Comparison of intra subject repeatability of quantitative fluoroscopy and static radiography in the measurement of lumbar intervertebral flexion translation

Alexander Breen1, Emilie Claerbout1, Rebecca Hemming2, Ravi Ayer3 & Alan Breen4*

Low back pain patients are sometimes offered fusion surgery if intervertebral translation, measured from static, end of range radiographs exceeds 3 mm. However, it is essential to know the measurement error of such methods, if selection for back surgery is going to be informed by them. Fifty-five healthy male (34) and female (21) pain free participants aged 21–80 years received quantitative fluoroscopic (QF) imaging both actively during standing and passively in the lateral decubitus position. The following five imaging protocols were extracted from 2 motion examinations, which were repeated 6 weeks apart: 1. Static during upright free bending. 2. Maximum during controlled upright bending, 3. At the end of controlled upright bending, 4. Maximum during controlled recumbent bending, 5. At the end of controlled recumbent bending. Intervertebral flexion translations from L2-S1 were determined for each protocol and their measurement errors (intra subject repeatability) calculated. Estimations using static, free bending radiographic images gave measurement errors of up to 4 mm, which was approximately twice that of the QF protocols. Significantly higher ranges at L4-5 and L5-S1 were obtained from the static protocol compared with the QF protocols. Weight bearing ranges at these levels were also significantly higher in males regardless of the protocol. Clinical decisions based on sagittal translations of less than 4 mm would therefore require QF imaging.

Low back pain is responsible for the world's largest number of days lost to disability1 and although its diagnosis is often problematical, it is agreed that mechanics generally, and segmental stability in particular, plays a significant role2–4. However, the measurement of segmental stability in patients is problematical due to lack of a unified concept of the condition. Yet while biomechanical measurements alone are not considered to be good predictors of prognosis, patients with sufficiently severe symptoms may be offered fusion surgery if intervertebral translation exceeds 4 mm5. There are many imaging methods for determining this, but practicality and economics dictates that it is generally performed using standing end-range radiographs6.

For this measurement, a radiograph is taken in the neutral standing position and then with the patient flexing forward as far as possible. This is repeated with the patient bending backwards into extension. On the resulting images lines are drawn on adjacent vertebrae from which to measure the translation or sliding movement between vertebrae. This is generally preferred by clinicians to angular movement for the assessment of stability7. However, it has long been recognised that inaccuracies and population variations using this technique may limit its usefulness and make selection of a cut off for excessive translation difficult6. Static views have also been found to underestimate intervertebral translation compared to dynamic imaging and the lateral decubitus position to better detect excessive motion in spondylolisthesis cases6,10. Furthermore, complexity increases if the patient also has spinal stenosis11 or if revision surgery is being considered12.

1Centre for Biomechanics Research, AECC University College, Parkwood Rd, Bournemouth, BH5 2DF, UK. 2Arthritis Research UK Biomechanics and Bioengineering Centre, School of Healthcare Sciences, Cardiff University, Eastgate House 35 - 43 Newport Road, Cardiff, CF24 0AB, UK. 3Radiology Department, Poole General Hospital NHS Foundation Trust, Longfleet Rd, Poole, BH15 2JB, UK. 4Faculty of Science and Technology Bournemouth University, Fern Barrow, Poole, BH12 5BB, UK. *email: alanbreen4@bournemouth.ac.uk
Recently, advances in fluoroscopic imaging have made it possible to register and track multi segmental vertebral image sequences throughout the entire motion. This method is called quantitative fluoroscopy (QF) and has been able to identify motion patterns that discriminate patients with chronic, nonspecific back pain from pain free controls\textsuperscript{13–17}. It has also been used to measure positional changes at individual levels, where for translation, it has been reported to have an accuracy of 0.1 mm and inter-observer repeatability of 1.1 mm (agreement) and ICC 0.533–0.988 (reliability)\textsuperscript{18,19}. Given the ubiquity of fluoroscopes in general hospitals, these might be repurposed to provide an alternative method for measuring inter vertebral translation in such patients.

Continuous standardised motion measurement has a number of potential advantages. First, although the motion is not ‘naturally performed’, controlled motion enables standardisation for trunk range, velocity, ramp up and ramp down speeds and is therefore potentially more reproducible. Second, QF can be conducted either actively weight-bearing or passively in recumbence, to avoid muscle contraction, or guarding, and to test the passive structures with minimal uncontrolled movement variation\textsuperscript{20}. Third, the option of a passive recumbent examination has the advantage of additional patient comfort, where upright bending may be inhibited by pain. Fourth, the range of translation may be measured at the end of the maximum range of the segment, which may not coincide with its range at the end of the trunk bending motion (Fig. 1).

As QF allows for a number of protocols for measuring intervertebral translation it was thought useful to assess the measurement properties of these in terms of random and intra subject variability for measuring maximum displacement. In addition, a direct comparison of end range vs through range translation is lacking, as is measurement during free and guided bending\textsuperscript{21}. The main aim of this study was to compare the intra subject variability, or measurement error, of 5 methods for measuring intervertebral flexion translation to determine the level of difference that could be detected by each. The evaluation of extension was not included as the standing range of lumbar spine extension is small (20°)\textsuperscript{22}.

Methods

Participants. Fifty-five healthy control participants were recruited from staff, students and visitors of the AECC University College (Bournemouth, UK). To be eligible, participants had to be aged 21–80 years, BMI < 30, with no history of previous back or abdominal surgery or spondylolisthesis, no medical radiation exposure of >8 mSV in the previous 2 years and no current pregnancy. Participants also had to have been free of any back pain that limited their normal activity for more than 1 day in the previous year. All imaging was carried out in accordance with AECC UC Local Rules and ethical approval was obtained from the National Research Ethics Service (South West 3, 10/H0106/65). Written Informed consent was obtained from all individual participants included in the study. All images of models were submitted with the express permission and signed informed consent of the model for publication of identifying information/images in an online open-access publication.

Data collection. Participants (median age 30 years, range 21 to 69), received fluoroscopic imaging of their lumbar spines during both lying (passive recumbent) and standing (weight-bearing guided) flexion. In passive recumbent flexion. For passive imaging they lay unconstrained in the lateral decubitus position on a motorised table that flexed their upper body to 40° flexion and return during fluoroscopic screening (Atlas Clinical Ltd.) (Fig. 2a). They were then imaged whilst weight-bearing, standing with their right side against the motion frame (Fig. 2b). With their pelvisses stabilised and during active voluntary motion, participants were guided through a standardised range of 60° standing flexion and return by a moving arm. The motion controllers accelerated at 6°s\textsuperscript{-2} for the first second followed by a uniform 6°s\textsuperscript{-1} thereafter. The guiding arm was then removed, and the participants were asked to bend forward freely to the end of their comfortable range (weight-bearing unguided flexion) (Fig. 2c). Single fluoroscopic images were obtained at the beginning and end of the weight-bearing unguided flexion motion. Fluoroscopic motion sequences were recorded at 15 Hz using a Siemens Arcadis Avantic digital C-arm fluoroscope (Siemens GMBH) and stored in DICOM format. They were then exported to a computer workstation and analysed using manual first image registration (Fig. 3) and thereafter using bespoke
frame-to-frame tracking using codes written in Matlab (V2011a, The Mathworks Inc). These measurements were repeated 6 weeks later by the same operator using the same equipment at approximately the same time of day for the determination of intra-subject measurement error.

**Image analysis.** Sagittal plane translation was calculated using the method of Frobin et al. in vertebral body units (VBU) which were converted to millimetres for presentation by multiplying the result by 35 - the standard chosen for vertebral body depth in millimetres. In order to address the degree of translation that could be considered excessive, sagittal plane translation of each intervertebral level from L2-S1 was determined and the levels pooled to provide means and upper reference ranges of variation (± 1.96 SD) for the following five measurement protocols:

1. Maximum IV translation during passive recumbent flexion
2. IV translation at maximum bend of passive recumbent flexion
3. Maximum IV translation during guided weight-bearing flexion
4. IV translation at maximum bend of guided weight-bearing flexion
5. IV translation at maximum bend of unguided weight-bearing flexion (reflective of traditional static radiograph acquisition)

**Statistical analysis.** All data were tested for normality using the Shapiro-Wilk test. The significance of differences was calculated using 2-way paired t-tests for normally distributed data and the Wilcoxon test for non-normal data. Repeatability was calculated using the following formula, where $S_w$ is the within-subject
The median effective dose received per participant was 0.27 mSv for weight bearing motion (range 0.20–0.68), 0.18 mSv for recumbent motion (range 0.11–0.31) and 0.04 mSv for single frame maximum bend images (range 0.01–0.09).

### Discussion

This research found that static radiographs gave twice the measurement error of QF and higher L4-5 and L5-S1 ranges when used to measure flexion translation. In effect, this means that it is not possible to detect translation of under 4 mm using static radiographs, 2.5 mm using weight bearing QF or 2.0 mm using recumbent QF.

Furthermore, the normative ranges for each protocol are different for males and females, but not in older people.

The least population variability and measurement error was found when participants were imaged during passive recumbent motion, as has been recommended for the detection of excessive translation in spondylolisthesis.

### Table 1. Translation ranges, reliability and measurement error for five measurement protocols (L2-S1 pooled data).

| Measurement                      | Protocol               | n  | Median translation (IQR) mm | Reliability | Measurement error |
|----------------------------------|------------------------|----|-----------------------------|-------------|-------------------|
|                                  |                        |    | Baseline | Follow up | ICC$_{3,1}$ (95% CI) | MDC$_{95}$ |
| During motion 40 deg             | Passive recumbent       | 219 | 0.74 (0.69) | 0.86 (0.78) | 0.639 (0.528, 0.724) | 1.33 |
| End of motion 40 deg             | Passive recumbent       | 219 | 0.74 (0.58) | 0.86 (0.53) | 0.611 (0.486, 0.706) | 1.43 |
| During motion 60 deg             | Active weight bearing   | 216 | 1.21 (1.26) | 1.21 (1.37) | 0.550 (0.413, 0.655) | 1.97 |
| End of motion 60 deg             | Active weight bearing   | 216 | 1.22 (1.05) | 1.31 (1.08) | 0.782 (0.715, 0.833) | 2.14 |
| End of uncontrolled flexion      | Active weight bearing   | 200 | 1.54 (1.42) | 1.47 (1.67) | 0.697 (0.605, 0.768) | 3.36 |

The association between test-retest differences and their means was assessed using Kendall's tau. As no significant and/or substantial associations were found, the data were not transformed for the calculation of MDC$_{95}$.
The 4 mm measurement error for weight bearing, static, unguided, end of range measurements was especially applicable to L4-5 and L5-S1. These levels are frequently of interest in terms of translatory slip, however, this may be uncommon in back pain populations. A recent study of aberrant motion in chronic, nonspecific back pain did not find translation to be greater in patients than healthy controls. Even in patients with spondylolisthesis, excessive translation is also not necessarily a feature, while in older individuals with degenerative spinal stenosis, bone loss, arthritic outgrowth and vertebral mal-alignment may make the measurement of translation using any current form of radiographic imaging additionally problematical.

The tendency for static views, acquired at the end of trunk motion, to give different values from QF may be thought to be because the range of trunk motion at the end of a weight-bearing unguided flexion motion could be greater than 60°, which is the standard range of flexion used for standing guided weight-bearing QF. However, free bending resulted in only approximately 0.5 mm greater translation than controlled bending to 60°. Indeed, the median ranges of translation found in this study, by all of the protocols, compare favourably with those found in a separate study of healthy volunteers. However, studies of intervertebral translation in back pain patients have concluded that it is related to age and disc height, it does not differentiate patients from controls. This may be partially a result of the uncontrolled variation associated with current measurement methods. However, composite disc degeneration throughout the lumbar spine has been associated with disproportionate sharing of angular motion between the lumbar spine segments in chronic, nonspecific back pain patients. Thus, it may be that it is the distribution of degenerated discs in the lumbar spine, rather than large changes in ranges of motion at individual levels, that is most closely associated with symptoms in chronic, nonspecific low back pain.

Finally, the qualitative use of fluoroscopy tends to be associated with prolonged exposures, raising the expectation of higher radiation dosage. However, the QF protocols are, by definition, quantitative and in this study resulted in effective radiation dosages of less than 0.3 mSv each. This is considerably less than the 1.3 mSv quoted as the typical effective dose expected for a series of X-rays of the lumbar spine for diagnostic purposes. This makes continued use of plain radiographs difficult to justify for most cases where degrees of increased translation that are not measurable might be acted upon.
Limitations. The present study did not include extension motion; however, its purpose was to compare radiographic techniques for their measurement properties while minimising radiographic exposure. The levels considered also did not include L1 because the intensifier diameter was too small to permit it.

Further work. These methods, although tested on a healthy asymptomatic population here, have also been utilised to evaluate back pain populations\(^1\)\(^6\)\(^17\). Therefore, this study should be repeated in symptomatic cohorts to establish repeatability and variability of translation.

Conclusion
Quantitative fluoroscopic measurement of lumbar intervertebral flexion translation in healthy control participants during passive recumbent QF gave significantly lower values than static, weight-bearing unguided imaging. It also resulted in lower population variation and approximately half the measurement error, which for static images during uncontrolled motion was in the region of 4 mm. Thus, clinical decisions based on smaller amounts of sagittal translation would require QF imaging.

Received: 15 May 2019; Accepted: 2 December 2019; Published online: 17 December 2019

References
1. Hoy, D. et al. The global burden of low back pain: estimates from the Global Burden of Disease 2010 study. Annals of Rheumatic Diseases 73, 968–974 (2014).
2. Borenstein, D. Mechanical low back pain - a rheumatologist's view. Nature review. Rheumatology 9, 643–653 (2013).
3. Barz, T. et al. A conceptual model of compensation/decompensation in lumbar segmental instability. Medical Hypotheses 83, 312–316 (2014).
4. Panjabi, M. M. A hypothesis of chronic back pain: ligament subfailure injuries lead to muscle control dysfunction. European Spine Journal 15, 668–676 (2006).
5. Leone, A., Guglielmi, G., Cassar-Pullicino, V. N. & Bonomo, L. Lumbar intervertebral instability: a review. Radiology 245, 62–77 (2007).
6. Mannion, A. F. et al. Development of appropriateness criteria for the surgical treatment of symptomatic lumbar degenerative spondylolisthesis (LDS). European Spine Journal 23, 1903–1917 (2014).
7. Iguchi, T. et al. Lumbar instability and clinical symptoms. Which is the more critical factor for symptoms: sagittal translation or segment angulation? J Spinal Disord Tech 17, 284–290 (2004).
8. Dvorak, J., Panjabi, M. M., Chang, D. G., Theiler, R. & Grob, D. Functional radiographic diagnosis of the lumbar spine. Flexion-extension and lateral bending. Spine 16, 562–571 (1991).
34. Breen, A., Hemming, R., Mellor, F. & Breen, A. Intrasubject repeatability of

33. Public Health England. Patient dose information: guidance; Available from: https://www.gov.uk/government/publications/medical-

32. Von Forell, G. A., Stephens, T. K., Samartzis, D. & Bowden, A. E. Low Back Pain: A Biomechanical Rationale Based on “Patterns” of

31. Taghipour-Darzi, M., Takamjani, E. E., Salavati, M., Mobini, B. & Zekavat, H. The validity of vertebral translation and rotation in

29. Staub, B. N., Holman, P. J., Reitman, C. A. & Hipp, J. Sagittal plane lumbar intervertebral motion during seated flexion-extension

26. Yone, K. & Sakou, T. Usefulness of Posner’s Definition of Spinal Instability for Selectionof Surgical Treatment for Lumbar Spinal

20. Santos, E. R. G., Goss, D. G., Morcom, R. K. & Fraser, R. D. Radiological assessment of interbody fusion using carbon fibre cages.

19. Breen, A. C. et al. Measurement of inter-vertebral motion using quantitative fluoroscopy: Report of an international forum and

18. Breen, A. & Breen, A. Accuracy and repeatability of quantitative fluoroscopy for the measurement of sagittal plane translation and

17. Breen, A., Mellor, F. & Breen, A. Aberrant intervertebral motion in patients with treatment-resistant non-specific low back pain: a

16. Breen, A. & Breen, A. Uneven intervertebral motion sharing is related to disc degeneration and is greater in patients with chronic, non-specific low back pain: an in vivo, cross-sectional cohort comparison of intervertebral motions using quantitative fluoroscopy. Eur Spine J 27, 145–153, https://doi.org/10.1007/s00586-017-5155-y (2018).

15. Ahmadi, A., Maroufi, N., Behtash, H., Zekavat, H. & Parianpour, M. Kinematic analysis of dynamic lumbar motion in patients with lumbar segmental instability using digital videofluoroscopy. European Spine Journal 18, 1677–1685 (2009).

14. Mellor, F. E., Thomas, P., Thompson, P. & Breen, A. C. Proportional lumbar spine inter-vertebral motion patterns: A comparison of

13. Breen, A. & Breen, A. Mid-range dynamic lumbar instability not evident on static clinical radiographs. European Spine Journal 17, 752–762 (2008).

12. Eisenstein, S. B. A. In 10th International Conference for the Failed Back. 1–11.

11. Liang, H.-F., Liu, S.-H., Chen, Z.-X. & Fei, Q.-M. Decompression plus fusion versus decompression alone for degenerative lumbar spondylolisthesis: a systematic review and meta-analysis. European Spine Journal 26, 3084–3095 (2017).

10. Wood, K. B., Popp, C. A., Transfeldt, E. E. & Geissele, A. E. Radiographic evaluation of instability in spondylolisthesis. Spine 19, 1697–1703 (1994).

9. Dombrowski, M. E. et al. ISSLE Prize in Bioengineering Science 2018: dynamic imaging of degenerative spondylolisthesis reveals mid-range dynamic lumbar instability not evident on static clinical radiographs. European Spine Journal 27, 752–762, https://doi.org/10.1007/s00586-018-5489-0 (2018).

8. Santos, E. R. G., Goss, D. G., Morcom, R. K. & Fraser, R. D. Radiological assessment of interbody fusion using carbon fibre cages. Spine 28, 997–1001 (2003).

7. Blain, N., Altman & D. G. Statistics Notes: Measurement error. British Medical Journal 313 (1996).

6. Van Herp, G., Rowe, P., Salter, P. & Paul, J. P. Three-dimensional lumbar spinal kinematics: a study of range of movement in 100 healthy subjects aged 20 to 60 years. Rheumatology 39, 1337–1340 (2000).

5. Frobin, W., Brincmann, P., Biggemann, M., Tillotson, M. & Burton, K. Precision measurement of disc height, vertebral height and sagittal plane displacement from lateral radiographic views of the lumbar spine. Clinical Biomechanics 12, S22–S30 (1997).

4. Nizard, R. S., Wybier, M. & Laredo, J.-D. Radiologic Assessment of Lumbar Intervertebral instability and degenerative spondylolisthesis. Radiologic Clinics of North America 39, 55–71 (2001).

3. Posner, I. R. A., White, A. A., Edward, W. T. & Hayes, W. C. A biomechanical analysis of the clinical stability of the lumbar and lumbosacral spine. Spine 7, 374–389 (1982).

2. Yone, K. & Sakou, T. Usefulness of Posner’s Definition of Spinal Instability for Selectonof Surgical Treatment for Lumbar Spinal Stenosis. Journal of Spinal Disorders 12, 40–44 (1999).

1. Frobin, F., Brinckmann, P., Lievseth, G., Biggemann, M. & Reikeras, O. Precision measurement of segmental motion from flexion-extension radiographs of the lumbar spine. Clinical Biomechanics 11, 457–463 (1996).

Acknowledgements
Prof. Alan Breen received a project grant from the European Chiropractors Union Research Fund (ECURF), and Dr Rebecca Hemming received a Seedcorn Bursary from the Cardiff Institute of Tissue Engineering and Repair (CITER).

Author contributions
The studies were designed by Ax.B, AL.B and R.A. Data and Figures were acquired by Ax.B, E.C and AL.B. Data were analysed by them and R.H. The manuscript was drafted by Ax.B. and edited by R.H., R.A., E.C and AL.B. All authors reviewed the manuscript.

Competing interests
I declare that the authors have no competing interests as defined by Nature Research, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

Additional information
Correspondence and requests for materials should be addressed to A.B.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.
