

Arthrokinematics in a Subgroup of Patients Likely to Benefit From a Lumbar Stabilization Exercise Program

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Background and Purpose

A clinical prediction rule (CPR) has been reported to identify patients with low back pain who are likely to benefit from stabilization exercises. The aim of this study was to characterize the spinal motion, using digital fluoroscopic video, of a subgroup of subjects with low back pain.

Subjects

Twenty subjects who were positive on the CPR were compared with 20 control subjects who were healthy.

Methods

The magnitude and timing of lumbar sagittal-plane intersegmental angular and linear displacement were assessed. Receiver operating characteristic curves and accuracy statistics were used to develop a kinematic model.

Results

A 10-variable model was developed that could distinguish group membership. Seven of these variables described a disruption in timing of angular or linear displacement during mid-range movements. None of the variables suggested hypermobility.

Discussion and Conclusion

The findings suggest that individuals with mid-range aberrant motion without signs of hypermobility are likely to benefit from these exercises. The developed model describes altered kinematics of this subgroup of subjects and helps to provide construct validity for the developed CPR.

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For The Bottom Line:
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Next to the common cold, low back pain (LBP) is the most common reason that people visit a physician's office,¹ and billions of dollars in medical expenditures and lost labor costs are incurred each year.^{2,3} Attempts to identify effective nonsurgical treatment approaches such as exercise for all individuals with LBP and not for specific subclassifications of LBP, have been largely unsuccessful with only moderate effect sizes,⁴ resulting in a variety of disparate treatment recommendations in LBP practice guidelines.⁵

The variety of conclusions regarding the effectiveness of exercise for LBP may be attributable to the failure of researchers to adequately consider the importance of classification.⁶ Using broad inclusion criteria results in a heterogeneous population that may include many patients for whom no benefit should be expected, thus masking the intervention's true value.^{7,8} It seems logical that LBP resulting from different underlying causes responds differently to different treatments. Consequently, the development of methods for matching patients with LBP to the treatments most likely to benefit them has become an important research priority.^{9,10} Initial reports assessing classification systems for the treatment of LBP have demonstrated greater improvements in disability measures, increased rates of return to full-duty work, and cost savings.^{11,12}

Clinical prediction rules (CPRs) are tools designed to assist in decision making when caring for patients.^{13,14} Several CPRs have been developed recently to improve clinical decision making in the management of LBP by matching patients to treatments from which they are likely to receive the most benefit.¹⁵⁻¹⁷ One subgroup of patients that recently has been identified are those likely to benefit from a lumbar stabilization exercise

program (LSEP), which comprises motor control and coordination exercises directed at key trunk musculature.¹⁷ Hicks et al¹⁷ found that age, straight leg raise, prone instability testing, aberrant motion, clinical mobility assessment, and fear-avoidance beliefs were all characteristics that helped to predict success or failure with an LSEP (Tab. 1). Additionally, Hicks et al¹⁷ found that approximately 33% of all subjects with acute LBP in their study responded favorably to LSEP.

Despite the emergence of clinical criteria predictive of successful outcome, the lumbar spine arthrokinematics associated with this subgroup of patients remains unknown. Theoretically, this subgroup of patients with LBP includes those suspected to have underlying clinical lumbar instability. The diagnosis of clinical lumbar instability has been widely debated and remains controversial because of measurement and validity concerns associated with the use of static imaging techniques. For example, in addition to unacceptable measurement error associated with traditional nondistortion compensated measurement of static imaging,¹⁸⁻²³ large variability of normal human movement in individuals who were asymptomatic also have been documented,²⁴⁻²⁷ making cutoff values to diagnose the condition difficult to validate. Moreover, flexion-extension images are assessed statically at the end-range of motion,^{22,24,25,28} posing significant limitations for generalizing to a condition theorized to occur within the mid-range of movement.^{29,30}

These problems limit the usefulness of static imaging for identifying underlying mechanisms in this subgroup of patients with LBP. Given the potential benefits of dynamic measurement techniques to overcome these limitations,³¹⁻³⁵ the purposes of this study were: (1) to determine whether digital fluoroscopic

video (DFV) parameters measured at L3-S1 were able to distinguish movement patterns of the subgroup of patients who were likely to benefit from an LSEP¹⁷ compared with those without LBP and (2) to describe the underlying differences in arthrokinematics.

Materials and Method

Participants

A convenience sample of 40 men and women (22-52 years of age) from the Department of Defense beneficiary population volunteered to participate. Twenty subjects met the CPR for success with an LSEP (Tab. 1). These individuals were seeking medical attention, had lost work secondary to symptoms, or had limited recreational activities secondary to their current episode of LBP. Additionally, they had to meet 2 of 4 positive predictive variables while not meeting 2 of 4 negative predictive variables for success with an LSEP.¹⁷ Based on the limited field of view of the DFV, all subjects were required to have a positive prone instability test at L3, L4, or L5 to be enrolled in the study. The reliability (kappa) of different raters to recognize an aberrant movement patterns and the results of a prone instability test were reported as .60 and .87, respectively.³⁶ Patients with LBP who were unable to perform the test motion secondary to pain were excluded from the study.

The sex-, age-, and body mass index (BMI)-matched control group consisted of 20 subjects without a history of LBP for at least 3 years prior to the study. The lack of LBP was defined as an absence of symptoms resulting in medical attention, lost work, or limited recreational activities,²⁶ and the subjects were required to have an Oswestry Disability Index score of $\leq 4\%$ to confirm the absence of LBP.

All individuals were required to be generally healthy and between the ages of 18 and 60 years, with no

history of uncontrolled coronary artery disease or hypertension based on self-report. Furthermore, subjects were excluded if they had a recent history of open abdominal or pelvic surgery based on the possibility that the surgical influence on the trunk muscles could affect the underlying arthrokinematics. The baseline characteristics of the subjects are presented in Table 2. All subjects provided informed consent prior to participation. The data were collected during the conduct of a related study, parts of which have been published elsewhere.^{37,38}

Instrumentation

A Philips Radiographic/Fluoroscopy Diagnostic 76 system* and an I-75 frame grabber† were used to capture the images at 8 bits per pixel. The following software programs were used for processing and analysis: Image Pro-Plus,‡ MATLAB,§ Microsoft Excel,|| Confidence Interval Analysis (version 2.0),* and SPSS (version 11.0).**

Collection of DFV

The technique used to capture the DFVs has been described elsewhere³⁸ and was based on previous research assessing lumbar motion using DFV.^{33,34,39,40} Lateral-view DFVs of L3-S1 were obtained at 30 Hz while the subjects performed sagittal-plane flexion and extension (return to upright posture) within their available range of motion. Hyperextension (extension beyond the upright posture) was not tested in this study. An exam-

Table 1.

Inclusion and Exclusion Criteria for Subjects With Low Back Pain Who Were Predicted to Succeed With a Lumbar Stabilization Exercise Program¹⁷

	Variables	Accuracy Statistics ^a
Predictors of success	Positive prone instability test	If 2 of the 4 variables are present: Sensitivity: 0.83 (0.61-0.94) Specificity: 0.56 (0.40-0.71)
	Aberrant motion present ^b	
	Average straight leg raise >90°	
	Age <40 y	
Predictors of failure	Negative prone instability test	If 2 of the 4 variables are present: Sensitivity: 0.85 (0.70-0.93) Specificity: 0.87 (0.62-0.96)
	Hypomobility with spring testing	
	Aberrant motion absent ^b	
	FABQ ^c score ≤9	

^a Values represent accuracy statistics with 95% confidence intervals in parentheses.

^b Aberrant motion was defined as having 1 of the following 5 variables present during flexion and extension: painful arc in flexion, painful arc in extension, Gower sign, instability catch, or reversal of normal lumbopelvic rhythm.

^c FABQ= Fear-Avoidance Behavior Questionnaire, physical activity subscale.

ple of the digitally enhanced DFV of one subject during flexion is provided in Figure 1.

Subjects performed the sagittal-plane motion in approximately 4 to 5 seconds. To ensure that dynamic motion was captured through a full cycle, subjects completed 4 consecutive cycles of flexion and extension, with the third cycle being captured by the fluoroscopic system. Sagittal-plane motion was selected because it is a movement associated with symptoms in those people with lumbar segmental instability, it has greater range of motion relative to other

uniplanar motions, and it is normally associated with only minimal out-of-plane motion relative to frontal-plane movement.⁴¹⁻⁴³ Subjects were secured in a lower-extremity stabilization device^{33,39} to minimize ankle, knee, hip, and out-of-plane motion, but not restrict lumbar motion (Fig. 2).

Kinematic Analysis

Distortion-compensated roentgen analysis was originally developed for analysis of intersegmental motion from standard radiographs.⁴⁴⁻⁴⁶ This technique was validated using stereophotogrammetric roentgen

Table 2.

Subject Demographics^a

Variable	LBP Group	Control Group
Age (y)	36.0±8.0 (24-52)	36.0±8.1 (22-51)
BMI (kg/m ²)	25.9±3.6 (18.6-32.4)	25.0±3.7 (17.9-31.4)
Waist:hip ratio	0.84±0.07 (0.72-0.97)	0.84±0.06 (0.74-0.99)
Oswestry Disability Index (0%-100%)	28.6±10.9 (0-46)	0.4±1.0 (0-4) ^b
FABQ score (0-24)	16.3±4.1 (7-24)	Not applicable

^a Values are mean ± standard deviation, with range shown in parentheses. Twenty subjects (14 men, 6 women) in the low back pain (LBP) group, and 20 subjects (14 men, 6 women) in the control group. BMI=body mass index, FABQ= Fear-Avoidance Behavior Questionnaire, physical activity subscale.

^b None of the subjects in the control group had a history of LBP within the last 14 years. Two subjects in the control group scored 2%, scoring 1 for the sleep-related question; one volunteer scored 4%, scoring 1 for both prolonged sitting and standing questions.

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† Foresight Imaging, 70 Industrial Ave, Lowell, MA 01852.

‡ MediaCybernetics Inc, 8484 Georgia Ave, Suite 200, Silver Spring, MD 20910.

§ The Mathworks Inc, 3 Apple Hill Dr, Natick, MA 01760-2098.

|| Microsoft Computer Corp, One Microsoft Way, Redmond, WA 98052-6399.

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** SPSS Inc, 233 S Wacker Dr, Chicago, IL 60606.



Figure 1.

Enhanced digital fluoroscopic videos of lumbar flexion. The digital fluoroscopic videos were digitally enhanced to accentuate the differences between the vertebral bodies and the surrounding soft tissue.³⁸ This allowed for a computer algorithm to be applied that was able to measure angular and linear displacement. These images represent 4 images from one cycle of upright to flexed posture.

analysis⁴⁷ and recently was found to yield reliable data when applied to DFV.³⁸ The L3-S1 lordosis angle⁴⁸ and intersegmental motion (angular and linear displacement)⁴⁶ are defined in Figure 3. Upright posture at the start of flexion and at the end of extension was defined as a local maximum of the L3-S1 lordosis angle. The end of flexion, which also represents the start of extension, was defined as a local minimum of the L3-S1 lordosis angle near the center of the flexion-extension cycle.

The rate of attainment of intersegmental (L3-4, L4-5, and L5-S1) angular and linear displacement during flexion and extension was based on the work by Kanayama et al.³⁵ These measurements were quantified to help describe the sequence and timing of how the segmental motion was occurring with respect to the L3-S1 lordosis angle. The denominator, L3-S1 lordosis angle, represents a normalized value to account for the variability in lumbar motion between subjects. The movement patterns of flexion and extension were each divided into 10% increments represented by their midpoints. For example, the average of upright posture to 10% of L3-S1 flexion was represented by 5% of flexion, the average from the 10% to 20% of L3-S1 flexion represented by

15% of flexion, and so on. The same process was repeated for extension, resulting in values representing 0% to 100% of flexion and 0% to 100% of extension.

To control for variation across subjects in segmental range, each of the variables in the numerator (L3-4, L4-5, and L5-S1 linear and angular displacement values) were divided by its segmental range; resulting in a range of 100% of motion for each segment. Therefore, the slope between successive markers represents the rate of attainment of angular or linear displacement segmental range (expressed as a percentage) with respect to L3-S1 global motion (expressed as a percentage); resulting in an unitless ratio.

Data Analysis

A kinematic model was developed to help describe the differences in angular and linear kinematics between subjects with LBP who were predicted to succeed with an LSEP and subjects without a history of LBP. The steps used to develop this model were similar to the procedures used to develop a CPR.¹⁵⁻¹⁷ To narrow the number of variables of interest, independent *t* tests were performed on all of the angular and linear displacement descriptive variables (mean, maximum, minimum, and range) for

both flexion and extension, on each segmental level (L3-4, L4-5, and L5-S1). Furthermore, independent *t* tests were performed on the rate of attainment of angular and linear displacement range of motion during flexion and extension for each segmental level (L3-4, L4-5, and L5-S1).

Kinematic variables with a probability value of $P < .20$ were further analyzed. A more liberal significance level was used in this step to filter variables without excluding potentially useful variables. These variables were plotted individually on a receiver operating characteristic (ROC) curve. Predictors proceeded to the next level of analysis if the ROC curve had a cutoff value maximizing the distinction between subjects with LBP and the control group was possible. The cutoff value was determined by calculating sensitivity (Sn) and specificity (Sp) values for all possible cutoff points, then plotting the Sn and (1-Sp) values on a ROC curve.⁴⁹ 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 cutoff point distinguishing subjects with and without LBP. If a cutoff value was present, this variable was considered a potential discriminator between group memberships and proceeded to the next level of analysis.

The Sn, Sp, positive likelihood ratio (+LR), and negative (-LR) likelihood ratio were calculated for each variable that had an identifiable cutoff point on its ROC curve. The 95% confidence intervals for Sn and Sp were calculated using the Wilson method.⁵⁰ For the +LR and -LR, the 95% confidence intervals were calculated using the score method.^{50,51} A +LR, defined as Sn/(1-Sp), describes the proportion of individuals with LBP with an identified aberrant movement characteristic relative to those without LBP who

also have that aberrant movement characteristic. Because the goal was to distinguish individuals that would succeed with an LSEP, a +LR of ≥ 2.0 was used to develop a multivariate kinematic model. The final LRs were calculated based on the total number of predictive variables present or absent in order to identify a cluster of these variables that could distinguish group membership.

Results

There was an average (\pm SD) of 3.3 ± 0.8 positive predictor variables for success with an LSEP in the group of subjects with LBP predicted to succeed with an LSEP. Furthermore, each subject in the LSEP group had at least one sign of aberrant motion (average [\pm SD] = 2.4 ± 1.0 signs), all had at least one segment with a positive spring test (average [\pm SD] = 2.2 ± 0.6 segments), all had a positive prone instability test (average [\pm SD] = 1.8 ± 0.7 segments), and only 1 subject had a Fear-Avoidance Behavior Questionnaire score (physical activity subscale) of < 9 points. Thirteen of these 20 subjects had a straight leg raise of > 90 degrees. Additionally, 17 of the 20 subjects in the LSEP group reported recurrent LBP, with 9 of them reporting symptoms becoming more frequent in nature. The sex-, age-, and BMI-matched subjects in the control group did not have a history of LBP for at least 14 years prior to participating in this study.

The average time (\pm SD) required for the subjects to complete the motion was 5.75 ± 0.81 seconds, resulting in an average of 172.5 ± 24.3 frames per motion sequence, or $2,415.0 \pm 340.0$ point placements per motion sequence, for over 6,900 frames or 96,600 point placements to complete this analysis.

Twenty-two kinematic variables met the criteria for further analysis based

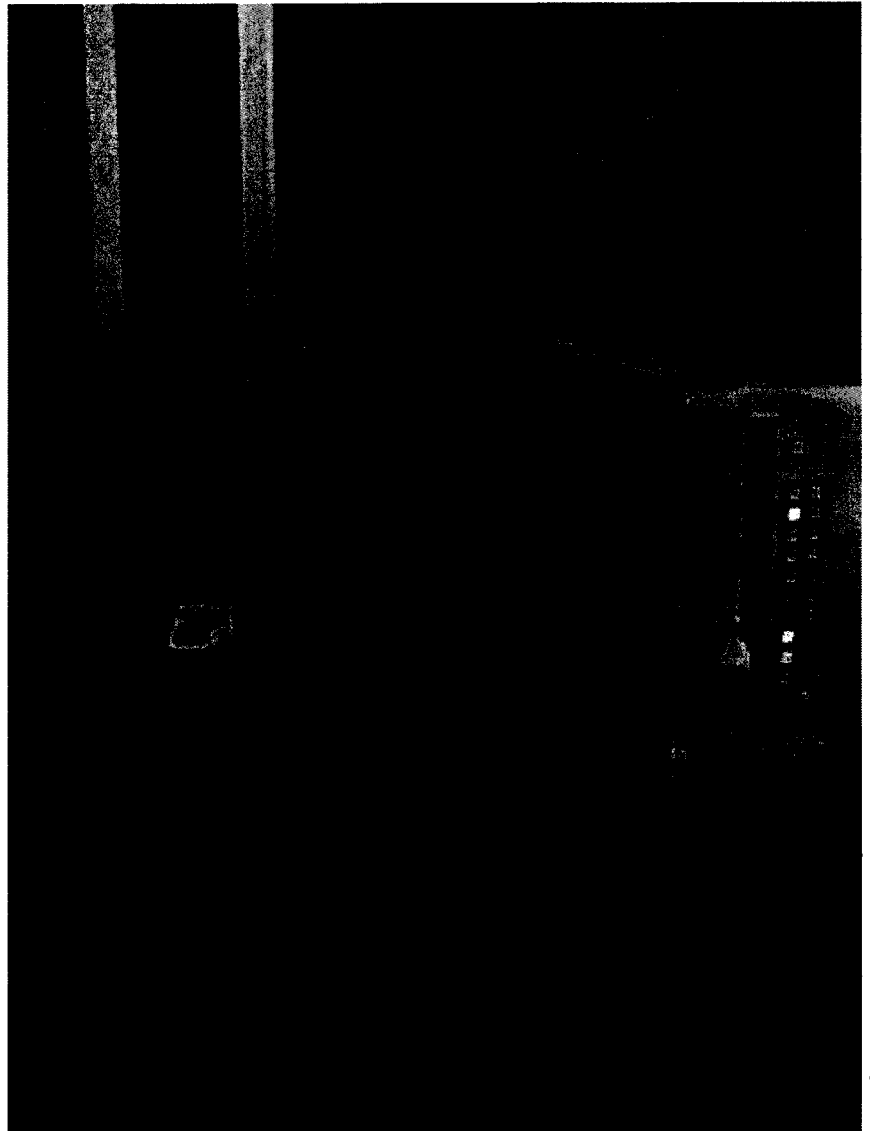


Figure 2.

Subject in the upright posture in the lower-extremity stabilization device. The stabilizing device consists of a rock-climbing harness with 4 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 2 straps around the knee are to prevent knee flexion.

on the independent *t* tests. Of the initial 22 variables that could possibly distinguish group membership, 15 (4 traditional variables describing angular and linear displacement and 11 variables associated with the rate of attainment of angular and linear displacement) had an ROC curve in which an identifiable cutoff value was present. A list of these variables

and the associated Sn, Sp, +LR, and -LR are provided in Table 3. Of these variables, 10 had a +LR of ≥ 2.0 . Three of these variables were considered to be more "traditional" variables that could be measured by standard radiographs and described hypomobility of linear displacement in those with LBP. The other 7 variables were unique to DFV analysis

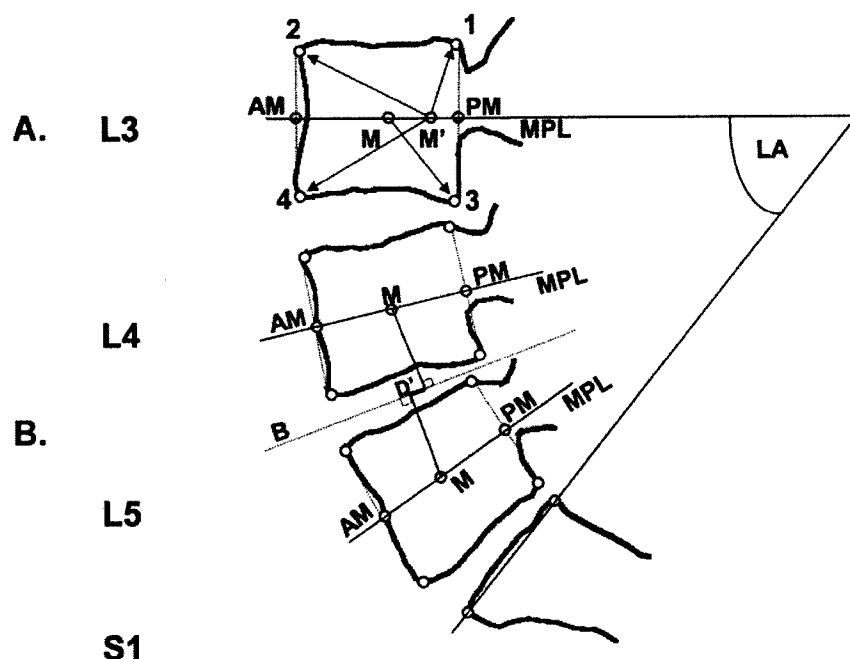


Figure 3.

Measurements of angular and linear displacement. Vertebral body detection and kinematic analysis based on the work by Frobin et al.⁴⁵ and Saraste et al.⁴⁸ Part A of image: The locations of the vertebral corners (numbered 1–4) are demonstrated on the L3 vertebral body. The anterior (AM), posterior (PM), and vertebral body (M and M') midpoint locations also are demonstrated. The algorithm to find the vertebral corner locations was based on the maximum distance from the appropriate midpoint location. Frobin et al.⁴⁵ found that the midpoint (M) between AM and PM was the most reliable location to determine vertebral corner 3, whereas a posteriorly displaced midpoint along that line (M') was more reliable to determine vertebral corners 1, 2, and 4. Part B of image: The intervertebral angle was defined as the angle between adjacent midplane lines (MPL). As demonstrated between L4–L5, the first step to measure intervertebral linear displacement was to find the distance (D') between the perpendicular projections of the vertebral body center points to the bisectrix (B). Note the bisectrix (B), which is determined as the midpoint between adjacent AM and PM locations, is approximated in this representative diagram of the measurement technique and drawn within the intervertebral space to improve clarity of the figure. Linear displacement then was determined by dividing D' by the mean depth of the cephalad vertebral body. 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) linear displacement was defined when the reverse occurred. Measurement of linear 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 Allen⁴¹ to have a symmetrical measurement of linear displacement that is compensated for distortion in the field of view. L3–S1 lordosis angle (LA) was defined as the angle between the MPL of L3 and the cephalad border of S1. Reproduced by permission of Lippincott Williams & Wilkins from: Teyhen DS, Flynn TW, Bovik A, Abraham L. A new technique for digital fluoroscopic video assessment of sagittal-plane lumbar spine motion. *Spine*. 2004;30:E409; Fig. 3.

and described segmental (L3–4, L4–5, and L5–S1) variations in the rate of attainment of angular and linear displacement. Five of these variations in the rate of attainment of angular and linear displacement occurred during the first 15% of flexion

(Figs. 4 and 5), the other 2 variables occurred during the last 35% of the return to the upright posture.

These 10 kinematic variables with a +LR of ≥ 2.0 were used to develop a multivariate kinematic model to

maximize the ability to distinguish group membership (Tab. 4, Fig. 6). The greatest accuracy ([true positive + true negative]/total) of the model was 87.5%, which was achieved when individuals were required to have at least 4 variables present to be classified as having LBP. When 4 or more variables were present, only one subject from the LBP group would be classified as having normal motion and 4 subjects in the control group would be classified as having abnormal motion. The remaining subjects (n=35) would have been accurately classified. The +LR was 6.0 when 6 or more variables present were required to determine group membership.

The +LR approached infinity after that point because no subjects in the control group had more than 6 of the 10 variables present. The –LR was 0.1 when 4 or more of the variables were present. When 3 or fewer variables were present, the –LR approached zero because only one person in the LBP group had fewer than 4 altered kinematic variables. Figure 6 graphically depicts the presence or absence of each of the movement parameters that had a +LR of ≥ 1.6 by subject, thus allowing a comparison between the true positive and false positive values for each group based on a +LR of ≥ 2.0 as the cutoff value.

Of note, there were no variables representing L3–S1 lordosis angle, or L3–4, L4–5, or L5–S1 segmental angular values that were able to distinguish group membership. None of these variables had an independent *t* test with a probability value of $P < .20$, demonstrating that both groups moved through similar amounts of lumbar lordosis and segmental angular motion.

Discussion

Using DFV, we were able to create a model of kinematic variables that

Table 3.

Accuracy Statistics (95% Confidence Interval) for Potential Motion Variables for Distinguishing Group Membership^a

	Sn	Sp	+LR	-LR	Cutoff Value ^b (Range)
Linear displacement (%)					
Extension range L4-5 ^B	0.55 (0.34-0.74)	0.85 (0.64-0.95)	3.67 (1.35-11.09)	0.53 (0.30-0.85)	<7.66 (3.03 to 15.94)
Total displacement range ^F	0.55 (0.34-0.74)	0.75 (0.53-0.89)	2.20 (0.99-5.28)	0.60 (0.33-1.01)	<26.93 (16.96 to 50.66)
Flexion range L4-5 ^G	0.55 (0.34-0.74)	0.75 (0.53-0.89)	2.20 (0.99-5.28)	0.60 (0.33-1.01)	<6.30 (1.58 to 15.88)
Extension minimum L4-5 ^K	0.75 (0.53-0.89)	0.60 (0.39-0.78)	1.88 (1.08-3.56)	0.42 (0.18-0.90)	NA ^c
Rate of attainment of angular displacement (%/%)					
5%-15% flexion L3-4 ^C	0.70 (0.48-0.86)	0.75 (0.53-0.89)	2.80 (1.35-6.50)	0.40 (0.19-0.76)	>1.38 (-0.60 to 4.02)
5%-15% flexion L4-5 ^E	0.70 (0.48-0.86)	0.70 (0.48-0.86)	2.33 (1.20-5.02)	0.43 (0.20-0.84)	<0.59 (-1.84 to 3.01)
0%-5% flexion L5-S1 ^H	0.65 (0.43-0.82)	0.70 (0.48-0.86)	2.17 (1.09-4.71)	0.50 (0.25-0.93)	<-0.20 (-5.07 to 5.51)
95%-100% extension L4-5 ^I	0.60 (0.39-0.78)	0.70 (0.48-0.86)	2.00 (0.98-4.40)	0.57 (0.30-1.02)	<-0.83 (-4.65 to 3.42)
75%-85% extension L4-5 ^L	0.70 (0.48-0.86)	0.60 (0.39-0.78)	1.75 (0.99-3.36)	0.50 (0.23-1.02)	NA
0%-5% flexion L3-4 ^N	0.75 (0.53-0.89)	0.55 (0.34-0.74)	1.67 (0.99-3.02)	0.46 (0.19-1.01)	NA
Rate of attainment of linear displacement (%/%)					
65%-75% extension L5-S1 ^A	0.60 (0.39-0.78)	0.90 (0.70-0.97)	6.00 (1.83-22.30)	0.44 (0.24-0.72)	<-0.95 (-2.42 to 5.61)
5%-15% flexion L3-4 ^D	0.60 (0.39-0.78)	0.75 (0.53-0.89)	2.40 (1.11-5.69)	0.53 (0.28-0.93)	<0.21 (-2.93 to 4.78)
5%-15% flexion L4-5 ^J	0.60 (0.39-0.78)	0.70 (0.48-0.86)	2.00 (0.98-4.40)	0.57 (0.30-1.02)	<-0.63 (-6.34 to 6.89)
85%-95% extension L5-S1 ^M	0.70 (0.48-0.86)	0.60 (0.39-0.78)	1.75 (0.99-3.36)	0.50 (0.23-1.02)	NA
55%-65% flexion L4-5 ^O	0.70 (0.48-0.86)	0.55 (0.34-0.74)	1.56 (0.91-2.85)	0.55 (0.25-1.14)	NA

^a Variables in each section are provided in descending order of +LR values, and each variable is coded (A-O) as a reference for Figure 6. Sn=sensitivity, Sp=specificity, +LR=positive likelihood ratio, -LR=negative likelihood ratio (Fritz JM, Wainner RS. Examining diagnostic tests: an evidence-based perspective. *Phys Ther.* 2001;81:1546-1564.).

^b Cutoff values represent the value within the range of measured values used to define a positive test in distinguishing subjects with low back pain who were predicted to succeed with a lumbar stabilization exercise program. For example, the range of linear displacement at L4-5 for all subjects in the study was 3.03% to 15.94%; the accuracy statistics (Sn, Sp, +LR, and -LR) were calculated based on a cutoff score of 7.66%. A score of <7.66% was indicative of subjects with low back pain. Cutoff values are only provided for variables with a +LR value of ≥ 2.0 .

^c N/A=not applicable because +LR was not ≥ 2.0 and, therefore, the variable was not further analyzed.

was able to describe movement characteristics among those individuals who met the CPR for success with an LSEP.¹⁷ Furthermore, the majority of these variables (70%) described multisegmental disruptions in the rate of attainment of angular and linear displacement in the subjects with LBP. These multisegmental differences are in agreement with findings reported by Okawa et al.³³ Additionally, these disruptions in the rate of attainment of angular and linear displacement occurred not at end-range, but during mid-range postures, therefore, describing disruptions in neutral zone kinematics.^{29,30}

These disruptions in the sequence and timing of how the motion occurred in subjects with LBP can be viewed as alterations in the neuromotor control of segmental motion. The kinematic model developed helps to establish construct validity for the CPR designed by Hicks et al¹⁷ because the study sample was individuals with LBP who were predicted to succeed with an LSEP. Furthermore, this result and the fundamental underlying tenet that an LSEP should improve motor control in individuals with LBP^{52,53} suggest a clear relationship between the underlying biomechanical aspects of

the LBP group identified by the CPR and the prescription of an LSEP.

Five of the 7 differences in the rate of attainment of angular and linear displacement occurred during the first 15% of flexion. In the control group, there was a simultaneous initiation of angular motion during the first 15% of flexion (Fig. 4). Conversely, in the LBP group, there was a greater rate of attainment of L3-4 accompanied by a "delay" in the rate of attainment of angular range at L4-5 and L5-S1 (Fig. 4). This may represent a compensatory mechanism in which the individuals likely to succeed with

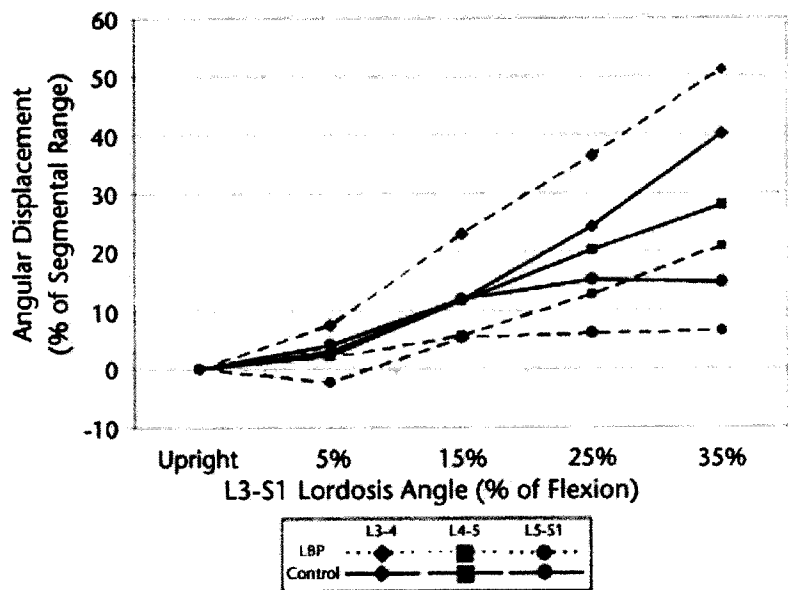


Figure 4. Rate of angular displacement during the first 35% of flexion. Comparison of normalized segmental angle trajectory (percentage of angular range of motion) per L3-S1 global angle (percentage of L3-S1 flexion) during the first 35% of flexion. Note that the solid lines representing the subjects without low back pain are centrally located, whereas the dotted lines representing the subjects with low back pain are dispersed.

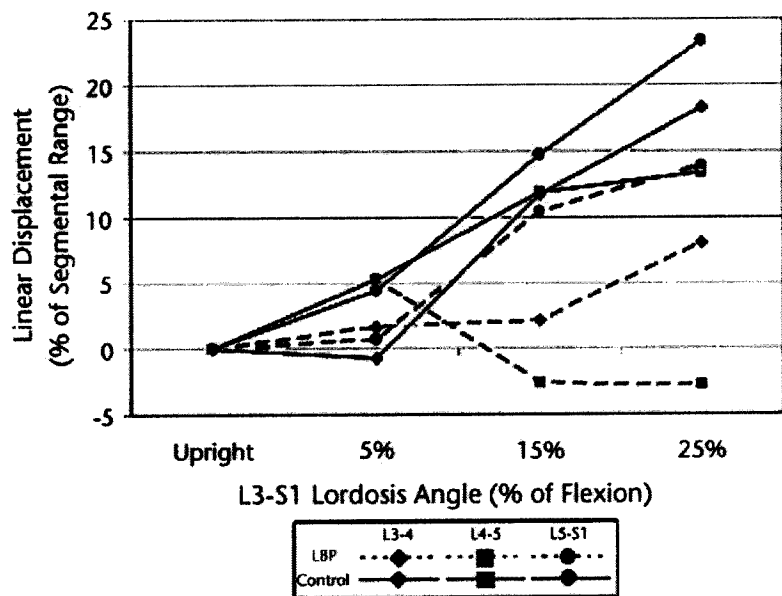


Figure 5. Rate of linear displacement during the first 25% of flexion. Comparison of normalized segmental linear displacement trajectory (percentage of linear displacement range) per L3-S1 global angle (percentage of L3-S1 flexion) during the first 25% of flexion. Note that the solid lines representing the subjects without low back pain have a positive slope after 5% of flexion, whereas the dotted lines representing the subjects with low back pain are varied.

an LSEP-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. Furthermore, this different rate of attainment of angular range in the LBP group may represent underlying muscle guarding or a pain-avoidance movement pattern. More research is needed.

Similar to the rate of attainment of angular range during flexion, the rate of attainment of linear displacement for the LBP group demonstrated a disordered movement pattern during 5% to 15% of flexion (Fig. 5). During the initiation of flexion, the control group experienced a positive and increasing rate of attainment of linear displacement across all segments, whereas only L5-S1 had a positive slope in the LBP group. In the LBP group, L3-4 was basically in a paused state (slope=0.05), and L4-5 was basically moving in the opposite direction, as indicated by the negative slope (slope=-0.8). Therefore, the LBP group was attaining linear displacement at the most caudal segment (L5-S1) during the onset of motion, while the more cephalad segments of the LBP group were either in a relative pause or displacing in a negative direction. The delayed attainment of linear displacement in the subjects with LBP was similar to the concept of prolonged deflection reported by Okawa et al.³³

As discussed, multiple segmental differences occurred during the initiation of flexion (5%-15% of flexion) with the rate of attainment of both linear and angular displacement. These differences during the onset of flexion are consistent with the neutral zone theory outlined by Panjabi³⁰ in which the dysfunctional movement occurs during the range of motion under neuromuscular control and not at the end-range of flex-

Table 4.

Accuracy at Each Level of the Model to Distinguish Group Membership for the Symptom-based Groups^a

No. of Predictor Variables Present	Sn	Sp	+LR	-LR
9 or more present	0.10 (0.03-0.30)	1.00 (0.84-1.00)	Approaches infinite (0.6-infinite)	0.9 (0.7-1.1)
8 or more present	0.20 (0.08-0.42)	1.00 (0.84-1.00)	Approaches infinite (1.2-infinite)	0.8 (0.6-1.0)
7 or more present	0.45 (0.26-0.66)	1.00 (0.84-1.00)	Approaches infinite (2.7-infinite)	0.5 (0.3-0.7)
6 or more present	0.60 (0.39-0.78)	0.90 (0.70-0.97)	6.0 (1.8-22.3)	0.4 (0.2-0.7)
5 or more present	0.80 (0.58-0.92)	0.85 (0.64-0.95)	5.3 (2.1-15.5)	0.2 (0.1-0.5)
4 or more present	0.95 (0.76-0.99)	0.80 (0.58-0.92)	4.8 (2.3-11.8)	0.1 (0.0-0.3)
3 or more present	1.00 (0.84-1.00)	0.60 (0.39-0.78)	2.5 (1.6-4.6)	Approaches 0 (0.0-0.3)
2 or more present	1.00 (0.84-1.00)	0.20 (0.08-0.42)	1.3 (1.0-1.7)	Approaches 0 (0.0-0.9)
1 or more present	1.00 (0.84-1.00)	0.20 (0.08-0.42)	1.3 (1.0-1.7)	Approaches 0 (0.0-0.9)

^a Values represent accuracy statistics with 95% confidence intervals (CI). Sn=sensitivity, Sp=specificity, +LR=positive likelihood ratio, -LR=negative likelihood ratio (Fritz JM, Wainner RS. Examining diagnostic tests: an evidence-based perspective. *Phys Ther.* 2001;81:1546-1564.). If 5 or more motion parameters present were required to define subjects in the low back pain group, then the kinematic model would have values of Sn=0.8, Sp=0.85, +LR=5.3, and -LR=0.2.

ion, which has been theorized to be limited by the passive osteoligamentous system. Although more research is needed, these disruptions may be consistent with the “slipping” or “catching” sensation felt by these patients during the onset of flexion. Additionally, restoration of optimal neuromuscular control through an exercise regimen targeted at the onset of lumbar flexion may be an appropriate primary focus for these individuals.

During extension, there were differences in the rate of attainment of angular motion at L5-S1 during the last phase of returning to the upright posture and a variation in the attainment of linear displacement during 65% to 75% of extension. These uni-segmental differences noted were in contrast to the multi-level differences found during flexion. The different role of the spinal extensor muscles during these actions (concentric versus eccentric) is one suggested explanation for the disparity that warrants further analysis. Further research should assess the kinematic movement pattern coupled with electromyographic analysis to further understand this disparity.

Although both groups moved through the same lordosis (L3-S1) and segmental (L3-4, L4-5, and L5-S1) angular range, factors related to linear displacement range were able to distinguish between group membership. However, linear displacement hypomobility, not linear or angular hypermobility, was found in the LBP group. Therefore, the direction of the difference was opposite of what was expected. Specifically, the combined total displacement range (L3-4 + L4-5 + L5-S1) of the control group (33.5%±9.2%) was greater than that of the LBP group (27.9%±7.4%). Furthermore, there was a significant decrease (approximately 2%) in the linear displacement range of L4-5 during flexion and the return to upright posture in the LBP group.

The lack of angular hypermobility in the subjects with LBP supports previous findings by Abbott and colleagues.^{54,55} Previous researchers have demonstrated that a combined manual therapy and LSEP approach is more beneficial than LSEP without manual therapy in patients with acute LBP¹⁵ and more beneficial than consultation alone in those with

chronic LBP.⁵⁶ It is possible that our finding of segmental hypomobility rather than hypermobility may offer some biomechanical explanation to support the clinical utility of a combined approach. Although further research is needed, the combination of clinical evidence and these biomechanical data may challenge the prevailing notion that patients with signs and symptoms of clinical lumbar instability have underlying hypermobility.

Overall, the greater linear displacement range noted in the control group may be associated with previous findings of a “flexion-relaxation” phenomenon, in which there is electromyographic electrical silence of the lumbar paraspinal muscles at the end-range of flexion noted in individuals who are healthy that does not occur in those with LBP.⁵⁷⁻⁵⁹ Continued activity of the lumbar paraspinal muscles at the end-range of flexion in those with LBP may limit segmental linear displacement range. More research is needed to explore these concepts.

A theoretical benefit of measuring lumbar kinematics with DFV over

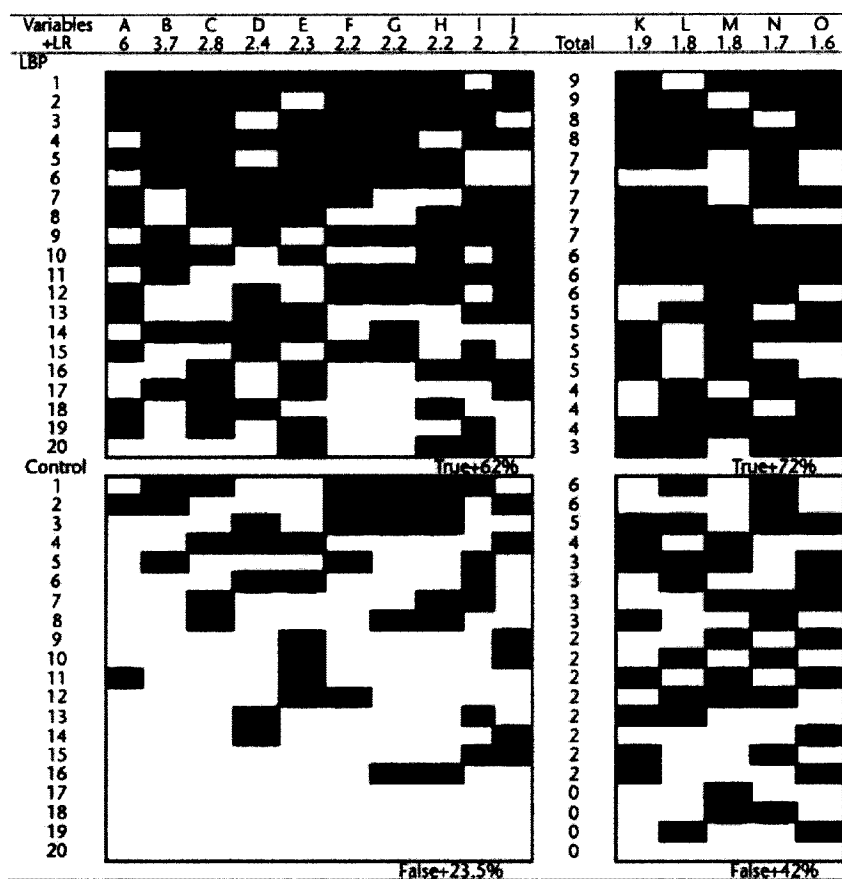


Figure 6. Representation of the distribution of positive tests among the variables with a positive likelihood ratio (+LR) of >2.0 (A–J) and those with a +LR of <2.0 (K–O) for the subjects with low back pain (LBP) and the control subjects. Variable codes provided in Table 3. Comparing the 10 factors with a +LR of >2.0 (A–J) between subjects with and without LBP, the true positive values for those with LBP was 62%, whereas the false positive rate was only 23.5% in those without LBP. The total number of factors for each subject are provided in the column to the right of factor “J.” Additionally, comparing the factors that had a +LR of >2.0 compared with the factors with a +LR of <2.0, the increase in false positives (42%) becomes apparent. Note that subject 1 had 9 of the 10 variables with a +LR of >2.0 present, whereas subjects 17 through 20 had none of these variables present.

static images is the ability to measure the sequence and timing (ie, pattern) of the motion attained, with specific interest in the motion that occurs within the neutral zone (mid-range postures).^{30–32,60,61} We have developed a kinematic model that was able to distinguish group membership and thus provides construct validity for DFV. Additionally, altered rates of attainment of linear and angular displacement in the LBP group

supports prior researchers^{31–33,35,62–68} who have advocated the need for dynamic analysis to assess dysfunctions in lumbar arthrokinematics. Moreover, the lack of differences in the traditional angular motion and displacement variables in distinguishing group membership supports prior researchers^{25–27,31,68–72} who have suggested the difficulty of using these types of mobility measurements from standard radiographs to identify sub-

groups of people with LBP. Specifically, measurements attainable from standard radiographs are limited based on measuring vertebral position at end-range postures, influenced by the wide variation of normal movement across a population and the differences in segmental mobility observed with different stages of a dysfunction.^{24,25,40,41,70,73,74}

Limitations

We developed a 10-variable kinematic model that describes the motion pattern in individuals who are predicted to succeed with an LSEP¹⁷ when compared with those without a history of LBP. However, the greatest accuracy (87.5%) and the best combination of Sn, Sp, +LR, and –LR of the model occurred if the cutoff criterion to define this population was based on a person having 4 or more of the 10 criteria (Tab. 4). By adding an additional level of review, qualitative analysis by fellowship-trained orthopedic spine surgeons, the model’s accuracy was able to increase to 96% with a +LR of 14.0.³⁷ Therefore, the addition of expert review of the DFV was a successful step in deriving more homogenous groups for comparison. Future researchers who query the effectiveness of treatment modalities for people with suspected underlying instability 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.

This study described the differences between a group of subjects with LBP predicted to succeed with an LSEP compared with a control group of subjects with a 14-year history free from LBP. Although this comparison provides insight on how kinematic motion should be restored in those who meet the rule for success with LSEP, it does not provide information regarding the ability to use

DFV to distinguish between subclassifications of LBP. The decision to limit the study to these populations was based on the work by Okawa et al.³³ They were able to determine kinematic distinctions between individuals with clinical lumbar instability and control subjects, but they were unable to find differences between those with mechanical LBP and control subjects.³³ Therefore, in order to optimize the distinctions between the groups, the current study compared only subjects with suspected clinical lumbar instability compared with a control group of subjects who were healthy. We did not compare subjects with suspected clinical lumbar instability with subjects with other categories of LBP.

Consequently, the differences found in this study may reflect the entrance criteria for this study or may just reflect differences in the movement pattern that are common to several or all types of mechanical LBP. Future studies should compare individuals with different types of LBP. As technology improves, it would be advantageous to analyze the entire lumbar motion (T12-S1) instead of the more limited analysis of the lower lumbar spine (L3-S1) performed in this study based on the limited field of view available. Finally, longitudinal studies that are able to measure changes in lumbar arthrokinematics associated with symptom resolution would be beneficial in understanding which of these kinematic variables are amendable to an LSEP.

Conclusions

A kinematic model was developed that can distinguish a subgroup of individuals with LBP from those without LBP. The model developed suggests that patients with LBP who are predicted to succeed with an LSEP have linear displacement hypomobility coupled with aberrant rates of attainment of angular and linear

displacement around the mid-range postures. These results provide construct validity for the LSEP CPR and suggest that individuals with LBP who are likely to succeed with an LSEP may have some combination of altered segmental structural integrity, segmental stiffness, and altered neuromuscular control during lumbar spine movement. Furthermore, capability of DFV to identify altered kinematics is established.

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This research study complies with the current laws of the United States of America, and the protocol was approved by the Institutional Review Boards at Brooke Army Medical Center and the University of Texas in Austin.

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