Fluoroscopic Video to Identify Aberrant Lumbar Motion

Deydre S. Teyhen, PT, PhD, OCS,*†‡ Timothy W. Flynn, PT, PhD, OCS, FAAOMPT,§ John D. Childs, PT, PhD, MBA, OCS, FAAOMPT,* Timothy R. Kuklo, MD, JD,‡ Michael K. Rosner, MD,∥ David W. Polly, MD,¶ and Lawrence D. Abraham, EdD†

The current paradigm shift in spinal surgery from fusion to motion offers a compelling reason to understand better in vivo lumbar spinal motion. Claims have been made that various mechanical devices can restore “normal” motion. Yet our understanding of “normal” or abnormal motion is limited. Historically, the diagnosis of abnormal motion has been based on exceeding predetermined thresholds of angular and linear displacement as measured on end-range flexion and extension radiographs.1–3

Despite its acceptance as a valid reference criterion for establishing the diagnosis of movement impairments in patients with low back pain (LBP), traditional radiographic assessment has several limitations. First, large variability of normal human movement in asymptomatic individuals has been documented.4–7 Second, the images have been assessed statically at end-range motion,1,5,8,9 which poses significant limitations for generalizing to a dysfunction theorized to occur within the neutral zone (midrange postures) by Panjabi.10,11 Third, traditional measurement techniques have been associated with large measurement error.7,12–16 Finally, quantitative assessment of static radiographs fails to account for dynamic segmental movement parameters that may be the source of dysfunction.

Based on these limitations, it has been suggested that LBP may be better understood if the spinal kinematics of normal and abnormal intersegmental motion were quantified during dynamic motion patterns.17–20 Therefore, there is a need for tools to assess in vivo kinematics in order to measure the motion in the midrange where aberrant motion and dysfunction have been theorized to occur.11,19,21,22 New image processing technology and techniques,18–20,23,24 along with improved distortion compensated measurement techniques,23,25–28 have provided the opportunity to use digital fluoroscopic video (DFV) to reliably29 evaluate normal and abnormal angular and linear displacement motion patterns in vivo. To date, researchers22,30–36 have successfully used DFV (typically limited to angular motion measures at 3–5 Hz) to describe lumbar kinematics. However, the analysis of both the quality and quantity of angular and linear displacement has been limited by the low resolution of the DFV, slow frame rate of the DFV, and the measurement techniques applied to the DFV. The disparity between the theorized kinematic abnormalities presumed to occur in the midrange movements10,11 and the traditional assessment of these individuals with static end-range radiographs may be overcome by image processing techniques, such as enhanced DFV. Therefore, the purpose of this study was to establish construct validity for the ki-
nematic assessment of individuals with LBP by developing a kinematic model that characterizes movement patterns in patients with LBP through the use of higher resolution DFV (30 Hz) and a distortion compensated roentgen analysis technique. Ultimately, this line of research may allow us to develop classification criteria to identify specific subgroups of patients with LBP likely to benefit from specific treatment methods ranging from neuromuscular retraining to surgical motion-sparring implants.

- **Materials and Methods**

**Study Participants.** A convenience sample of 40 males and females (22–52 years) from the Department of Defense beneficiary population were enrolled and subsequently categorized into 2 groups (Table 1). The first group included a sample of 20 volunteers with LBP. These individuals were either seeking medical attention, lost work secondary to symptoms, or limited recreational activities secondary to their current episode of LBP. Additionally, they had to have at least 2 of 4 positive predictive variables (<40 years of age, aberrant movement present, positive prone instability test, and an average straight leg raise test >9°; Table 1) that comprise an established clinical prediction rule for identifying patients likely to benefit from a nonoperative lumbar stabilization exercise program, which has been shown to reduce recurrence of LBP at a 3-year follow-up. This clinical prediction rule was used as the entrance criteria for this study based on previously documented efficacy for successfully treating patients diagnosed with spondylolisthesis, posterior pelvic pain after pregnancy, chronic LBP, and hypermobility. Potential subjects were excluded if they met 2 or more of the predictors of failure according to the clinical prediction rule (no aberrant movement, negative prone instability test, and Fear Avoidance Behavior Questionnaire physical activity subscale score less than 9), had greater than grade 2 spondylolisthesis, pain distal to the popliteal fold, had radicular symptoms (decreased sensation in a dermatomal pattern, decreased lower extremity strength, or a positive straight leg raise test), or they were unable to perform the test motion secondary to pain. The prone instability test is performed with the patient prone on the examining table with the legs over the edge and feet resting on the floor. Provocation of symptoms is tested using segmental passive intervertebral motion while the patient is at rest with feet on the floor and after the patient lifts the legs from the floor. A positive test is defined as pain with passive intervertebral motion at 1 segment while the subject is at rest that is reduced or disappears when the legs are lifted from the floor, requiring activation of the stabilizing spinal musculature. The reliability (k) of different raters to recognize an aberrant movement pattern and the results of a prone instability test was reported as 0.60 and 0.87, respectively.

The age, gender, and body mass indexed-matched control group consisted of 20 volunteers without a history of LBP for at least 3 years before the study. Individuals in the control group were required to have an Oswestry Disability Index score ≤4% to confirm the absence of LBP. Outside of their LBP status, individuals in both groups were required to be generally healthy with no history of uncontrolled coronary artery disease or hypertension based on self-report. Furthermore, 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.

Previous researchers have been unable to use DFV to differentiate those with chronic LBP and healthy control subjects when assessing sequential attainment of angular motion of the lumbar spine. To increase the likelihood of enrolling a homogenous subgroup of patients, 3 fellowship-trained spine surgeons additionally assessed the participants’ DFVs to determine final group membership (Figure 1). Agreement by 2 of the 3 reviewers that a DFV of an individual with LBP was at least probably abnormal (aberrant motion present, nonsequential motion, nonharmonious, or delayed motion) and that a DFV of an individual without LBP was at least probably normal motion (no aberrant motion present, sequential motion, and harmonious motion) was required for final group membership. The reviewers were blinded to group membership during their analysis. The institutional review boards at Brooke Army Medical Center and the University of Texas approved the protocol, and all subjects provided informed consent before participation.

**Instrumentation.** The DFVs were collected with a Philips Radiographic/Fluoroscopy Diagnostic 76 system (Philips Medical Systems, Andover, MA). An I-75 frame grabber (Foresight Imaging, Lowell, MA) digitized the images and captured them at 8 bits per pixel. Image Pro-Plus (version 4.5; Media Cybernetics, Silver Springs, MD), MATLAB (Student version 12; The MathWorks, Natick, MA), Microsoft Excel (Microsoft Computer Corp., Redmond, WA), Confidence Interval Analysis, Version 2.0 (Trevor Bryant, University of Southampton, UK), and SPSS Graduate Pack (version 11.0; SPSS Inc., Chicago, IL) were used for processing and analyses.

---

*Table 1. Inclusion and Exclusion Criteria*

<table>
<thead>
<tr>
<th>LBP group: Inclusion criteria</th>
<th>1. LBP within the last year that required medical attention, lost work, or limited recreational activities</th>
<th>2. &lt;40 yr of age (If 2 other ⦨“” variables present, age can range from 18 to 60 yr)</th>
<th>3. Aberrant movement present†</th>
<th>4. Positive prone instability test*</th>
<th>5. Average straight leg raise (≥90°)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>LBP group: Exclusion criteria</td>
<td>1. Aberrant movement absent‡</td>
<td>2. Negative prone instability test at all segmental levels†</td>
<td>3. FABQ–physical activity subscale (≥9)=</td>
<td>4. Unable to perform the test motion secondary to pain</td>
<td>5. Pregnancy</td>
</tr>
<tr>
<td>Control group: Inclusion criteria</td>
<td>1. No history of LBP that resulted in medical attention, lost work or limited recreational activities within the last 3 yr</td>
<td>2. 18–60 yr of age</td>
<td>3. Oswestry ≤4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Must have at least 2 of the 4 findings to be included in this LBP group. This decision rule has been reported to have a sensitivity of 0.83 (0.61, 0.94) and specificity of 0.56 (0.40, 0.71).† Aberrant motion is defined as at least 1 of the following 5 signs: painful arc in flexion, painful arc in extension, Gower’s sign, instability catch, or reversal of normal lumbopelvic motion. † Aberrant movement absent defined as at least 2 of the following 5 signs: painful arc in flexion, painful arc in extension, Gower’s sign, instability catch, or reversal of normal lumbopelvic motion. § The lowest negative likelihood ratio of 0.18 (0.08, 0.38) with lumbar stabilization based on the clinical prediction rule resulted when the volunteers had at least 2 of the 3 criteria present with a sensitivity of 0.85 (0.70, 0.93) and specificity of 0.87 (0.62, 0.96).† Aberrant motion is defined as at least 1 of the following 5 signs: painful arc in flexion, painful arc in extension, Gower’s sign, instability catch, or reversal of normal lumbopelvic motion. † The lowest negative likelihood ratio of 0.18 (0.08, 0.38) with lumbar stabilization based on the clinical prediction rule resulted when the volunteers had at least 2 of the 3 criteria present with a sensitivity of 0.85 (0.70, 0.93) and specificity of 0.87 (0.62, 0.96).77 FABQ indicates Fear Avoidance Behavior Questionnaire.
Data Analysis. A kinematic model was developed to determine if assessment of DFV was able to distinguish between L5–S1) was calculated for angular and linear displacement during flexion and extension. These angular and linear displacement indexes were used to assess the variability of motion among the segments and to control for variation among volunteers with possible pathology at different segmental levels. An individual with a higher index value would indicate that 1 segment was more hypermobile compared to the group mean, and an individual with a lower index value indicated equivalent motion among all 3 segments.

Quantification of the intersegmental movement pattern during flexion and extension was based on the work by Kanayama et al.22 These measurements describe the rate of attainment of angular and linear displacement at each lumbar segment (L3–L4, L4–L5, and L5–S1) with respect to the change in 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. Flexion was defined as a local maximum of the L3–S1 lordosis angle at the start of the motion pattern to its local minimum value at the end-range of flexion. Extension was defined as the local minimum of the L3–S1 lordosis angle at the end-range of flexion to its local maximum value at the end of the return to the upright posture. Both movement patterns, flexion and extension, were then divided into 10% increments. For example, the average of upright to 10% of global flexion represented by 5% of flexion, and the average from the 10% to 20% of global flexion represented by 15% of flexion, etc. 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 volunteers in segmental range, each variable was divided by its segmental range, resulting in a range of 0% to 100% of motion for each segment. Therefore, the slope between successive sequential data points represents the rate of attainment of angular or linear displacement segmental range (%) as a function of L3–S1 global motion (%).

Kinematic Analysis. The distortion compensated roentgen analysis was originally developed for analysis of intersegmental motion from standard radiographs.25–27 This technique was validated using stereophotogrammetric roentgen analysis28 and recently found to be reliable when applied to DFV.29 The L3–S1 lordosis angle29,31 and intersegmental motion (angular and linear displacement)33,34 were defined in Figure 2. A local maximum of the L3–S1 lordosis angle at the start of flexion and the end of the return to upright was used to define 1 cycle of motion. A local minimum of the L3–S1 lordosis angle near the center of this period defined the end of flexion and start of extension. In addition to traditional descriptor variables of intersegmental motion (minima, maxima, mean, and range values), angular and linear displacement indexes were defined as the lumbar segment with the maximal range value divided by the mean value of all segmental ranges (L3–L4, L4–L5, and L5–S1) was calculated for angular and linear displacement during flexion and extension. These angular and linear displacement indexes were used to assess the variability of motion among the segments and to control for variation among volunteers with possible pathology at different segmental levels. An individual with a higher index value would indicate that 1 segment was more hypermobile compared to the group mean, and an individual with a lower index value indicated equivalent motion among all 3 segments.
individuals with and without LBP. The steps used to develop this model are similar to the procedures used to develop a clinical prediction rule.49,50 To narrow the number of variables of interest, all variables (i.e., angular and linear displacement and rate of attainment during flexion and extension at each segmental level) were tested against the reference criterion (with or without LBP) using independent-samples t tests. Variables with a significance level of $P < 0.20$ were retained as potential variables that may discriminate between individuals with and without LBP. A more liberal $P$ value was selected in this initial step to protect against eliminating a potentially meaningful discriminating variable. For the variables that remained after this initial screening step, sensitivity and specificity values were calculated for all possible cutoff points and then plotted as a receiver operator characteristic curve.51 The point on the curve nearest the upper left-hand corner corresponds to the threshold that most accurately discriminates between individuals with and without LBP. This point was selected as the cutoff defining a “positive” test. Sensitivity, specificity, and positive likelihood ratios were then calculated. The 95% confidence intervals (CIs) for sensitivity and specificity were calculated using the Wilson method.52 For the positive and negative likelihood ratios, the 95% CIs were calculated using the score method.52,53 Because the goal was to distinguish between individuals with and without LBP, variables with a positive likelihood ratio $>2.5$ were used to develop a multivariate kinematic model.52,53

A multivariate model based on the total number of predictive variables present or absent was analyzed to determine if a cluster of these variables could distinguish between individuals with and without LBP. Sensitivity, specificity, and likelihood ratios were calculated. The number of variables present required to maximize the positive likelihood ratio was considered to be the best cutoff value to distinguish between these populations.

### Results

The volunteers analyzed in the final analysis consisted of 11 volunteers with LBP that were viewed to have abnormal motion on DFV, while the control group consisted of 14 volunteers without a history (>10 years) of LBP that were perceived to have relatively normal motion on DFV (Figure 1, Table 2). Volunteers in the LBP group presented with 3.1 $\pm$ 0.7 of the positive predictor variables for success and had none of the negative predictor variables for the nonoperative treatment approach for LBP. Moreover, all volunteers had at least 1 sign of aberrant motion (average 2.5 $\pm$ 1.2 signs), all had a positive prone instability test at least at 1 segmental level (average 2.1 $\pm$ 0.7 segments), and all had a Fear Avoidance Behavior Questionnaire,14 physical activity subscale score $>9$. Additionally, 9 of the 11 subjects reported recurrent episodes of LBP.

The average time required for the subject to complete the motion was 5.75 $\pm$ 0.81 seconds, resulting in an average of 172.5 $\pm$ 24.3 frames per motion sequence, or 2415.0 $\pm$ 340.0 point placements per motion sequence, for over 6900 frames or 96,600 point placements to complete this analysis.

### Table 2. Demographics (Descriptive and Comparative Group Studies)

<table>
<thead>
<tr>
<th></th>
<th>LBP (n = 11)*</th>
<th>Control (n = 14)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>36.5 $\pm$ 9.2 (24–52)</td>
<td>34.0 $\pm$ 8.3 (22–51)</td>
</tr>
<tr>
<td>Body mass index (kg/m²)</td>
<td>26.8 $\pm$ 4.1 (18.6–32.4)</td>
<td>25.3 $\pm$ 3.3 (20.0–31.4)</td>
</tr>
<tr>
<td>Waist-hip ratio</td>
<td>0.846 $\pm$ 0.083 (0.715–0.970)</td>
<td>0.839 $\pm$ 0.047 (0.773–0.930)</td>
</tr>
<tr>
<td>Oswestry (0% to 100%)</td>
<td>26.7 $\pm$ 13.4 (0–46)</td>
<td>0.4 $\pm$ 1.0 (0–4)†</td>
</tr>
<tr>
<td>FABQ (0–24)</td>
<td>16.9 $\pm$ 4.0 (11–24)</td>
<td>Not applicable</td>
</tr>
</tbody>
</table>

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

* Fourteen volunteers were in the control group (10 men, 4 women) and 11 in the LBP group (7 men, 4 women).
† One individual in the control group scored 2%, scoring 1 for the sleep related question; 1 volunteer scored 4%, scoring 1 for both prolong sitting and standing questions.

FABQ indicates Fear Avoidance Behavior Questionnaire.
Twenty-three kinematic variables met the criteria for further analysis based on the independent t tests. Of these 23 variables that could possibly distinguish group membership, 19 had a receiver operator characteristic curve in which an identifiable cutoff value was found. Six (31.6%) of these variables were more traditional variables that described differences in angular and linear displacement, and 13 (68.4%) of these variables were associated with the dynamic rate of angular and linear displacement unique to DFV analysis. Of these variables, 16 had a positive likelihood ratio ≥2.0, and 8 had a positive likelihood ratio ≥2.5 (Table 3). Two (25%) of these variables described linear and angular displacement hypomobility, measurable with traditional radiographs. While 6 (75%) of these variables described differences in the dynamic rate of attainment of angular and linear displacement unique to DFV analysis.

These 8 variables were used to identify clusters of motion variables that maximized the ability to distinguish group membership (Tables 4, 5). The greatest accuracy ([true positive + true negative]/total) was achieved if 4 variables were present (96.0%); in which case, only 1 individual from the control group was misclassified as having LBP. The positive likelihood ratio was 14.0 and the negative likelihood ratio was approaching zero when 4 or more variables were present. The positive likelihood ratio approached infinity after that point because there was no one in the control group that had more than 4 of the 8 variables present. The negative likelihood ratio approached zero when 4 or fewer variables were present because none of those in the LBP group had fewer than 4 variables present. Table 5 graphically depicts the presence or absence of each of the movement parameters that had a positive likelihood ratio ≥2.0 by

**Table 4. Accuracy at Each Level of the Model to Distinguish Group Membership**

<table>
<thead>
<tr>
<th>No. Predictor Variables Present</th>
<th>Sensitivity</th>
<th>Specificity</th>
<th>Positive Likelihood Ratio</th>
<th>Negative Likelihood Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>All 8 present (none)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>≥7 Present</td>
<td>0.27 (0.10–0.57)</td>
<td>1.00 (0.78–1.00)</td>
<td>Approaches infinite (1.1–Infinity)</td>
<td>0.7 (0.4–1.0)</td>
</tr>
<tr>
<td>≥6 Present</td>
<td>0.45 (0.21–0.72)</td>
<td>1.00 (0.78–1.00)</td>
<td>Approaches infinite (1.1–Infinity)</td>
<td>0.5 (0.3–0.8)</td>
</tr>
<tr>
<td>≥5 Present</td>
<td>0.91 (0.62–0.98)</td>
<td>1.00 (0.78–1.00)</td>
<td>Approaches infinite (1.2–Infinity)</td>
<td>0.1 (0.0–0.4)</td>
</tr>
<tr>
<td>≥4 Present</td>
<td>1.00 (0.74–1.00)</td>
<td>0.93 (0.68–0.99)</td>
<td>14.0 (3.2–78.5)</td>
<td>Approaches zero (0.0–0.3)</td>
</tr>
<tr>
<td>≥3 Present</td>
<td>1.00 (0.74–1.00)</td>
<td>0.86 (0.60–0.96)</td>
<td>7.0 (2.5–24.9)</td>
<td>Approaches zero (0.0–0.3)</td>
</tr>
<tr>
<td>≥2 Present</td>
<td>1.00 (0.74–1.00)</td>
<td>0.50 (0.27–0.73)</td>
<td>2.0 (1.3–3.7)</td>
<td>Approaches zero (0.00–0.6)</td>
</tr>
<tr>
<td>≥1 Present</td>
<td>1.00 (0.74–1.00)</td>
<td>0.07 (0.01–0.31)</td>
<td>1.1 (0.8–1.5)</td>
<td>Approaches zero (0.0–0.4)</td>
</tr>
</tbody>
</table>

Values represent accuracy statistics with 95% CIs. Note that if ≥4 motion parameters present were required to define LBP, then the kinematic model would have a sensitivity of 1.0, specificity 0.93, positive likelihood ratio 14.0, and negative likelihood ratio approaching zero. NA indicates not applicable.
subject, thus allowing a comparison between the true-positive and false-positive values for each group based on a positive likelihood ratio $\geq 2.0$ and 2.5 cutoff values.

During the onset of flexion, those with LBP attained their motion with a greater rate of angular motion at L3–L4, while there was an initial delay in the rate of attainment of angular motion at L4–L5 (Figure 3). The greater rate of attainment of angular range at L3–L4 during 5% to 15% of flexion and the slower rate of attainment of angular range at L4–L5 during both 5% to 15% and 15% to 25% of flexion in the LBP group occurred while those without LBP had consistent positive slopes across all segments during the onset of flexion.

Those with LBP displayed alterations in the rate of attainment of linear displacement range during the onset of flexion (Figure 4). During the onset of flexion in the LBP group, the rate of attainment of linear displacement occurred in a caudal to cephalad direction. Specifically, during 5% to 15% of flexion, the LBP group displayed an average negative rate of attainment of linear displacement at L3–L4 and L4–L5, while on average the L5–S1 segment had a positive rate of attainment of linear displacement. Although these trends were noted, only the values from L3 to L4 (positive likelihood ratio of 3.4) entered the final kinematic model. This is in contrast to those without LBP that attained its linear displacement in a more cephalad to caudal direction, with the greatest slope attained at L3–L4 during 5% to 15% of flexion relative to L4–L5 and L5–S1. The altered rate of attainment of linear displacement at L3–L4 during the onset of flexion was in direct contrast to the higher rate of attainment of angular displacement at L3–L4 in those with LBP during the same initial stages of flexion.

During the return to upright, the LBP group demonstrated alteration in the rate of attainment of angular motion at L3–L4 and L4–L5 (Table 3) in those with LBP during the last 25% of returning to the upright posture. Finally, there was alteration in the rate of attainment of linear displacement at L5–S1 during 65% to 75% of the return to upright posture.
Of note, there were no variables representing L3–S1 lordosis angle, or L3–L4, L4–L5, or L5–S1 segmental angular values within the model. None of these variables had an independent t test with a P value < 0.20, demonstrating that both groups moved through similar amounts of angular motion. Furthermore, all minima and maxima values for angular and linear displacement occurred at end-range postures. None of these values occurred during midrange motions.

Discussion

Although prior researchers using DFV have been able to use similar techniques to document normal sequential angular motion in those without LBP\(^1\)\(^2\)\(^3\)\(^4\) and have been able to use the technique to differentiate movement patterns in those with spondylolisthesis,\(^30\)\(^34\)\(^36\) this is the first study that has been able to distinguish altered rates of attainment of angular and linear displacement in those with LBP and healthy controls. The results of our study establish construct validity for the distortion compensated measurement technique application to DFV\(^29\) based on its ability to distinguish between individuals with and without LBP.

The kinematic variables that were able to distinguish group membership demonstrate the limitations of using traditional radiographic measures of angular and linear displacement. While 25% of the variables could be assessed using standard radiographs, 75% of the variables that were able to distinguish group membership were unique to DFV analysis. The results lend credibility to previous reports questioning the suitability of basing the diagnosis of LBP, which is inherently a problem that occurs during movement, on static radiographs.\(^6\)\(^54\)\(^55\)\(^57\)

Additionally, the greater number of variables associated with the rate of attainment of motion in the model lends credibility to researchers\(^19\)\(^21\)\(^25\)\(^57\)\(^58\) who have advocated the need for dynamic analysis of lumbar kinematics to describe those with LBP and the use of multifactorial models to describe these individuals.

**Traditional Variables Attainable From Static Radiographs**

Individuals in both groups moved through the same angular range of motion. Specifically, global motion (L3–S1) and segmental angular motion (L3–L4, L4–L5, and L5–S1) did not differ. Therefore, the changes observed in the rate of attainment of motion occurred when both groups moved through a similar range of angular motion. One possible reason for the lack of differences in the variables pertaining to angular motion was our requirement that subjects with LBP be able to perform the movement in a relatively normal movement pattern that was not limited by pain. These entrance criteria were based on critiques from prior researchers\(^55\)\(^59\) suggesting that pain status may alter volitional movement, and, hence, increase error and underestimation of the measured movement pattern.

In those with LBP, linear displacement hypomobility was noted (Table 3). Clearly, the presence of hypomobility rather than hypermobility calls into question the current theoretical basis for labeling individuals with physical examination findings that have been traditionally associated with clinical lumbar instability and have been predicted to succeed with lumbar stabilization exercises programs as having underlying instability. Future researchers should investigate the relationship between alterations in muscle activation and the influence on linear displacement.

The use of standard functional radiographs may be adequate to measure the global and segmental range of motion from upright to flexed posture. The extremes (minima and maxima) of angular and linear displac-
ment range occurred at the upright and flexed postures. An extreme value did not occur during the movement pattern from upright to flexion or on the return to upright in any volunteer. Therefore, clinicians and researchers could use standard functional radiographs to measure range, minima, and maxima variables in a similar patient population. However, these descriptive variables had a limited role in distinguishing between individuals with and without LBP in this study.

**Variables Unique to DFV**

The hypothesis that variables describing the rate of attainment of angular and linear displacement would be able to distinguish group membership was supported. Specifically, based on the criterion of a positive likelihood ratio ≥2.5 to enter the kinematic model, there were more differences related to the rate of attainment of motion (4 related to the attainment of angular motion and 2 related to the attainment of linear displacement motion) that were able to distinguish group membership (Table 3). Assessing these variations in the rate of attainment of angular and linear displacement as a group, it appears that those with LBP have an altered movement pattern at the onset of flexion and on returning to the upright posture. These dysrhythmias are consistent with the neutral zone theory outlined by Panjabi, in which the dysfunctional movement occurs during the range of motion 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 or during the final stages of the return to upright may represent altered motor control patterns that are perceived by the patient as the “catching” or “slipping” sensation, or viewed by the clinician as aberrant motion.

**Clinical and Technical Implications**

DFV overcomes the limitations of standard radiographs in assessing LBP by capturing relevant information that is only observed during movement. It is speculated that the advantage in DFV assessment of lumbar motion is its ability to quantify the rhythm, delays, and alterations in the movement pattern related to the patient’s symptoms. Although researchers have used DFV (typically limited to 3–5 Hz) to describe specific aspects of lumbar kinematics, their success and the clinical applicability has been limited. The technique outlined in this report is unique in its ability to capture the motion at a higher resolution (30 Hz) while capturing the dynamic quality of the rate of attainment of segmental motion for both angular and linear displacement.

Dupuis et al stated that dysfunctional movement should be assessed by addressing both the abnormal quantity and quality of motion. Standard radiographs are limited to the quantity of lumbar segmental motion. Furthermore, DFV captured at lower frame rates (3–5 Hz) are only able to describe very general trends in the quality of the angular motion occurring. Ours is the first study that has been able to distinguish successfully group membership in those with LBP using dynamic quantitative and qualitative parameters that are only attainable on higher resolution DFV using a distortion compensated measurement technique. Specifically, this study was able to “quantify” a component of lumbar motion (rate of attainment of angular and linear displacement) at an individual motion segment previously considered as a more “qualitative” analysis. Furthermore, this quantification of qualitative variables was capable of distinguishing those individuals with LBP. We are currently conducting research to validate the ability of this technique to identify individuals with different subclassifications of LBP, and determine the prognostic capability of this assessment tool in determining those that will succeed with both surgical and nonsurgical treatment regimens.

**Role of the Qualitative Analysis of the DFV**

There currently is no agreed on reference or gold standard for identifying dysfunctional spinal movement, and the addition of expert opinion appeared warranted. Three fellowship-trained spine surgeons were used to determine if abnormal motion was probably present or absent among the DFVs. Agreement of 2 of the 3 surgeons was required for final group membership. This additional step resulted in more homogenous subgroups for analysis, as evident from the improved accuracy of the kinematic model from 87.5% to 96% and the increase in the positive likelihood ratio of the model from 6.0 to 14.0. Future researchers using imaging techniques to identify or treat a subgroup of patients with LBP may want to consider entrance criteria that use a combination of signs, symptoms, and a dynamic imaging assessment of movement in order to obtain more homogenous samples.

**Limitations**

LBP was initially defined based on the criteria outlined by Hicks. These criteria were selected based on the ability to use signs and symptoms to distinguish a subgroup of patients with LBP that have historically been thought to have signs of underlying clinical lumbar instability (spondylolisthesis, posterior pelvic pain after pregnancy, chronic LBP, and hypermobility on physical examination). To our knowledge, there are no other clinical prediction rules currently available to assist with this process. Although these volunteers had more signs and symptoms than required by the entrance criteria, they displayed the same amount of angular motion as the control group and actually displayed less linear displacement range than the control group. The lack of measures indicating hypermobility was unexpected and may differ in future studies that use different criteria. Therefore, future researchers measuring volunteers with frank instabilities on static radiographic assessments may find a different set of kinematic variables associated with frank instabilities. The fact that the model was developed from a single sample also necessitates that cross-validation studies be performed before this procedure can be recommended for clinical use.
Conclusions

The assessment of kinematic patterns of movement using DFV can discriminate between individuals with LBP and asymptomatic controls. The model that emerged provides construct validity for using this technique in future research. Specifically, differences in the rate of attainment of angular and linear displacement range, especially during the onset of flexion, were variables that were able to distinguish the movement patterns of those with LBP relative to asymptomatic controls. Physical therapy treatment regimens focused on the restoration of these variables may be beneficial. The results from this study serve as the initial step in developing guidelines for using DFV for diagnostic purposes.

Key Points

- DFV appears to be a useful technology for quantifying lumbar segmental motion.
- Disruptions in the rate of attainment of angular and linear displacement during midrange postures were able to distinguish those with LBP better than traditional range of motion measures obtained from static radiographs.
- Dynamic assessment of sagittal plane motion using DFV offers the potential to develop diagnostic prediction rules to identify subgroups of patients with LBP who may preferentially benefit from specific interventions.

Acknowledgment

The authors thank Mr. Larry Wyatt, SPC Matthew Call, and SPC Bran McGee for their assistance and dedication to quality in the obtainsment of the DFVs.

References


