($p = .018$) and at L5-S1 ($p = .003$) in the symptom-based groups. The percent of motion at L3-4 was 38-39%, at L4-5 32-33%, and at L5-S1 was 28-30% for both the INST-I and CONTROL-I groups (Table 4.11, Figure 4.10). The analysis of the motion-based groups revealed a non-significant main effect for level ($p = .236$) and for the interaction between group membership and level ($p = .450$); however the observed power was low for both of these comparisons (power = .302 and .181, respectively). However, an analysis of the group means revealed a similar pattern of displacement for the CONTROL-F group across the levels (38% at L3-4, 32% at L4-5, and 30% at L5-S1), while the INST-F group had a trend towards less variation (34.5% at L3-4, 32% at L4-5, and 33.5% at L5-S1; Table 4.34). Less variation among the levels for angular motion in the INST-F group and a possible trend towards decreased variation of displacement motion among the levels warrants further investigation. The trend towards decreased variation across the segmental levels among the INST-F group for both angular and displacement range values may help to describe this population with future research. Further, restoration of normal relative movement among the levels may be a clinically important goal for the rehabilitation of these individuals with LSI.

The maximum translational speed during flexion demonstrated a decrease in maximum speed from cephalad to caudal vertebral bodies (Figure 4.18). Specifically, all relationships from a cephalad vertebral body (i.e. L3) was greater than all of its caudal

vertebral bodies (i.e. L4, L5 or S1; $p < .01$). This relationship was observed in both the symptom-based and motion-based groups. The cephalad to caudal decrease in maximum speed during flexion was expected secondary to the longer path of movement required by the more cephalad segment during flexion.

Timing of Flexion

Sequential attainment of angular motion during flexion occurred in both the symptom and motion-based groups (Figures 4.8A-C, 4.9A, 4.26A-C, and 4.27A). Both the symptom-based and motion-based groups demonstrated a level (L3-4, L4-5, and L5-S1) by motion (0-25%, 25-55%, 55-75%, and 75-100%) interaction effect ($p < .001$). The rate of attainment of L3-4 was greatest during the first 0-55% of the motion relative to the last half of the motion, L4-5 was greatest during 25-55% of the motion relative to the first 0-25% of flexion, and L5-S1 was greatest during the last 25% of flexion (75-100%) regardless of group membership (instability or control) and regardless of the decision rule for group membership (symptom-based or motion-based groups). Assessment of the differences between the segmental levels across the movement pattern (Tables 4.7 and 4.30) also demonstrated a sequential movement pattern. Specifically, the slope at L3-4 was greater than L4-5 from 0-25% of flexion, and greater than L5-S1 from 25-55% of flexion. At L4-5, the slope was great than L3-4 from 55-100% of flexion, and greater than L5-S1 from 25-75% of flexion. Finally, at L5-S1 the slope was greater from 75-100% of flexion compared to both L3-4 and L4-5. Therefore, the onset of motion was predominately occurring at L3-4, followed by L4-5 during the mid-rang of motion, and towards the end of flexion, L5-S1 predominately was attaining its angular range. The sequential attainment of angular range during flexion was in agreement with conclusions drawn by prior researchers.[55,65,66,73]

Although previous studies have addressed the timing of angular range,[55,65,66,106] this was the first study to measure the timing of attainment of displacement range. Displacement in both the symptom-based (Figures 4.15A-C and 4.16) and motion-based groups (Figures 4.32A-C and 4.33) tended to occur during the last portion (75-100%) of flexion and not in a sequential pattern. This movement pattern appears to be in conflict with previously reported dependent measurements techniques that have tried to define translation as a function of angular motion (i.e. translation per degree of rotation).[46,47] Based on the late attainment of displacement range, measurements such as translation per degree of rotation, does not appear to be representative of the actual movement patterns of the lower lumbar spine during dynamic *in vivo* measurements.

Timing of Extension

Unlike flexion, sequential angular motion, as defined by this study, was not measured during the return to upright movement in any group (Figures 4.9B, 4.27 B). The pattern demonstrates an overall increased rate of angular obtainment during 0-25% and then again from 55-75% of extension. In all four groups (INST-I, INST-F, CONTROL-I and CONTROL-F) the greatest rate of attainment of angular motion during extension occurred during 55-75% of motion (Figures 4.8A-C and 4.26A-C). The lack of sequential attainment of angular range was in agreement with Kanayama et al[65] but was in disagreement with Harada et al.[55] Although Harada et al[55] found a sequential motion pattern during extension, which he defined as flexion to hyperextension, the lack of sequential motion found in this study may be explained by the testing of a more limited definition of extension (flexion to the upright posture).

Similar to the timing of the displacement range during flexion, the majority of the attainment of displacement range during extension occurs at the later stages of the motion

(Figures 4.16 and 4.33). The symptom-based groups demonstrated a greater absolute rate of attainment of displacement range from 55-75% of extension at L3-4 (Figure 4.15A) and at 75-100% at L5-S1 (Figure 4.16C). Further, the motion-based groups demonstrated a greater rate of attainment of displacement range from 75-100% of extension relative to 0-25% of extension (Figure 4.32A-C). Therefore, the greatest rate of attainment of displacement tended to occur at the end of the movement pattern (flexion or extension) regardless of group membership.

Although this description of the movement pattern did not test any specific hypothesis, the information has potential utility. A better understanding on the relative angle and displacement motion among the segmental levels has the potential to help develop future dependent measures that accounts for the relative cephalad to caudal decrease in motion observed, the sequential attainment of angular range during flexion, and the attainment of displacement range towards the end of the movement pattern (either flexion or extension). Additionally, this information has potential impact on the research and development of segment specific surgical implants. Further, the difference between sequential and non-sequential angular motion during eccentric and concentric movements may be beneficial in future research focusing on the effects of these different movement patterns on the lumbar spine.

CLINICAL IMPORTANCE

Although not an original goal of this study, it appears that the use of standard functional radiographs may be adequate to measure the global and segmental ROM from upright to the flexed posture. The extremes (minima and maxima) of angular and displacement range occurred at the upright and flexed postures (as noted in Figures 4.1-5, 4.4.11-4.14, 4.19-4.24, and 4.28-4.31). An extreme value did not occur during the

movement pattern from upright to flexion or upon the return to upright in any subject. Therefore, researchers who want to address these variables should be able to use standard functional radiographs to measure range, minima, and maxima variables. However, these descriptive variables had a limited role in distinguishing group membership in this study. Further, this study supported the use of timing variables to help distinguish group membership (Table 5.4), which functional radiographs are unable to measure.

Dynamic imaging of the vertebral movement patterns appears to be more advantageous than other attempts at measuring lumbar movement to distinguish those with LSI.[18,33,55,65,66,95-97,103,106,143] One benefit of the DFV, as per the expert reviewers comments, was the ability to visualize the pattern of movement, any delays in the movement, and any velocity or rhythm dysfunctions. The DFV technique developed has allowed for these timing related kinematic variables to be used to successfully distinguish group membership that would otherwise be immeasurable using more standard radiographic techniques. Prior researchers [79,90] using dynamic imaging tools but measuring more descriptive global kinematic variables were unable to distinguish group membership. Specifically, the use of better quality images with open MRI[90] and the use of surgically implanted ESF to measure 3-D movement[79] were unable to measure differences successfully when using more traditional descriptive measurements of ROM. Therefore, it appears there is a requirement not only for tools that can assess the movement patterns dynamically, but dependent measures that are designed to address the dynamic movement of the spine rather than the more traditional angular and displacement ROM measurements.

Although DFV have been used frequently in the clinical setting to assess the movement in the extremities, its use as a clinical tool for the lumbar spine has been

limited secondary to poor image quality.[95] The addition of a band-passed filter to the DFV of the lumbar spine resulted in an improved image quality. Specifically, the band-passed DFV was preferred over the both the unfiltered DFV and the final filtered version of the DFV in observing the movement of the lumbar spine in 100% of the pilot cases reviewed by the expert reviewers. Further, the spine surgeons reported that about 90% of the time the DFV provided different information from what one can gain from static radiographs and they believed that information was helpful in 80% of the DFV in those that were viewed as having abnormal motion. The surgeons not only reported that DFV would be a good adjunct to the current imaging options but it may lead to new definitions and understanding of instability as the motion pattern in these individuals can be directly observed.

For this study, LSI was defined by the CPR developed by Hicks[58] based on those that succeed with a lumbar stabilization exercise program. Therefore, the developed 10 variable model provides further insight into the movement pattern of these patients. Specifically, restoration of normal motor control patterns during the onset of flexion should be a primary focus for these individuals. Traditionally, improved motor control has been one of the objectives of lumbar stabilization training.[129] Therefore, this model helps to provide construct validity to this CPR. Further, the general hypomobility of L3-S1 and the specific hypomobility at L4-5, provides support for the combined use of manual therapy and lumbar stabilization training, as advocated by Niemisto et al.[102]

The addition of the expert review process resulted in more homogenous groups with a larger mean +LR for the variables in the models and a larger average area under ROC curves. The addition of expert review of the DFV was a successful step in deriving more homogenous groups of subjects for comparison. Future researchers who query the

effectiveness of treatment modalities for those with suspected LSI should consider entrance criteria that use a combination of signs, symptoms and a dynamic imaging assessment of movement in order to obtain more homogenous samples.

Although specific hypotheses were not developed around the description of the relative movement of the FSUs during the movement patterns, the within-group study designed has provided an initial step in understanding the relationships of angle and displacement variables of the L3-S1 segments during flexion and the return to upright. This type of analysis has the potential to impact the research and development of spinal implants (i.e. disc replacements) and the requirements of these implants at different segmental levels of the lumbar spine. Further, this technique may be able to provide a tool to help surgeons select their patients for spinal surgery with more precision. Better patient selection may improve the success rate of these surgical procedures, which have been reported to be between 60-80% for the first spine surgery and only 25% with a third surgery.[97,150]

LIMITATIONS

LSI was defined based on the criteria outlined by Hicks.[58] These criteria, as previously discussed, were selected based on its ability to use signs and symptoms to distinguish a group of individuals with suspected LSI and the lack of other prediction rules currently available. These subjects displayed the same amount of angular range as the control group and actually had less displacement range than the control group. These unexpected findings may be based on the entrance criteria used in this study and may differ in future studies that use different diagnostic (entrance) criteria. This limitation was also supported by the spine surgeon review of the DFV. During this analysis, the spine surgeons labeled 15 out of 40 DFV as having abnormal movement patterns, but

only 5 out of 40 as unstable. Therefore, future researchers using a sample that have frank instabilities on static radiographic evaluations may find different movement patterns and a different set of kinematic variables to distinguish group membership.

The models developed in this analysis were a first step in developing a diagnostic prediction rule for those with LSI using DFV. Although both the symptom-based and motion-based groups were able to use kinematic variables successfully to distinguish group membership between those with LSI and asymptomatic control subjects; the models have some limitations. First, the developed models were from a single sample. Implementation of this kinematic model will require cross-validation on a new sample prior to the clinical utilization of these variables and the development of a diagnostic prediction rule. Further, the 95% confidence intervals for the + and - LR were large secondary to the small sample size. Future researchers should use a larger sample. Specifically a *post hoc* power analysis determined that a sample size of at least 40 per group would be required. In the symptom-based 10 variable model, a sample size of 40 would have resulted in the lower limit of the 95% confidence interval to be > 2.0. Therefore, before this model can be clinically implemented as a diagnostic prediction rule it requires replication with a larger sample to help cross-validate the model and decrease the width of the confidence intervals.

Another limitation of this study was that it described the differences between a group of subjects with sign and symptoms of LSI compared to a group of asymptomatic controls without a 10-year history of LBP. The decision to limit the study to these populations was based on the work by Okawa et al.[106] They were able to determine kinematic distinctions between those with LSI and controls, but were unable to find differences between those with MLBP and control subjects.[106] Therefore, in order to

optimize the distinctions between the groups, this study compared only those with LSI compared to healthy controls and did not compare those with LSI to other categories of LBP. Consequently, the differences found in this study may describe those with LSI or may just reflect differences in the movement pattern that are common to other types of mechanical LBP. Future study should repeat this study comparing different types of LBP.

Of the four different types of segmental instability discussed by Frymoyer (axial rotational, translational, retrolisthetic and post-surgical),[50] only translational instability in the sagittal plane during flexion and extension was assessed in this study. Although, Keessen et al[67] and Edwards et al[34] found that sagittal plane motion was ideal for kinematic assessment of the spine secondary to maximal intersegmental motion and a lack of coupled movement patterns during flexion and extension it only provides a two dimensional representation of the movement pattern. Application of this technique to biplanar fluoroscopy, as suggested by Pearcy et al,[117] would allow for a three-dimensional representation of the movement pattern and may allow for a better understanding of the total movement pattern.

FUTURE RESEARCH

Although this technique incorporated an automated computer algorithm to determine the corners of the vertebral body using a geometric principle of maximum distance, the algorithm was not designed to use an automatic vertebral body locator between the video frames. In order to make this technique useable in a clinical setting a more automated vertebral body location technique is required. Although prior attempts[14,15,95,160] at automatically locating the vertebral body have had some partial success, the use remains limited secondary to the continued technical restrictions. None,

of these previous techniques have tried to enhance the DFV prior to the application of an edge-detection technique. Therefore, future research should focus on an image enhancement protocol prior to the application of edge detection and automatic vertebral body location algorithms.

In addition to automating the analysis, other types of technique-based and validity-based studies are required. This study used one repetition of movement as a representation of the subject's motion pattern. An average of multiple movement trials may be more representative of their movement pattern and may be able to decrease the SEM. A smaller SEM would allow this technique to detect change in movement patterns over time with more precision. Further, analysis of the type of motion that should be measured needs to be determined. Specifically, previous researchers have used motion studies with the subject seated, standing, side lying, and/or a combination of positions with or without overpressure.[18,33,133,144,158] A second difference is the movement itself; some have studied eccentric and concentric flexion,[106] as measured here, while others have measured the movement cycle from hyperextension to full flexion.[55] A comparison of how these movement patterns differ would allow for greater understanding on the interpretation of these different testing conditions. Additionally, the impact of different measurement techniques to determine intersegmental angle and displacement values[96,136] should be evaluated to determine the influence of their different approaches on the outcome measures. Further validating this technique with cadaveric models should be analyzed.

The prognostic capability of these types of measurements remains unknown. Future functional studies could apply this measurement tool pre- and post- rehabilitation or surgical care of those with LSI to help predict success with the different treatment

approaches. This new measurement technique may be able to measure the short- and long-term effects of manipulation and/or lumbar stabilization exercise programs in improving lumbar kinematics. Further, pre- and post-surgical measurements of lumbar kinematics for lumbar fusion procedures, discectomy, and disc replacements may help to describe the mechanical effects of these surgeries on lumbar kinematics.

CONCLUSION

The measurement of kinematic variables on DFV was found to be a reliable measurement technique with average inter-image error measurements < 2.0° and 1.2 mm (95% CI). Studies designed to measure the responsiveness to change of these variables may require smaller error measurements. The use of an average score representing several repetitions of the movement may help to minimize the effects of variation of human movement on the inter-image error measurements.

The use of DFV to measure the kinematic patterns of movement during flexion and extension was able to successfully discriminate between those with LSI and asymptomatic controls. This result helped to establish construct validity for the use of this technique in future research. Specifically, differences in the attainment of angular and displacement range, especially during the onset of flexion, and displacement hypomobility were variables that were able to distinguish the movement patterns of those with LSI relative to asymptomatic controls. Physical therapy treatment regimens focused on the restoration of these variables may be beneficial.

Combining the patient's presentation (signs and symptoms) with expert review of the DFV resulted in a stronger discriminatory model. The additional step of qualitative review of DFV appears to be beneficial in the process of defining a homogenous group of individuals both with LSI and healthy controls. The use of a cluster of descriptive and

timing variables of movement has the potential to develop a diagnostic prediction rule for those with LSI. The models developed in this study provide a foundation for such a diagnostic prediction rule; however cross-validation is still required.

Appendices

APPENDIX A: ABBREVIATIONS

Abbreviation	Term
+LR	Positive Likelihood Ratio
-LR	Negative Likelihood Ratio
ALARA	As Low As Reasonably Achievable
AM	Anterior Midpoint on the midplane line
ANOVA	Analysis Of Variance
B	Bisectrix
BAMC	Brooke Army Medical Center
BMI	Body Mass Index
CAD	Coronary Artery Disease
CONTROL-I	The initial control group without a history of low back pain
CONTROL-F	The final control group without a history of low back pain and viewed as demonstrating normal motion by expert reviewers
CPR	Clinical Prediction Rule
CT	Computerized Tomography
D	Distance between the perpendicular projection of two adjacent vertebral body midpoints to its bisectrix
DCRA	Distortion Compensated Roentgen Analysis
DFV	Digital Fluoroscopic Videos
DoD	Department of Defense
EMG	Electromyography
ESF	External Spine Fixator
EZ	Elastic Zone
FABQ	Fear Avoidance Behavior Questionnaire
FOV	Field Of View
FSU	Functional Spinal Unit
HIPAA	Health Insurance Portability & Accountability Act
IAR	Instantaneous Axis of Rotation
ICC	Intraclass Correlation Coefficient
ICR	Instantaneous Center of Rotation
INST-I	The initial instability group based on symptoms and physical exam
INST-F	The final instability group based on symptoms and viewed as demonstrating abnormal motion by expert reviewers
kVp	Kilovolts peak
L3	3rd lumbar vertebral body
L3-4	The FSU including the 3rd and 4th lumbar vertebral bodies

Abbreviation	Term
L3-S1	The segment of the spine from the 3rd lumbar vertebral body to the 1st sacral body
L4	4th lumbar vertebral body
L4-5	The FSU including the 4th and 5th lumbar vertebral body
L5	5th lumbar vertebral body
L5-S1	The FSU including the 5th lumbar and 1st sacral vertebral body
LA	Lordosis Angle
LBP	Low Back Pain
LR	Likelihood Ratio
LSI	Lumbar Segmental Instability
M	Midpoint of vertebral body
M'	Point 60% posterior to vertebral body midpoint on midplane line
mA	Milliampere
MLBP	Mechanical Low Back Pain
MPL	Midplane Line
MRI	Magnetic Resonance Imaging
NS	Expert reviewer #3: neurosurgeon with spine specialty
NZ	Neutral Zone
ODI	Oswestry Disability Index
OS1	Expert reviewer #1: orthopedic spine surgeon
OS2	Expert reviewer #2: orthopedic spine surgeon
PIT	Prone Instability Test
PM	Posterior Midpoint on the midplane line
ROC	Receiver Operator Characteristic
ROM	Range Of Motion
RSA	Roentgen Stereophotogrammetric Analysis
S1	The first sacral body
SEM	Standard Error of the Measurement
Sn	Sensitivity
Sp	Specificity
TLSO	Thoracolumbosacral Orthoses
VF	Video Fluoroscopy

APPENDIX B: SUBJECT RECRUITMENT FLYERS AND INFORMATION LETTERS

Recruitment flyer: Subjects without low back pain

RESEARCH SUBJECTS NEEDED

If you are between 18 and 60 years old, a military beneficiary and you NEVER had low back pain; you may qualify to participate in a study that will evaluate your low back movement patterns. The research study involves one visit of 60 minutes or less at BAMC radiology. (Women will require a pregnancy test at laboratory at BAMC because the study involves x-rays)

Please call MAJ Deydre Teyhen at XXX-XXXX if you are interested.

Letter to potential subjects without LBP:

Purpose of Research:
You are being asked to consider participation in this research study. The purpose of this study is to determine the reliability of the video fluoroscopy (VF) (motion analysis system) in measuring bending forward and backwards (sagittal plane flexion and extension). The results of this study will help clinicians better understand the movement patterns of those with functional instability of the lower back. Further, these results will help clinicians better diagnose and treat movement disorders of the lower back.

What to do if you would like to find out more about this study:
If you would like to find out more about this study, please call MAJ Deydre Teyhen, PT, MPT, OCS at XXX-XXX-XXXX.

Where do I go for this study:
This study is being conducted within the radiology department at BAMC. You can sign-in at the main reception desk for radiology, which is in the medical mall area.

What do I wear for this study:
We will be taking radiographic images of your spine, therefore men will be asked to wear shorts and remove their shirt during testing, and women will be asked to wear shorts and a sports bra (without a shirt) during testing. There are changing rooms available.

What do I need to do before the study:
1. All non-post-menopausal women will be required to take a pregnancy test.

2. To help ensure a good image we would like to request that you refrain from "gassy" foods the 24 hours prior to the study. Although everyone has slightly different reactions to these foods, typical foods that may cause gas include: high fiber foods, beans, nuts, bran, cabbage, cauliflower, broccoli, dried peas, whole grain breads, oatmeal, fibrous fruits and vegetables, milk products, carbonated beverages, beer, and fried foods.

3. Again to help ensure a good image, please try to have a bowel movement prior to arriving for the study.

What type of time commitment:
This study itself will require 60 minutes. Women will be required to have a pregnancy test taken (as stated above).

Recruitment flyer: Subjects with instability

RESEARCH SUBJECTS NEEDED

If you are between 18 and 60 years old, a military beneficiary and you NEVER had low back pain; you may qualify to participate in a study that will evaluate your low back movement patterns. The research study involves one visit of 60 minutes or less at BAMC radiology. (Women will require a pregnancy test at laboratory at BAMC because the study involves x-rays)

Please call MAJ Deydre Teyhen at XXX-XXXX if you are interested.

Letter to potential participants with instability:

Purpose of Research:

You are being asked to consider participation in this research study. The purpose of this study is to determine the reliability of the video fluoroscopy (VF) (motion analysis system) in measuring bending forward and backwards (sagittal plane flexion and extension). The results of this study will help clinicians better understand the movement patterns of those with functional instability of the lower back. Further, these results will help clinicians better diagnose and treat movement disorders of the lower back.

What to do if you would like to find out more about this study:
If you would like to find out more about this study, please call MAJ Deydre Teyhen, PT, MPT, OCS at XXX-XXX-XXXX. If you request, your provider will give your name and phone number to MAJ Teyhen and she can call you to explain the study in further detail.

Where do I go for this study:
This study is being conducted within the radiology department at BAMC. You can sign-in at the main reception desk for radiology, which is in the medical mall area.

What do I wear for this study:
We will be taking radiographic images of your spine, therefore men will be asked to wear shorts and remove their shirt during testing, and women will be asked to wear shorts and a sports bra (without a shirt) during testing. There are changing rooms available.

What do I need to do before the study:
1. All non-post-menopausal women will be required to take a pregnancy test.

2. To help ensure a good image we would like to request that you refrain from "gassy" foods the 24 hours prior to the study. Although everyone has slightly different reactions to these foods, typical foods that may cause gas include: high fiber foods, beans, nuts, bran, cabbage, cauliflower, broccoli, dried peas, whole grain breads, oatmeal, fibrous fruits and vegetables, milk products, carbonated beverages, beer, and fried foods.

3. Again to help ensure a good image, please try to have a bowel movement prior to arriving for the study.

What type of time commitment:
This study itself will require 60 minutes. Women will be required to have a pregnancy test taken (as stated above).

APPENDIX C: INFORMED CONSENT FORM

PROJECT TITLE: **Kinematics in individuals with and without functional lumbar instability: An in vivo assessment using cineradiographic technique**

BROOKE ARMY MEDICAL CENTER/WILFORD HALL MEDICAL CENTER
INFORMED CONSENT DOCUMENT
(ICD Template Version 4.Feb 02)

Kinematics in individuals with and without functional lumbar instability: An in vivo assessment using cineradiographic technique

PRINCIPAL INVESTIGATOR: MAJ Deydre Smyth Teyhen, PT, MPT, OCS

If you choose not to participate in this research study, your decision will not affect your eligibility for care or any other benefits to which you are entitled.

DESCRIPTION/PURPOSE OF RESEARCH

You are being asked to consider participation in this research study. The purpose of this study is to determine the reliability of the videoflouroscopy (VF) (motion analysis test) in measuring bending forward and backwards (sagittal plane flexion and extension). The results of this study will help us better understand the movement patterns (kinematics) of those with instability of the lower back. Further, these results will help us better diagnose and treat movement disorders of the lower back.

This study will enroll 40 subjects at the Brooke Army Medical Center (BAMC), Fort Sam Houston, over a period of no more than 1 year. One group of 20 (the experimental group) will have a history of lower back pain, while the second group of 20 (the control group) will never have had back pain. You will be required to make one to two appointments based on your situation. All subjects will be required to make one outpatient visit with MAJ Deydre Teyhen, USA for the motion analysis test. Women participating in this study will be required to obtain a pregnancy test at the BAMC laboratory prior to all testing. After all steps are completed, it will not be necessary for you to return to BAMC.

PROJECT TITLE: **Kinematics in individuals with and without functional lumbar instability: An in vivo assessment using cineradiographic technique**

PROCEDURES:

As a participant, you will undergo the following steps: Subjects agreeing to participate will complete a short questionnaire and undergo a brief examination of the lower back region to ensure that they meet the inclusion criteria. If inclusion criteria are met, subjects will read and sign this informed consent form. If you are a subject with low back pain, your physical therapist will have filled out a form during your last appointment that will be used to determine your eligibility for this study.

Step One: All women in this study will obtain a pregnancy test prior to all testing. Medical certification of menopause or other medical conditions that proves you cannot be pregnant will satisfy this requirement. This can be obtained in the laboratory during normal business hours on a walk-in basis. One of the symptoms of pregnancy is delayed menstruation; please let the researcher know if your period has been delayed.

Step Two: The motion analysis test will take place on one day and will last approximately 60 minutes. If you agree to participate in this study, you will be asked to wear loose-fitting gym clothes at the testing session. Women will be required to wear a sports bra. You will then be asked to walk for 5 minutes to allow your body to warm-up prior to the test. We will then place you in a device that will limit your knee and hip movement. This device will ensure that when you bend forward and backward that the motion is coming from your lower back and not from your hips and knees. Once you are ready, you will be asked to bend forward and backward 4 times. You will then be given a 2-minute break followed by 2-minutes of walking. Then we will perform the bending forward and backward test a second time. The test will require that the back region be exposed, so the test will require that male subjects be shirtless during the test. Women will be asked to wear a sports bra.

Should it be necessary for you to have a procedure requiring additional informed consent, a separate consent form will be completed at the time of the procedure.

RISKS OR DISCOMFORTS:

All subjects participating in this study may experience discomfort (low back pain) from bending forward and backwards. The radiation used in this study is a risk for an unborn child (fetus), therefore all women capable of child-bearing are required to get a pregnancy test to minimize the risk.

PROJECT TITLE: **Kinematics in individuals with and without functional lumbar instability: An in vivo assessment using cineradiographic technique**

Radiation Risk Statement

The tests you will have include cineradiography (digital pictures that allow for measurement of motion). The average effective ionizing radiation dose received from this study is 50 millirems (0.05 rem). This is equivalent to about one-sixth of the average dose a person receives annually from natural background radiation, which includes sources of radiation such as the sun and radioactive materials in the air and soil. The health risk from an effective dose of 50 millirems is extremely small, similar to the health risk of a fatal automobile accident during a trip of 800 miles, or of contracting fatal lung cancer from smoking 30 cigarettes. To put this in perspective, one death from highway driving occurs for every 18 million miles driven, and one death from lung cancer occurs among smokers for every 7.3 million cigarettes smoked.

There may also be unforeseen risks associated with this study.

BENEFITS:
There is the potential for this test tc discover problems with how your spine moves that may directly help you. However, the investigators have designed this study to learn if this new testing device can help assess those with instability of the lower spine. The goal is to understand movement of the spine so that we can design better treatment programs in the future. There is no guarantee you will receive any benefit from this study other than knowing that the information may help future patients. This study may help medical providers better understand the spine.

PAYMENT (COMPENSATION)
You will not receive any compensation (payment) for participating in this study. All tests will be provided to you by the military healthcare system.

ALTERNATIVE TREATMENT:
Choosing not to participate in this study is your alternative to volunteering for the study.

PROJECT TITLE: **Kinematics in individuals with and without functional lumbar instability: An in vivo assessment using cineradiographic technique**

CONFIDENTIALITY OF RECORDS OF STUDY PARTICIPATION:
Records of your participation in this study may only be disclosed in accordance with federal law, including the Federal Privacy Act, 5 U.S.C. 552a, and its implementing regulations. DD Form 2005, Privacy Act Statement-Health Care Records, contains the Privacy Act Statement for the records. By signing this document, you give your permission for information gained from your participation in this study to be published in medical literature, discussed for educational purposes, and used generally to further medical science. You will not be personally identified in publications; all information will be presented as anonymous data.

Your records will be archived and stored in the physical therapy laboratory indefinitely and may be used for future research. All archived data will be stored without any personal identifiers. Future research from the database of images will be used with the same confidentiality guidelines.

Your records may be reviewed by the U.S. Food & Drug Administration (FDA), other government agencies, the BAMC/WHMC Institutional Review Boards and the University of Texas (UT) Institutional Review Board (The principal investigator is also a graduate student at UT in Austin).

Complete confidentiality cannot be promised, particularly for military personnel, because information regarding your health may be required to be reported to appropriate medical or command authorities.

ENTITLEMENT TO CARE:
In the event of injury resulting from this study, the extent of medical care provided is limited and will be within the scope authorized for Department of Defense (DoD) health care beneficiaries.

Your entitlement to medical and dental care and/or compensation in the event of injury is governed by federal laws and regulations, and if you have questions about your rights as a research subject or if you believe you have received a research-related injury, you may contact the Brooke Army Medical Center Protocol Coordinators, 210-916-2598 or BAMC Judge Advocate, 210-916-2031.

PROJECT TITLE: **Kinematics in individuals with and without functional lumbar instability: An in vivo assessment using cineradiographic technique**

VOLUNTARY PARTICIPATION:
The decision to participate in this study is completely voluntary on your part. No one has coerced or intimidated you into participating in this project. You are participating because you want to. The Principal Investigator or one of his/her associates has adequately answered any and all questions you have about this study, your participation, and the procedures involved. If significant new findings develop during the course of this study that may relate to your decision to continue participation, you will be informed.

You may withdraw this consent at any time and discontinue further participation in this study without affecting your eligibility for care or any other benefits to which you are entitled. Should you choose to withdraw, all you have to do is simply tell the investigator. There are no penalties or hazards from withdrawing. Your condition will continue to be treated in accordance with acceptable standards of medical treatment.

The investigator of this study may terminate your participation in this study at any time if he/she feels this is to your best interest.

CONTACT INFORMATION:
Principal Investigator (PI) The principal investigator or a member of the physical therapy staff will be available to answer any questions concerning procedures throughout this study.

Principal Investigator: MAJ Deydre Smyth Teyhen 210-566-2094 or 210-221-8410

Institutional Review Board (IRB) In addition if you have any comments, questions, concerns or complaints, you may also contact the Chairperson of the IRB, at (210) 916-3511. Or mail to: Department of Clinical Investigation, Brooke Army Medical Center, Fort Sam Houston, TX 78234.

Your consent to participate in this study is given on a voluntary basis. All oral and written information and discussions about this study have been in English, a language in which you are fluent.

A copy of this form has been given to you.

PROJECT TITLE: **Kinematics in individuals with and without functional lumbar instability: An in vivo assessment using cineradiographic technique**

Questions:

If you wish to discuss the information above with the investigator now, you may do so. If you have a question once you go home, please call the investigator listed in the contact information.

_____ _____-____-_____ _____

VOLUNTEER'S SIGNATURE **VOLUNTEER'S SSN** **DATE**

_____ _____ _____-____-_____ _____

VOLUNTEER'S PRINTED NAME **FMP** **SPONSOR'S SSN** **DOB**

VOLUNTEER'S ADDRESS (street, city, state, zip)

____-____-_____

(PHONE #)

_____ _____

ADVISING INVESTIGATOR'S SIGNATURE **DATE**

_____

PRINTED NAME OF ADVISING INVESTIGATOR

_____ _____

WITNESS' SIGNATURE **DATE**
(Must witness ALL signatures)

_____

PRINTED NAME OF WITNESS

APPROVED
SEP 3 2003
B.A.M.C. IRB
IRB Approval

The University of Texas at Austin
Institutional Review Board
Approved: SEP 08 2003
Expires: SEP 08 2004

For Protocol Office Use Only:
Human ICD version 4_2002 Page 6 of 6

APPENDIX D: HEALTH INSURANCE PORTABILITY AND ACCOUNTABILITY ACT (HIPAA) FORM

BROOKE ARMY MEDICAL CENTER/WILFORD HALL MEDICAL CENTER
AUTHORIZATION TO USE AND DISCLOSE PROTECTED HEALTH INFORMATION FOR RESEARCH
(APHI Template Version 1, Apr 03)

You are being asked for permission to use or disclose your protected health information for research purposes in the research study entitled *"Kinematics in individuals with and without functional lumbar instability: An in vivo study using cineradiographic assessment."*

The Privacy Law, the Health Insurance Portability & Accountability Act (HIPAA), protects your individually identifiable health information (protected health information). This law requires you to sign an authorization (or agreement) in order for researchers to be able to use or disclose your protected health information for research purposes in the study listed above.

Your protected health information that may be used and disclosed in this study includes:

- Demographic Information: age, sex, race, and body mass index.
- Medical History: This study will need to use the medical diagnosis associated with your back pain (mechanical low back pain, discogenic low back pain, functional instability, stenosis, etc). Further, if you are participating in the study as a subject without low back pain, your status will be labeled as a "control" subject. No other medical diagnoses will be reported.
- Imaging Studies: The main purpose of this study is to measure how your lower back moves. The measurements obtained from these images will be used as the main analyzed measurements.
- Other: All participants are asked to fill out the Oswestry and "FABQ" Questionnaire, your score from that questionnaire will also be used in our analysis.

Your protected health information will be used for:

The purpose of this study is to determine the reliability of the videoflouroscopy (VF) (motion analysis system) in measuring bending forward and backwards (sagittal plane flexion and extension). The results of this pilot study will be used towards future studies that will help clinicians better diagnose and treat movement disorders of the lower back.

The disclosure of your protected health information is necessary in order to be able to conduct the research project described. Records of your participation in this study may only be disclosed in accordance with federal law, including the Federal Privacy Act, the Health Insurance Portability and Accountability Act of 1996, 5 U.S.C.552a, and its implementing regulations. DD Form 2005, Privacy Act Statement - Military Health Records, contains the Privacy Act

statement for the records. Note: Protected health information of military service members may be used or disclosed for activities deemed necessary by appropriate military command authorities to ensure the proper execution of the military mission.

By signing this authorization, you give your permission for information gained from your participation in this study to be published in medical literature, discussed for educational purposes, and used generally to further medical science. You will not be personally identified; all information will be presented as anonymous data.

The Principal Investigator may use and share your health information with:

- The BAMC/WHMC Institutional Review Board
- Government representatives, when required by law
- BAMC, WHMC, or Department of Defense representatives
- US Army-Baylor University Graduate Program in Physical Therapy, or the University of Texas, Austin representatives

The researchers agree to protect your health information by using and disclosing it only as permitted by you in this Authorization and as directed by state and federal law.

If your protected health information is disclosed to anyone outside of this study, the information may no longer be protected under this authorization.

You do not have to sign this Authorization. If you decide not to sign the Authorization:

- It will not affect your treatment, payment or enrollment in any health plans or affect your eligibility for benefits.
- You may not be allowed to participate in the research study.

After signing the Authorization, you can change your mind and:

- Notify the researcher that you have withdrawn your permission to disclose or use your protected health information (revoke the Authorization).
- If you revoke the Authorization, you will send a written letter to Deydre Teyhen 101 Tierra Grande, Cibolo, TX 78108, phone: 210-566-2094 to inform him/her of your decision.
- If you revoke this Authorization, researchers may only use and disclose the protected health information already collected for this research study.
- If you revoke this Authorization your protected health information may still be used and disclosed should you have an adverse event (a bad effect).
- If you withdraw the Authorization, you may not be allowed to continue to participate in the study.

This Authorization does not have an expiration date.

If you have not already received a copy of the Military Health System Notice of Privacy Practices, you may request one. If you have any questions or concerns about your privacy rights, you should contact the Brooke Army Medical Center Privacy Officer at phone number (210) 916-1029 or Wilford Hall Medical Center Privacy Officer at (210) 292-4617.

You are the subject or are authorized to act on behalf of the subject. You have read this information, and you will receive a copy of this form after it is signed.

Volunteer's Signature or Legal Representative	**Volunteer's SSN**	**Date**
Volunteer's Printed Name or Legal Representative	**Sponsor's SSN**	
Relationship of Legal Representative to Volunteer		
Signature of Witness		**Date**

APPENDIX E: SUBJECT ASSESSMENT FORMS

Control Subject Questionnaire:

Subject Number_____

Age: _____ (18-60 Years of Age) Sex: ☐Male ☐Female

Definition of Low Back Pain: Pain that either required medical attention, limited work, or limited recreational activities.

Please answer the following questions to the best of your ability. Your answers will be used only to determine whether it is safe and appropriate for you to participate in this research.

	YES	NO
Do you have any known back problems?		
Have you ever had any problems with back (with or without associated leg pains(s) that have resulted in medical care, loss work, or limited recreational activities?		
Have you ever been hospitalized for back or leg pain(s)		
Have you ever had back, pelvic, abdominal surgery?		
Have you ever had injections in your back?		
Have you ever been to a physician, physical therapist, orthopedic surgeon, physiatrist, or chiropractor for your lower back?		
Have you ever had back x-rays?		
Have you ever had a history of coronary artery disease or high blood pressure?		
Have you had foot drop?		
Is there anything else we should know about your personal medical history?		
For women only: Are you pregnant?		

Please explain any "yes" responses.

To be filled out by the researcher:

Height: _____ Weight: _____

Exclusion Criteria: Any of the following will result in exclusion from the study.

For therapist use only	Exclusion Criteria
Fit in the machine (Guide: BMI > 27)	
Oswestry (>30 Instability, > 4 Control)	
History of Abdominal, Pelvic, or Back Surgery	
Foot Drop	
History of Coronary Artery Disease/Uncontrolled Hypertension	
Pregnancy or LBP associated with pregnancy	

Summary of Subject's Condition (For Providers)

Definition of an episode of LBP: Pain that either required medical attention, limited work, or limited recreational activities.

1. Age: _____ 2. Sex: ☐Male ☐Female

3. Prior History: ☐ Prior History of LBP ☐No Prior History of LBP

3. Prior Episodes of LBP: ☐< 3 ☐ 3-5 ☐ 5-10 ☐ >10

4. Episode Frequency: ☐ Becoming more frequent ☐ Becoming less frequent ☐ No Change

Aberrant Movement Tests:			
5. Painful Arc in Flexion	☐ Yes	☐ No	One of these five signs must be present in order for aberrant motion to meet the definition of aberrant motion
6. Painful Arc on Return	☐ Yes	☐ No	
7. Gower's Sign	☐ Yes	☐ No	
8. Instability Catch	☐ Yes	☐ No	
9. Reversal of LP Rhythm on Return	☐ Yes	☐ No	

10. TESTS	L3	L4	L5
Spring Test	☐ Pos ☐ Neg	☐ Pos ☐ Neg	☐ Pos ☐ Neg
Prone Instability Test	☐ Pos ☐ Neg	☐ Pos ☐ Neg	☐ Pos ☐ Neg
Straight Leg Raise	Right:	Left:	Average:

12. Questionnaires: _____ Oswestry (≤ 30), _____ FABQ (≥ 9)

13. Inclusion/Exclusion Screening:

Inclusion		Exclusion	
< 40 years of age*		Oswestry > 30	
Aberrant movement present*, #		History abdominal, pelvic, or back surgery	
Positive prone instability test*, #		Foot drop	
Average straight leg raise > 90*		CAD/Uncontrolled HTN	
FABQ ≥ 9#		Pregnancy or LBP associated with pregnancy	
* 2 of 4, # 2 of 3		Fit in machine (Guide: BMI > 27)	

Provider's Name & Signature: _____Date: _____

This form should be given to the potential subject. The potential subject MUST bring this to the research session if they are interested.

Subject Number: _____ (Assigned after subject signs informed consent)

Examination Definitions:[59]

Aberrant Movement Tests (positive if at least 1/5 present)

1. A **Painful Arc in Flexion** is defined as pain only occurring during movement into flexion from the erect standing position. This typically occurs somewhere in the mid-range of the motion during the movement into flexion.
2. A **Painful Arc on Return** is defined as pain only occurring during return from flexion to the erect standing position. This typically occurs somewhere in the mid-range of the motion on the return from flexion.
3. **Gower's Sign** is defined as "thigh climbing" or pushing on the thighs with hands for assistance during return from flexion to the upright position.
4. An **Instability Catch** is defined as any trunk movement outside of the plane of specified motion during that particular motion (i.e. lateral sidebending during trunk flexion).
5. A **Reversal of Lumbopelvic Rhythm** is defined as the trunk being extended first, followed by extension of the hips and pelvis to bring the body back to upright position.

Segmental Mobility Testing (i.e. Spring testing): Spring testing of the lumbar spine is tested with the patient prone and the neck in neutral rotation. Testing is performed over the spinous processes of the vertebrae and is both a provocation test and a test of segmental mobility. The examiner stands at the head or side of the table and places the hypothenar eminence of the hand (i.e. pisiform bone) over the spinous process of the segment to be tested. With the elbow and wrist extended, the examiner applies a gentle but firm, anteriorly-directed pressure on the spinous process. The stiffness at each segment is judged as normal, hypomobile, or hypermobile. Interpretation of whether a segment is hypomobile is based on the examiner's anticipation of what normal mobility would feel like at that level and compared to the mobility detected in the segment above and below. In addition pain provocation at each segment is judged as painful or not painful and if painful, whether the symptoms are local (i.e. under the examiner's hand) or referred (away from the examiner's hand).

Segmental Instability Test (Prone Instability Test): The patient lies prone with the body on the examining table and legs over the edge with feet resting on the floor. While the patient rests in this position, the examiner applies posterior to anterior pressure to the lumbar spine. The patient is asked to report any provocation of pain (Note: If no provocation of pain is reported, the test cannot be performed.) The patient is lifts the legs off the floor (hand-holding to the table may be used to maintain position), and posterior compression is applied again to the lumbar spine at the level at which pain provocation was noted with the legs on the floor. If pain is present in the resting position but subsides in the second position, the test is positive.

Straight Leg Raise: The straight leg raise test is performed with attention to the amount of motion available. The patient is supine with the hips and knees extended. The inclinometer is positioned on the tibial crest just below the tibial tubercle. The inclinometer is zeroed. The examiner then passively lifts the straight leg to the maximum tolerated straight leg raise (not the onset of pain), and the degree of motion is recorded.

Inclusion/Exclusion Form:

Subject Number: _____
To be filled out by researcher:

Age: _____ Height: _____ Weight: _____ Sex: ☐Male ☐Female

Oswestry Score: _____ FABQ: _____ BMI: _____

Inclusion Criteria: Y: Inclusion Criteria Met, N: Inclusion Criteria Not Met

Criteria	Instability Standard	Met (Y/N)	Control Standard	Met (Y/N)
History of LBP*	Current episode		NONE (3 years)	
Age (< 40)**	18-60		18-60	
Aberrant Motion**, +	Positive		NONE	
Prone Instability Test**, +	Positive		NEGATIVE	
Average SLR**	@ 90 degrees		N/A	
FABQ +	≥ 9		N/A	

* LBP that resulted in a medical visit, limited work, or limited recreational activities.
** Two of the three must be positive for the instability group
+ Two of the three must be positive for the instability group

Exclusion Criteria: Any of the following will result in exclusion from the study.

For therapist use only	Exclusion Criteria
Fit in the machine (Guide: BMI > 27)	
Oswestry (>30 Instability, > 4 Control)	
History of Abdominal, Pelvic, or Back Surgery	
Foot Drop	
History of Coronary Artery Disease/Uncontrolled Hypertension	
Pregnancy or LBP associated with pregnancy	

Researcher's Name: _____

Researcher's Signature: _____

Date: _____

FABQ (Physical Activity Sub-Scale)

Subject Number: _____Date: _____

Here are some of the things which other patients have told us about their pain. For each statement please circle any number from 0 to 6 to say how much physical activities such as bending, lifting, walking or driving affect or would affect your back pain.

	COMPLETELY DISAGREE (0)			UNSURE (2)			COMPLETELY AGREE (6)
1. My pain was caused by physical activity	0	1	2	3	4	5	6
2. Physical activity makes my pain worse	0	1	2	3	4	5	6
3. Physical activity might harm my back	0	1	2	3	4	5	6
4. I should not do physical activities which (might) make my pain worse	0	1	2	3	4	5	6
5. I cannot do physical activities which (might) make my pain worse	0	1	2	3	4	5	6

Modified Oswestry Disability Index (ODI)[35-37,54]

Section 1: To be completed by researcher

Subject Number: _____

Section 2: To be completed by patient
This questionnaire has been designed to give your therapist information as to how your back pain has affected your ability to manage in every day life. Please answer every question by placing a mark on the line that best describes your condition today. We realize you may feel that two of the statements may describe your condition, but please mark only the line which most closely describes your current condition.

Pain Intensity

_____ Not Applicable – I have no low back pain
_____The pain is mild and comes and goes.
_____The pain is mild and does not vary much.
_____The pain is moderate and comes and goes.
_____The pain is moderate and does not vary much.
_____The pain is severe and comes and goes.
_____The pain is severe and does not vary much.

Personal Care (Washing, Dressing, etc.)

_____I do not have to change the way I wash and dress myself to avoid pain.
_____I do not normally change the way I wash or dress myself even though it causes some pain.
_____Washing and dressing increases my pain, but I can do it without changing my way of doing it.
_____Washing and dressing increases my pain, and I find it necessary to change the way I do it.
_____Because of my pain I am partially unable to wash and dress without help.
_____Because of my pain I am completely unable to wash or dress without help.

Lifting

_____I can lift heavy weights without increased pain.
_____I can lift heavy weights but it causes increased pain
_____Pain prevents me from lifting heavy weights off of the floor, but I can manage if they are conveniently positioned (ex. on a table, etc.).
_____Pain prevents me from lifting heavy weights off of the floor, but I can manage light to medium weights if they are conveniently positioned.
_____I can lift only very light weights.
_____I can not lift or carry anything at all.

Walking

_____I have no pain when walking.
_____I have pain when walking, but I can still walk my required normal distances.
_____Pain prevents me from walking long distances.
_____Pain prevents me from walking intermediate distances.
_____Pain prevents me from walking even short distances.
_____Pain prevents me from walking at all.

Sitting

_____Sitting does not cause me any pain.
_____I can only sit as long as I like providing that I have my choice of seating surfaces.
_____Pain prevents me from sitting for more than 1 hour.
_____Pain prevents me from sitting for more than 1/2 hour.
_____Pain prevents me from sitting for more than 10 minutes.
_____Pain prevents me from sitting at all.

Standing

_____I can stand as long as I want without increased pain.
_____I can stand as long as I want but my pain increases with time.
_____Pain prevents me from standing more than 1 hour.
_____Pain prevents me from standing more than 1/2 hour.
_____Pain prevents me from standing more than 10 minutes.
_____I avoid standing because it increases my pain right away.

Sleeping

_____I get no pain when I am in bed.
_____I get pain in bed, but it does not prevent me from sleeping well.
_____Because of my pain, my sleep is only 3/4 of my normal amount.
_____Because of my pain, my sleep is only 1/2 of my normal amount.
_____Because of my pain, my sleep is only 1/4 of my normal amount.
_____Pain prevents me from sleeping at all.

Social Life

_____My social life is normal and does not increase my pain.
_____My social life is normal, but it increases my level of pain.
_____Pain prevents me from participating in more energetic activities (ex. sports, dancing, etc.)
_____Pain prevents me from going out very often.
_____Pain has restricted my social life to my home.
_____I have hardly any social life because of my pain.

Traveling

_____I get no increased pain when traveling.
_____I get some pain while traveling, but none of my usual forms of travel make it any worse.
_____I get increased pain while traveling, but it does not cause me to seek alternative forms of travel.
_____I get increased pain while traveling which causes me to seek alternative forms of travel.
_____My pain restricts all forms of travel except that which is done while I am lying down.
_____My pain restricts all forms of travel.

Employment/Homemaking

_____My normal job/homemaking activities do not cause pain.
_____My normal job/homemaking activities increase my pain, but I can still perform all that is required of me.
_____I can perform most of my job/homemaking duties, but pain prevents me from performing more physically stressful activities (ex. lifting, vacuuming)
_____Pain prevents me from doing anything but light duties.
_____Pain prevents me from doing even light duties.
_____Pain prevents me from performing any job or homemaking chores.

Section 3: To be completed by researcher

SCORE:_____ or _____% (SEM 11, MDC 16)

Gender: Male Female

Qualitative Analysis of the DFV Form (For Expert Reviewers)

Rater's Name: _____ Subject's Number: _____

1. Based on viewing the initial static upright image, this subject displays:

☐ Normal Static Alignment ☐ Abnormal Static Alignment

2. Based on viewing the entire video of this subject, I believe the subject globally has:

☐ Definitely Normal Motion
☐ Probably Normal Motion
☐ Neutral/Indeterminate/Questionable Motion
☐ Probably Abnormal Motion
☐ Definitely Abnormal Motion

3. Based on viewing the entire video of this subject, I believe the subject globally is:

☐ Completely Stable
☐ Mostly Stable
☐ Indeterminate
☐ Slightly Unstable
☐ Unstable

3. Based on my observation of the entire video, I believe on a segmental level:

L3/4	is	☐ Normal	☐ Hypomobile	☐ Hypermobile
L4/5	is	☐ Normal	☐ Hypomobile	☐ Hypermobile
L5/S1	is	☐ Normal	☐ Hypomobile	☐ Hypermobile

4. Based on my observation of the video, I believe the problem is associated with (check all that apply)

☐ None – I think this is normal motion
☐ Translation/Displacement
☐ Angular Positioning
☐ Velocity
☐ Rhythm
☐ Other: _____

5. Does the entire video provide you with different information than the initial static image?

☐ Yes ☐No ☐Unsure COMMENT: _____

6. If this was a video of one of your patients, would it have been helpful to you?

☐ Yes ☐No ☐Unsure COMMENT:_____

7. Other Comments:

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Vita

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