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1 Dynamic interactions between lumbar intervertebral 2 motion segments during forward bending and return

3 Abstract

4 Continuous dynamic multi-segmental studies of lumbar motion have added depth to our
5 understanding of the biomechanics of back pain, but few have attempted to continuously
6 measure the proportions of motion accepted by individual levels. This study attempted to
7 compare the motion contributions of adjacent lumbar levels during an active weight bearing
8 flexion and return protocol in chronic, non-specific low back pain (CNSLBP) patients and
9 controls using quantitative fluoroscopy (QF).

10 Eight CNSLBP patients received QF during guided standing lumbar flexion. Dynamic motion
11 sharing of segments from L2 to S1 were calculated and analysed for interactions between
12 levels. Eight asymptomatic controls were then matched to the 8 patients for age and sex
13 and their motion sharing patterns compared.

14 Share of intersegmental motion was found to be consistently highest at L2-L3 and L3-L4 and
15 lowest at L5-S1 throughout the motion in both groups, with the exception of maximum
16 flexion where L4-L5 received the greatest share.

17 Change in motion sharing occurred throughout the flexion and return motion paths in both
18 participant groups but tended to vary more at L4-L5 in patients ($p < 0.05$). In patients, L5-S1
19 provided less angular range ($p < 0.05$) and contributed less at maximum bend ($p < 0.05$), while
20 L3-L4, on average over the bending sequence, provided a greater share of motion ($p < 0.05$).

21 Intervertebral motion sharing inequality is therefore a normal feature during lumbar flexion.
22 However, in patients, inequality was more pronounced, and variability of motion share at
23 some levels increased. These effects may result from differences in muscular contraction or
24 in the mechanical properties of the disc.

26 Introduction

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

40 Previous studies have suggested that passive recumbent lumbar flexion presents greater unevenness
41 of intervertebral motion sharing in patients with chronic, non-specific back pain (CNSLBP) than
42 asymptomatic controls, but did not find a difference during loaded flexion or explore interactions
43 between segments (Breen and Breen 2018, Breen, Mellor et al. 2018). Several studies have explored
44 how angular motion is shared between segments of the lumbar spine at points during weight
45 bearing flexion in both patients with back pain and healthy controls using either medical imaging or
46 surface markers (Teyhen, Flynn et al. 2007, Ahmadi, Maroufi et al. 2009, Aiyangar, Zheng et al. 2015,
47 Christe, Redhead et al. 2016, Gombatto, D'Arpa et al. 2017, Hemming, Sheeran et al. 2017, Papi, Bull
48 et al. 2019)

49 . These found greater flexion ranges in the upper than lower lumbar spine in patients when
50 compared to controls, however, no weight bearing studies have attempted to continuously measure
51 the proportions of the flexion and return motion that is accepted by individual levels, or to describe
52 the dynamic interactions between them during bending. This will be needed if we are to model
53 contemporaneous kinematics and loading to estimate relative intersegmental stresses during
54 bending motion.

55 The purpose of this study was to assess the motion contributions of adjacent lumbar levels during an
56 active weight bearing flexion and return protocol using quantitative fluoroscopy. Data were

57 collected using a guiding motion platform to minimise behavioural variation and allow the greatest
58 effects to be obtained from the morphology and muscular activity during the motion.

59 **Methods:**

60 **Participants**

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

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

72 **Data collection**

73 The Quantitative Fluoroscopy (QF) systems and procedures have been detailed extensively in the
74 literature (Breen and Breen 2018, Breen, Mellor et al. 2018, du Rose, Breen et al. 2018, Zanjani-Pour
75 2018, Breen, Hemming et al. 2019). However, in brief, participants undertook a standardised motion
76 protocol during active weight-bearing flexion and return that reduces behavioural aspects of
77 participant bending, guiding the participants speed and range of motion throughout their bend.

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

86 acquired using a Siemens Arcadis Avantic digital C-arm fluoroscope (Siemens GMBH) with the centre
87 of rotation of the motion platform aligned with participants' L3/L4 intervertebral disc. During the
88 bending protocol, fluoroscopic images were acquired at 15Hz frame rate. These were transferred to
89 a dedicated workstation where the vertebral body positions (L2, L3, L4, L5 and S1) were identified
90 for each by a semi-automated tracking process written in Matlab (V2013, The Mathworks Inc.). This
91 method has been previously validated and shown to have an accuracy in rotation measures of 0.52°
92 (Breen, Muggleton et al. 2006) and an inter- and intra-observer repeatability ranging from ICC 0.94–
93 0.96 (SEM 0.23°– 0.61°) (du Rose A. and Breen 2016).

94 Data analysis

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

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

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

109 We calculated the average inequality of the motion share (Motion Sharing Inequality, MSI) and its
110 standard deviation (Motion Sharing Variability, MSV) throughout the bend from the differences
111 between maximum and minimum contributions throughout the flexion and return sequences. To do
112 this, the range was calculated for each data point on the x-axis. Then, MSI was calculated as the
113 mean of all the ranges in the sequence and MSV as their standard deviation (Breen and Breen 2018).
114 We also determined the average percentage contribution, for individual levels, across the motion
115 (Average Motion Share, AvMS) and the standard deviation of each level's contribution across the
116 motion (Motion Sharing per Level Variance, MS(L)V). Lastly, in order to compare against the

117 literature, the percentage contribution at maximum bend (MS@max) was also computed. These
118 were compared between groups and with a systematic review of spinal kinematics by Widmer et al.
119 2019 (Widmer, Fornaciari et al. 2019)

120 **Statistical analysis**

121 The normality of the data was calculated using the Shapiro Wilk test in SPSS (version 24, IBM Corp.).
122 Independent t-tests were performed to test for differences between group data from a normally
123 distributed dataset and Mann-Whitney U was used for data that were not. Significance was set at
124 95%.

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

130 **Results:**

131 Each participant group consisted of 5 males and 3 females matched for age and sex. Shapiro Wilk
132 test for normality revealed that age, height and weight were likely to have come from a normally
133 distributed data set, but BMI data were unlikely to be normally distributed. Furthermore, the
134 Shapiro Wilk test found that motion metrics (range of motion and motion sharing within and
135 between levels) were a mix of normal and non-normally distributed data depending on level.
136 Therefore, for consistency all motion metrics were treated as non-parametric data. There were no
137 significant differences between groups in terms of age, height, weight, or BMI (Table 1). However,
138 the asymptomatic controls consistently gained higher ranges of intervertebral motion at all
139 measured levels, although this was only significant at the L5-S1 level ($p=0.012$) (Figure 4 & Table 2).
140 The L2-S1 range of motion was also significantly less among the patient population ($p=0.046$) (Figure
141 5 & Table 2)

142 **Motion sharing inequality and variability**

143 Among controls, in initial flexion and the latter part of the return phase, there was a top down
144 sharing of motion. However, at maximal bend the lumbar levels shared the motion more equally,
145 with L5-S1 receiving the least (Figure 6). Among patients, similar contributions to motion can be

146 seen during flexion, however, during return there was less symmetry of sharing, with L3-L4
147 continuing to receive more of the motion (Figure 7).

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

152 Individual level sharing

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

158 Comparison with the literature

159 Few studies have examined intervertebral motion sharing during dynamic flexion and return tasks
160 and none that can be compared directly. However, Widmer et al (2019) (Widmer, Fornaciari et al.
161 2019) recently presented a review of studies of lumbar kinematics and reported the segmental
162 contributions to flexion from multiple studies. On the whole, two different types of segmental
163 contribution profiles (spinal rhythms) were established. Type 1: A cranio-caudally decreasing
164 contribution pattern, in protocols where total lumbar RoM was limited either by restricting the
165 attempt or by starting the motion in a sitting position. Type 2: A cranio-caudally increasing
166 contribution pattern with a slight drop at the L5-S1 segment, in protocols where lumbar RoM was
167 unconstrained. Figure 8 and Figure 9, respectively, display these, with the control and patient data
168 from the present study included for each level.

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

176 In Figure 9, segmental contribution at maximum flexion for all studies, including the present one,
177 shows a cranio-caudally increasing contribution, with a drop at the L5–S1 segment. This suggests
178 that when participant range is standardised to 60° of trunk bend, the lumbar segments (L2-S1) are
179 flexed near to their maximal range. In the present study, which includes both patients and controls,
180 the L5-S1 contribution at maximum was significantly lower in patients (Table 2) and significantly less
181 than all other levels (Figure 7).

182 Discussion:

183 There were consistent but non-significant differences between patient and control motion sharing
184 patterns. This lack of significance may be due to the range of L2-S1 motion of patients' spines being
185 significantly less, particularly at the lower levels. The results also illustrate the effects of loading and
186 muscle activity on the differences between lumbar flexion and return motion in controls and
187 patients with CNSLBP. Widmer et al (2019) considered that contributions to flexion motion may be
188 RoM dependent and this is consistent with our findings, where patients had lower L2-S1 RoM
189 ($p=0.046$) and a lower contribution at maximum bend at L5-S1 ($p=0.046$). Thus, while calculating
190 intersegmental motion sharing metrics allows for standardised comparisons between cohorts and
191 has become the preferred method for doing so with a range of subjects, (Teyhen, Flynn et al. 2007,
192 Ahmadi, Maroufi et al. 2009, Aiyangar, Zheng et al. 2015, Christe, Redhead et al. 2016, Gombatto,
193 D'Arpa et al. 2017, Hemming, Sheeran et al. 2017, Papi, Bull et al. 2019) the more traditional
194 measurement of IV-RoM may still give valuable insights into the reasons why patient and control
195 motion patterns differ.

196 Our previous studies of passive recumbent proportional motion did not dis-aggregate intervertebral
197 levels, but unlike this study, did find MSI to be significantly higher in patients (Breen and Breen 2018,
198 Breen, Mellor et al. 2018). While the expression of motion in a single summary number is of limited
199 value in terms of interpretation, it has the advantage of indicating components for further
200 consideration of their possible relevance to pain or disability. For example, this study found
201 significant differences between patients and controls' Average Motion Share (AvMS) at L3-L4, which
202 is not revealed in IV-RoM data (Figures 4 & 8 and Table 2). The differences between these
203 populations that were found in this study may be due to any combination of contributions from
204 behavioural influences on bending strategy, involuntary muscle activity and/or changes in passive
205 tissue restraint. For example, the increased variability of motion sharing in patients (MS(L)V at L4-5,
206 $p=0.021$) may be consistent with the work of Du Rose et al (du Rose, Breen et al. 2018), who
207 measured local and global lumbar sEMG activity during bending in controls and found that it

208 correlated negatively with MSV. Considered in relation to patients, this may suggest a guarding
209 effect. This present study did not include muscle oxygenation or electrical activity, which could shed
210 considerable light on these issues.

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

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

222 The dynamic interactions between lumbar intervertebral motion segments during weight bearing
223 flexion and return were found to be different in patients with CNSLBP compared to healthy controls.
224 However, although global motion of participants in both groups were 60°, L2-S1 maximum range
225 was lower in patients, while individual level contributions changed during the motion and seem to
226 be RoM dependent. Therefore, it is unsurprising that only L5-S1 was significantly different between
227 groups in terms of motion sharing metrics. However, there also appears to be less variability in the
228 motion contributions of different levels in patients, although these were not significant in these
229 small populations. This lower variance in patients, particularly during return from full flexion, may be
230 related to increased muscle contraction. Therefore, muscle workload needs to be verified and/or
231 explained by further studies, with larger populations that dis-aggregate the outward and return
232 paths of motion. These could include muscle electrical activity and oxygenation alongside kinematics
233 and loading as well as comparisons with passive recumbent protocols within which muscle activity
234 and loading are likely minimal. Moreover, we acknowledge that agglomerating data into a summary
235 numbers such as MSI and AvMS is a potential limitation that may over simplify the findings of this
236 study. Indeed, there is potential for a secondary analysis in which continuous data are scrutinised,
237 (for example, using Statistical Parametric Mapping (Pataky, Robinson et al. 2013)) however, this
238 would be beyond the scope of this study.

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241 9 were kindly supplied by Jonas Widmer of the Department of Orthopaedics, University of
242 Zurich originally collated by Widmer and his colleagues as part of their recent systematic
243 review (Widmer, Fornaciari et al. 2019)

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