

Dynamic interactions between lumbar intervertebral motion segments during forward bending and return

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Introduction

Continuous dynamic multi-segmental studies of lumbar motion have brought new depth to our understanding of the biomechanics of back pain and these are becoming more prevalent than static radiographic studies in research. They are needed for the clinical validation of both laboratory and FE modelling outputs that include motion (Jones and Wilcox 2008, Oxland 2016) and are necessary before *in vivo* studies of loading can be attempted during bending tasks. Our previous work showed that it may be feasible to do this by adding finite element models from MRI to kinematic information from fluoroscopy to estimate intervertebral loading during motion, thereby revealing the time points when stresses are maximal (Zanjani-Pour 2018). However, we also now know that the motion shared between vertebral segments is more variable and less repeatable during loaded than passive recumbent bending and also changes during motion (Breen, Hemming et al. 2019). This represents a challenge to attempts to compare individuals or populations or to establish normative values. This highlights the need to explore the nature of the interactions between motion segments during these bending tasks.

Previous studies have suggested that passive recumbent lumbar flexion presents greater unevenness of intervertebral motion sharing in patients with chronic, non-specific back pain (CNSLBP) than asymptomatic controls, but did not find a difference during loaded flexion or explore interactions between segments (Breen and Breen 2018, Breen, Mellor et al. 2018). Several studies have explored how angular motion is shared between segments of the lumbar spine at points during weight bearing flexion in both patients with back pain and healthy controls using either medical imaging or surface markers (Teyhen, Flynn et al. 2007, Ahmadi, Maroufi et al. 2009, Aiyangar, Zheng et al. 2015, Christe, Redhead et al. 2016, Gombatto, D'Arpa et al. 2017, Hemming, Sheeran et al. 2017, Papi, Bull et al. 2019). These found greater flexion ranges in the upper than lower lumbar spine in patients when compared to controls, however, no weight bearing studies have attempted to continuously measure the proportions of the flexion and return motion that is accepted by individual levels, or to describe the dynamic interactions between them during bending. This will be needed if we are to model contemporaneous kinematics and loading to estimate relative intersegmental stresses during bending motion.

34 The purpose of this study was to assess the motion contributions of adjacent lumbar levels during an
35 active weight bearing flexion and return protocol using quantitative fluoroscopy. Data were
36 collected using a guiding motion platform to minimise behavioural variation and allow the greatest
37 effects to be obtained from the morphology and muscular activity during the motion.

38 **Methods:**

39 **Participants**

40 Eight patients with chronic non-specific low back pain (CNLSBP), yet without any obvious mechanical
41 disruption (for example surgery or spondylolisthesis) received fluoroscopic imaging during flexion
42 and return motion. These were matched for age and sex to 8 healthy controls who in turn were
43 extracted from a database of >100 asymptomatic individuals who had performed the same task.

44 Asymptomatic participants were included if they were between 21 and 80 years old, had a self-
45 reported body mass index of less than 30 kg.m^{-2} , were free of any back pain, had not experienced
46 back pain that limited their normal activity for more than 1 day in the previous year, had no history
47 of abdominal surgery or spondylolisthesis, had not received a medical radiation exposure of >8 mSv
48 in the previous 2 years, and were not currently pregnant. Ethical approval was provided by the
49 National Research Ethics Service (Bristol 10/H0106/65) and written Informed consent was obtained
50 from all participants.

51 **Data collection**

52 The Quantitative Fluoroscopy (QF) systems and procedures have been detailed extensively in the
53 literature (Breen and Breen 2017, Zanjani-Pour, Meakin et al. 2017, Breen, Mellor et al. 2018, du
54 Rose, Breen et al. 2018, Breen, Hemming et al. 2019). However, in brief, participants undertook a
55 standardised motion protocol during active weight-bearing flexion and return that reduces
56 behavioural aspects of participant bending, guiding the participants speed and range of motion
57 throughout their bend.

58 Participants were asked to fold their arms (left over right) out in front of them at chest height in a
59 comfortable position while standing upright in a neutral posture, the arm rest of a guided motion
60 control platform was then brought into position to meet the participants arms (See Figure 1). The
61 participants were guided by the motion control platform at $6^\circ/\text{s}$ to perform trunk flexion from
62 upright standing to 60° flexion, directly followed by guided return to a neutral standing position.
63 During motion, the pelvis was constrained to reduce sacral translation but still allow some rotation
64 of the hips. This was performed using a belt secured around the participants' hips and a bracing pad
65 applied to the lower sacral segments (See Figure 1). Concurrently, fluoroscopic images were

66 acquired using a Siemens Arcadis Avantic digital C-arm fluoroscope (Siemens GMBH) with the centre
67 of rotation of the motion platform aligned with participants' L3/L4 intervertebral disc. During the
68 bending protocol, fluoroscopic images were acquired at 15Hz frame rate. These were transferred to
69 a dedicated workstation where the vertebral body positions (L2, L3, L4, L5 and S1) were identified
70 for each by a semi-automated tracking process written in Matlab (V2013, The Mathworks Inc.). This
71 method has been previously validated and shown to have an accuracy in rotation measures of 0.52°
72 (Breen, Muggleton et al. 2006) and an inter- and intra-observer repeatability ranging from ICC 0.94–
73 0.96 (SEM 0.23°– 0.61°) (du Rose A. and Breen 2016).

74 Data analysis

75 In order to investigate population differences in intersegmental spinal motion sharing metrics and
76 intervertebral range of motion (IV-RoM) for each level, dynamic motion sharing of segments from
77 L2-S1 were calculated throughout the bend and return.

78 Vertebral positions were established for each vertebra from L2-S1 and tracked throughout the
79 bending sequence. To compare intervertebral motion sharing across and between populations,
80 segmental motion profiles were normalised to a motion cycle as a percentage that clearly
81 discriminated the outward (0-50%) from the return phase (50-100%). (See [Figure 2](#)).

82 Motion Sharing was calculated as the contribution of each motion pair as a percentage of the L2-S1
83 motion. Because segmental angular differences from the participants' starting positions are small at
84 the beginning and end of participants' bending sequences, they are close to the precision limit of the
85 QF Systems at these points (0.52 degrees). Therefore, contributions to motion sharing from points
86 where the L2-S1 angle was less than 10% of the maximum L2-S1 RoM were truncated to remove the
87 large relative contributions to errors (equivalent to data points at less than 5% and greater than 95%
88 of the motion cycle) ([Figure 3](#)).

89 We calculated the average inequality of the motion share (Motion Sharing Inequality, MSI) and its
90 standard deviation (Motion Sharing Variability, MSV) throughout the bend from the differences
91 between maximum and minimum contributions throughout the flexion and return sequences. [To do
92 this, the range was calculated for each data point on the x-axis. Then, MSI was calculated as the
93 mean of all the ranges in the sequence and MSV as their standard deviation](#) (Breen and Breen 2018).

94 We also determined the average percentage contribution, for individual levels, across the motion
95 (Average Motion Share, AvMS) and the standard deviation of each level's contribution across the
96 motion (Motion Sharing per Level Variance, MS(L)V). Lastly, in order to compare against the
97 literature, the percentage contribution at maximum bend (MS@max) was also computed. These

98 were compared between groups and with a systematic review of spinal kinematics by Widmer et al.
99 2019 (Widmer, Fornaciari et al. 2019)

100 Statistical analysis

101 The normality of the data was calculated using the Shapiro Wilk test in SPSS (version 24, IBM Corp.).
102 Independent t-tests were performed to test for differences between group data from a normally
103 distributed dataset and Mann-Whitney U was used for data that were not. Significance was set at
104 95%.

105 Mean motion share contribution and 95% confidence interval (\pm CI95) values across all participants
106 were computed at each 1% increment of the Motion Cycle of the controlled bending task for both
107 the asymptomatic control and CNSLBP patient populations. Statistically significant differences
108 between each level's contribution to motion was detected by the extent of overlap between the
109 \pm CI95 bands, i.e. the absence of \pm CI95 band overlap indicated statistically significant differences.

110 Results:

111 Each participant group consisted of 5 males and 3 females matched for age and sex. **Shapiro Wilk**
112 **test for normality revealed that age, height and weight were likely to have come from a normally**
113 **distributed data set, but BMI data were unlikely to be normally distributed. Furthermore, the**
114 **Shapiro Wilk test found that motion metrics (range of motion and motion sharing within and**
115 **between levels) were a mix of normal and non-normally distributed data depending on level.**
116 **Therefore, for consistency all motion metrics were treated as non-parametric data.** There were no
117 significant differences between groups in terms of age, height, weight, or BMI (Table 1). However,
118 the asymptomatic controls consistently gained higher ranges of intervertebral motion at all
119 measured levels, although this was only significant at the L5-S1 level ($p=0.012$) (Figure 4 & Table 2).
120 The L2-S1 range of motion was also significantly less among the patient population ($p=0.046$) (Figure
121 5 & Table 2)

122 Motion sharing inequality and variability

123 Among controls, in initial flexion and the latter part of the return phase, there was a top down
124 sharing of motion. However, at maximal bend the lumbar levels shared the motion more equally,
125 with L5-S1 receiving the least (Figure 6). Among patients, similar contributions to motion can be
126 seen during flexion, however, during return there was less symmetry of sharing, with L3-L4
127 continuing to receive more of the motion (Figure 7).

128 Although different in appearance, the MSI and MSV values for patients and controls (Figures 6 and 7)
129 were not significantly different. However, MS(L)V was significantly higher at L4-5 in the patients
130 ($p=0.021$). This lack of variation can be seen as a flatter curve, especially in the return phase of
131 bending. (Figure 7).

132 Individual level sharing

133 Among controls, the average share of motion was highest at L2-L3 and lowest at L5-S1 and this
134 tendency was greater with higher MSIs. Among patients, the average share of motion was highest at
135 L3-L4 and lowest at L5-S1, the L5-S1 contribution being significantly different from the other levels
136 throughout most of the bending protocol (as defined by the lack in of overlap of the 95% CI bands
137 about the L5-S1 level with any other level in Figure 7)

138 Comparison with the literature

139 Few studies have examined intervertebral motion sharing during dynamic flexion and return tasks
140 and none that can be compared directly. However, Widmer et al (2019) (Widmer, Fornaciari et al.
141 2019) recently presented a review of studies of lumbar kinematics and reported the segmental
142 contributions to flexion from multiple studies. On the whole, two different types of segmental
143 contribution profiles (spinal rhythms) were established. Type 1: A cranio-caudally decreasing
144 contribution pattern, in protocols where total lumbar RoM was limited either by restricting the
145 attempt or by starting the motion in a sitting position. Type 2: A cranio-caudally increasing
146 contribution pattern with a slight drop at the L5–S1 segment, in protocols where lumbar RoM was
147 unconstrained. Figure 8 and Figure 9, respectively, display these, with the control and patient data
148 from the present study included for each level.

149 When calculating the average motion sharing during flexion and return (AvMS), it was noticed that
150 the distribution of sharing was similar to Widmer's graph of limited flexion studies (Widmer,
151 Fornaciari et al. 2019). That is, decreasing contributions per level between L2-L3 and L5-S1, with the
152 exception of L3-L4 whose average contribution (AvMS) was greater in patients ($p=0.046$) (Figure 8 &
153 Table 2). This is consistent with L3-L4 and L4-L5 remaining in a relatively flexed position as
154 demonstrated by the high contribution to L2-S1 angle during the return phase in Figure 7. This
155 seems to characterise the difference in motion pattern between patients and controls.

156 In Figure 9, segmental contribution at maximum flexion for all studies, including the present one,
157 shows a cranio-caudally increasing contribution, with a drop at the L5–S1 segment. This suggests
158 that when participant range is standardised to 60° of trunk bend, the lumbar segments (L2-S1) are
159 flexed near to their maximal range. In the present study, which includes both patients and controls,

160 the L5-S1 contribution at maximum was significantly lower in patients (Table 2) and significantly less
161 than all other levels (Figure 7).

162 Discussion:

163 There were consistent but non-significant differences between patient and control motion sharing
164 patterns. This lack of significance may be due to the range of L2-S1 motion of patients' spines being
165 significantly less, particularly at the lower levels. The results also illustrate the effects of loading and
166 muscle activity on the differences between lumbar flexion and return motion in controls and
167 patients with CNSLBP. Widmer et al (2019) considered that contributions to flexion motion may be
168 RoM dependent and this is consistent with our findings, where patients had lower L2-S1 RoM
169 ($p=0.046$) and a lower contribution at maximum bend at L5-S1 ($p=0.046$).

170 Our previous studies of passive recumbent proportional motion did not dis-aggregate intervertebral
171 levels, but unlike this study, did find MSI to be significantly higher in patients (Breen and Breen 2018,
172 Breen, Mellor et al. 2018). These differences may be due to any combination of contributions from
173 behavioural influence on bending strategy, involuntary muscle activity and changes in passive tissue
174 restraint. For example, the increased variability of motion sharing in patients (MS(L)V at L4-5,
175 $p=0.021$) may be consistent with the work of Du Rose et al (du Rose, Breen et al. 2018), who
176 measured local and global lumbar sEMG activity during bending in controls and found that it
177 correlated negatively with MSV. Considered in relation to patients, this may suggest a guarding
178 effect. This present study did not include muscle oxygenation or electrical activity, which could shed
179 considerable light on these issues.

180 A further finding was that whether in patients or controls, contributions to motion change
181 continuously during bending. Although fairly consistent in groups, this makes static measurement of
182 IV-RoM of limited use as it is dependent on the phase of flexion as well as the restraint of the
183 segment.

184 Our finding that motion contributions change dramatically throughout the bend and seem to be
185 RoM dependent are consistent with the findings of the review by Widmer et al (2019). Therefore,
186 the significant reduction in patients' lumbar range of motion may be contributing to the significant
187 differences between population motion sharing characteristics. It may also be true that motion
188 sharing is dependent on the global position at which the participant starts their motion. This was not
189 investigated but highlights the need to standardise data collection protocols and only include those
190 which adhere to them in comparing studies.

191 The dynamic interactions between lumbar intervertebral motion segments during weight bearing
192 flexion and return were found to be different in patients with CNSLBP compared to healthy controls.
193 However, although global motion of participants in both groups were 60°, L2-S1 maximum range
194 was lower in patients, while individual level contributions changed during the motion and seem to
195 be RoM dependent. Therefore, it is unsurprising that only L5-S1 was significantly different between
196 groups in terms of motion sharing metrics. However, there also appears to be less variability in the
197 motion contributions of different levels in patients, although these were not significant in these
198 small populations. This lower variance in patients, particularly during return from full flexion, may be
199 related to increased muscle contraction. Therefore, muscle workload needs to be verified and/or
200 explained by further studies, with larger populations. These could include muscle electrical activity
201 and oxygenation alongside kinematics and loading **as well as comparisons with passive recumbent**
202 **protocols within which muscle activity and loading are likely minimal.**

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