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| Journal: MEDICAL ENGINEERING & PHYSICS | Title of Paper: Accuracy and repeatability of quantitative fluoroscopy for the measurement of sagittal plane translation and instantaneous axis of rotation in the lumbar spine |

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Ethical Approval

Work on human beings that is submitted to *Medical Engineering & Physics* should comply with the principles laid down in the Declaration of Helsinki; Recommendations guiding physicians in biomedical research involving human subjects. Adopted by the 18th World Medical Assembly, Helsinki, Finland, June 1964, amended by the 29th World Medical Assembly, Tokyo, Japan, October 1975, the 35th World Medical Assembly, Venice, Italy, October 1983, and the 41st World Medical Assembly, Hong Kong, September 1989. You should include information as to whether the work has been approved by the appropriate ethical committees related to the institution(s) in which it was performed and that subjects gave informed consent to the work.

Competing Interests

The authors have performed research for the Ortho Kinematics Company, which is commercialising a version of this technology in the United States..

Please state any sources of funding for your research

No external funding was obtained for this research.

DOES YOUR STUDY INVOLVE HUMAN SUBJECTS? Please cross out whichever is not applicable.

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If your study involves human subjects you MUST have obtained ethical approval.
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Ethical approval was given by the National Research Ethics Service (REC reference 0/H0502/99).

This information must also be inserted into your manuscript under the acknowledgements section prior to the References.

1 **Accuracy and repeatability of quantitative fluoroscopy for the measurement of sagittal**
2 **plane translation and finite centre of rotation in the lumbar spine**

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9

10   **Abstract**

11   Quantitative fluoroscopy (QF) was developed to measure intervertebral mechanics *in vivo*

12   and has been found to have high repeatability and accuracy for the measurement of

13   intervertebral rotations. However, sagittal plane translation and finite centre of rotation

14   (FCR) are potential measures of stability but have not yet been fully validated for current QF.

15   This study investigated the repeatability and accuracy of QF for measuring these variables.

16   Repeatability was assessed from L2-S1 in 20 human volunteers. Accuracy was investigated

17   using 10 consecutive measurements from each of two pairs of linked and instrumented dry

18   human vertebrae as reference; one which tilted without translation and one which translated

19   without tilt.   The results found intra- and inter-observer repeatability for translation to be

20   1.1mm or less (SEM) with fair to substantial reliability (ICC 0.533-0.998). Intra-observer

21   repeatability of FCR location for inter-vertebral rotations of 5° and above ranged from 1.5mm

22   to 1.8mm (SEM) with moderate to substantial reliability (ICC 0.626-0.988). Inter-observer

23   repeatability for FCR ranged from 1.2mm to 5.7mm, also with moderate to substantial

24   reliability (ICC 0.621-0.878). Reliability was substantial (ICC>0.81) for 10/16 measures for

25   translation and 5/8 for FCR location. Accuracy for translation was 0.1mm (fixed centre) and

26   2.2mm (moveable centre), with an FCR error of 0.3mm(x) and 0.4mm(y) (fixed centre). This

27   technology was found to have a high level of accuracy and with a few exceptions, moderate

28   to substantial repeatability for the measurement of translation and FCR from fluoroscopic

29   motion sequences.

30

31

Introduction

The *In vivo* measurement of intervertebral motion in the lumbar spine in individuals has been progressing. This information has traditionally been obtained as displacement on flexion-extension radiographs, however, this has been consistently found to be prone to large errors and variability between observers [1-5]. The method also suffers from the inability to detect the true end-range during motion and lack of standardised measurement methods [6].

Studies of quantitative fluoroscopy (QF) for measuring lumbar spine intervertebral kinematics using continuous motion tracking began in the 1980s [7]. QF measures continuous intervertebral motion and extracts end of range measurement from wherever it occurs in the bending sequence, giving a radiation dose similar to a conventional radiographic examination [8, 9]. Various iterations have been found to have good repeatability and accuracy for measuring intervertebral rotations at lumbar and cervical levels [5, 9-12]. However, excessive translation is thought to be more closely associated with back symptoms [13]. Translation also affects the finite centre of rotation (FCR) and the latter is an expression of the distribution of loading between the disc and facets during upright flexion-extension motion [14]. It is also said that the centre of reaction force (CR) can be extrapolated from the FCR [14].

QF technology employs standardised image registration and analysis protocols with relatively straightforward and inexpensive hardware in contrast to specialist MR, CT or dual fluoroscopic systems which are not as readily available in hospital settings. However, the literature addressing the repeatability and accuracy of translation and FCR measurement from fluoroscopy is based on different techniques. For example, Cerciello et al determined the accuracy of measuring intervertebral rotation and FCR location in 2-D using stepped positions in a calibration specimen rather than from continuous motion [15]. Wang et al and Lin et al determined the accuracy of translation measurement in ovine specimens using 2D-3D dual fluoroscopic systems where the geometry was informed by magnetic resonance or CT-based vertebral models of the same participant rather than a calibrated reference [16, 17]. These studies also found excellent accuracy - and in the case of Wang et al good repeatability - for translation measurement. However, they involved greater radiation dose and expense, while Yeager et al found good repeatability for pooled vertebral levels using a less elaborate low-dose 2-D clinical QF system, but did not assess levels individually [5, 18].

The validation of QF technology for *in vivo* translation and FCR measurement from continuous motion sequences is therefore incomplete. The aim of this study was to determine the current accuracy and repeatability of 2-D QF for measuring lumbar inter-

66 vertebral translation and FCR location during motion using a standardised patient motion

67 protocol. This research involved the use of two calibrated human cadaveric specimens to

68 assess accuracy during sagittal plane motion in a prescribed pathway and repeatability in

69 twenty volunteers executing a standardised bending protocol.

70 **Methods**

71 ***Accuracy study***

72 Two sets of dry cadaveric vertebral pairs were used to provide reference data. Specimen A

73 (Fig 1A) consisted of L4 and L5 vertebrae joined at their end-plate centres by a universal

74 joint 4mm high, representing a fixed centre of rotation with zero translation. Specimen B (Fig

75 1B) comprised of L3 and L4 vertebrae. These were joined at their end-plate centres by a

76 plastic linkage which allowed translation of the upper vertebra without rotation. It was driven

77 by an actuator motor and controller (Arduino Software Ltd. UK – resolution 0.01mm)

78 providing anterior to posterior translation across the lower vertebral end-plate during the

79 rotation.

80 Both specimens were mounted on rigid bases and positioned 15 cm from a motion frame

81 which incorporated a rotating disc (Fig 1 A and B). The central ray of a C-arm digital

82 fluoroscope (Siemens Arcadis Avantic – Siemens GMBH, Germany) was positioned so as to

83 pass through the centre of the disc space. A block of animal soft tissue was interposed

84 between the X-ray source, the models and the fluoroscope's image intensifier to degrade the

85 images by generating soft tissue scatter.

86 Fig 1A and B about here

87 The superior vertebra of specimen A was rotated to 18° of flexion and return representing an

88 arbitrary physiological maximum measured using a tilt sensor (Axminster instruments UK–

89 resolution +/- 0.002 degrees) [19]. This was done using a rod driven by a vertical rotating

90 disc embedded in a vertical motion frame (Fig 1A). It was controlled and driven by a laptop

91 computer using bespoke software (Daqfactory VSC – Heatherose Electronics Ltd. UK). The

92 superior vertebra of Specimen B was translated posteriorly across 50% of the lower

93 vertebral end-plate and back again. This was an arbitrary range designed to allow direct

94 comparison between the reference and index values, which should apply, within reason, no

95 matter how large or small the translation. Rotation was at 3°/sec and translation at

96 1.5mm/sec. These procedures were repeated 10 times for each specimen. Images were

4

97 recorded at 15 frames per second during the 10 sequences for each specimen.   All image

98 sequences were analysed by one trained observer.

99 *Repeatability study*

100 Data were obtained from a parallel study of twenty volunteers being examined for passive

101 recumbent lumbar motion [9]. These were recruited using the eligibility criteria described in

102 Table 1 and following a favourable opinion from the National Research Ethics Service (REC

103 reference 0/H0502/99).   Each participant was positioned in the lateral decubitus position on

104 a horizontal motion frame with the central ray of the fluoroscope positioned to pass through

105 the L4 vertebra (Fig 2). The inferior section of the motion frame was rotated through 40° of

106 flexion over a 12 second interval using the motion controller (Daqfactory VSC – Heatherose

107 Electronics Ltd, UK). This was immediately followed by 40° of extension. The effective

108 radiation dose for this procedure has been estimated as 0.24mSv [18].

109   Table 1 about here

110   Fig 2 about here

111 After transfer of images from the fluoroscope to an image processing workstation, two

112 trained observers (a senior radiographer and a medical physicist) analysed the same 40

113 image sequences for inter-observer repeatability (two sequences per participant for the 20

114 participants**).** Five repeated mark-ups of flexion and extension images of intervertebral

115 levels from L2-S1 took approximately 20 minutes. Observers were blinded to each other's

116 image registrations. The second observer also analysed each image sequence twice for

117 intra-observer repeatability.

118 *Kinematic data extraction*

119 The fluoroscopic sequences were transferred to a desktop computer and Image J (v 1.47 for

120 Windows OS) was used to separate the individual images from the digital sequences. The

121 images underwent user defined edge enhancement, after which templates were manually

122 placed five times around each vertebral body (L2–S1) in the first image. Bespoke software

123 written in Matlab (V R2007b, The Mathworks Inc.) used a cross-correlation method to obtain

124 automated frame to frame image tracking of the vertebral bodies in subsequent images [20].

125 Co-ordinates were placed on the vertebral body corners in the first image, linked to the

126 tracking templates and used to register the vertebrae in two dimensional space in each

127 frame. Tracking was verified for quality assurance by viewing all sequences and repeating

128 any tracking that failed.

129

130 The displacements between each pair of tracked positions were calculated using Distortion

131 Compensated Radiographic Analysis [21]. These were averaged over 25 registration

132 combinations and output as data series'. (Fig 3). Each data series was inspected for

133 tracking failure using video playback. Any failed tracking data were removed and if all

134 templates failed, the data were not used in the analysis.

135   Fig 3 about here

136 *Translation calculation*

137 Frobins method [21] for calculating translation (shown in Figures 4 and 5 A & B) is based on

138 landmarks identified on the vertebral body 'corners'. Vertebral midlines (Fig. 4) are defined

139 as lines passing through the midpoints between corners 1-2 and 3-4 respectively.

140   Fig 4 about here

141 The average gradient and y axis crossover of the two midlines are calculated for a vertebral

142 pair. The resultant line is called the bisectrix and normally passes through the inter-vertebral

143 disc space.

144 Using the method depicted in Figure 5, a line is drawn from the centre of each vertebra to

145 the coinciding bisectrix. These lines intersect the bisectrix at 90 degrees to the bisectors'

146 gradient.

147   Fig 5 A and B about here

148 Translation was calculated as the distance along the bisectrix between the points at which

149 these two lines independently cross the bisectrix (Fig 5). To standardise this measurement

150 this is given as a proportion of the mean vertebral body depth of the superior vertebra, where

151 1 VBU (vertebral body unit) is the mean of the upper and lower vertebral body end plate

152 depth of the superior vertebra. For the *in vivo* studies VBUs were converted to millimetres

153 based on a standard vertebral depth of 35mm and for the specimens by their actual

154 measurement.

155 *FCR calculation*

156   The FCR position and distance from the posterior superior corner of the inferior vertebral
157   body was calculated by finding the least squares solution between the four corners and the
158   corresponding co-ordinates on the subsequent image [22] (Fig 5 A and B).

159   The four corner reference template positions for two adjacent vertebrae were taken and re-
160   positioned so that the inferior vertebral position was superimposed. From these coordinate
161   positions, the centre of rotation between the two images was calculated by finding the least
162   squares solution between each of the four corners and their partners from the second image.
163   The least squares solution was taken as described by McCane et al [22] which gives the
164   Matlab script used to execute this calculation. The positions at which each of these least
165   squares solutions meet was taken as the FCR for those two vertebrae between those two
166   images. The axis of rotation was then displayed relative to the inferior vertebra in a pair as a
167   function of the four- corner template on the inferior vertebra. The superior-posterior corner of
168   the inferior vertebra was taken as the origin for this reference field where the X-axis is along
169   the template on the superior vertebral border and the Y-axis perpendicular to the X-axis
170   passing though the origin. The unit of distance used was the proportion of the average
171   vertebral body depth of superior vertebra (due to the non-uniform shape of the sacral
172   template) where the origin of this co-ordinate system is the anterior-superior corner of the
173   inferior vertebra.

174   FCR positional data were calculated at the maximum rotation angle between any two
175   template positions where the inter-vertebral angle was greater than 5 degrees as a cut-off -
176   as when intervertebral rotation interval decreases, the variation in FCR position increases.
177   This is a systematic error due to the way in which the FCR positions are calculated. FCR
178   was measured continuously between the first frame of the image sequence and the image
179   frame where angular rotation was at its maximum +/- 0.5^o. The limit of +/- 0.5^o was selected
180   as this was the increment through which the tracking templates rotated when calculating
181   vertebral body position within each image. The results were taken as the average position of
182   the FCR in X and Y co-ordinates over the 5 trackings.

183   Fig 6 A and B about here

184   ***Statistical analysis***

185   For the accuracy study, 10 sets of markings were performed for each specimen. Measured
186   translation was compared with zero translation reference data in the fixed centre specimen
187   (end plate depth 28.77mm) and with translation across 50% of the inferior end plate (depth
188   34.66mm) in the moveable centre specimen. Disagreement was expressed as the root-

189   mean-square (RMS) differences between measured and reference values for both

190   translation and FCR. 95% limits of agreement (LoA) were calculated and expressed in VBU

191   [23].

192   For the repeatability studies, 4 intervertebral levels (L2-S1) were analysed for both flexion

193   and extension translation for each of the 20 participants.   For FCR location, data were

194   removed from FCR analysis when rotation did not reach 5°. This range has been suggested

195   as the lowest over which intervertebral FCRs should be calculated from radiographs without

196   unacceptable error [24]. Therefore, in anticipation that not all levels would reach the

197   necessary 5°, the levels were pooled to give a maximum possible 80 observations for each

198   of flexion and extension. Intra and inter-observer reliability were expressed as intraclass

199   correlation coefficients ($ICC_{consistency}3,1$) using adjectives proposed by Shrout and Fleiss and

200   revised from the original scale of Landis and Koch [25, 26]. In the Shrout and Fleiss scale,

201   reliability as denoted by an ICC of 0.00-0.01 is considered as "virtually none", 0.11-0.40

202   "slight", 0.41-0.60 "fair", 0.61-0.80 "moderate" and 0.81-1.00 "substantial".

203   **Results**

204   *Accuracy*

205   The proportion of vertebral body depth that was translated in the moveable centre specimen

206   as measured by the actuator motor was 0.52 VBU (17.95mm). Table 2 shows the RMS

207   differences and 95% LoAs between the reference and measured translation and FCR

208   locations.

209   Table 2 about here

210   For the fixed centre of rotation specimen, the average discrepancy (RMS) in translation

211   range between reference and image data was 0.004 VBU (0.10mm) (LoA 0.01mm). For the

212   translating specimen, the discrepancy when the superior vertebra was translated across

213   50% of the end-plate of the lower one was 0.062 VBU (2.16mm) (LoA 0.52mm). For FCR,

214   the RMS x and y co-ordinate location differences between the reference and measured

215   locations in the fixed centre specimen were 0.009 VBU(x) or 0.25mm (LoA 1.30mm) and for

216   0.014 VBU(y) or 0.40mm (LoA 1.20mm). (Table 2). Bland-Altman plots for these are shown

217   in Fig 7 (A-D).

218   Fig 7 about here

219

220 *Repeatability*

221 The participant sample was made up of 9 females and 11 males aged 26 to 46 (mean age

222 35.7, SD 7.20). Their mean body mass index was 24.71 (SD 2.22).

223 Between 6 and 14 observations for each level in the 20 subjects were visible and tracked

224 successfully for translation. Not all levels and directions were visible or trackable in all

225 subjects. Artefacts due to the movement of bowel gas across images and tall patients

226 whose upper vertebral levels did not fit the image field) were the main causes of this. Intra

227 and inter-observer repeatability for each intervertebral level are shown in Table 3. All levels

228 and directions showed at least fair agreement and reliability. The best agreement was

229 between observers at L2-3 in extension (SEM=0.17mm) and the worst within observers at

230 L5-S1 in extension (SEM=1.14mm). The best reliability was within observers at L2-3 in

231 flexion ((ICC=0.998 (0.958-0.997)) and the worst within observers at L3-4 in flexion

232 ((ICC=0.533 (0.406-0.849)).

233   Table 3 about here

234 Repeatability results for FCR are shown in Table 4. Five degrees of rotation was reached by

235 30 intervertebral pairs. For both translation and FCR location, within observer disagreement

236 did not exceed 2mm for either flexion or extension. Inter-observer disagreement was high

237 for FCRy in extension (5.67mm**).** All directions otherwise showed moderate to substantial

238 reliability, the smallest ICC being 0.621 (0.429-0.813) for FCRx flexion between observers.

239   Table 4 about here

240 **Discussion**

241 Where mechanical impairment of intervertebral motion in the spine is at issue, its assessment

242 will depend on the availability of technology with which to perform standardised

243 measurements in patients during motion and to provide reference values and error estimates

244 for the various parameters.   This study is the first to assess the accuracy and level by level

245 repeatability of the measurement of sagittal plane translation and FCR location from moving

246 vertebral images using low dose 2-D QF. Its results indicate where the current strengths

247 and weaknesses in the technique lie when reporting results of patient studies to clinicians.

248 The accuracy of techniques for radiographic measurement of intervertebral kinematics has

249 been determined using calibration models for roentgen stereophotogrammetry, (which

250 although highly invasive, is sometimes considered the gold standard), biplanar radiography

251 and QF [10, 15, 27, 28]. In this study, idealised conditions were also avoided by degrading

252 the images with animal soft tissue and in the upright position, although It is not uncommon

253 for such studies to be undertaken with no loading or in an animal model with no tissue

254 degradation [16, 29, 30]

255 In this study, we compensated for radiographic image distortion using distortion-

256 compensated roentgen analysis and used an image intensifier that incorporated automatic

257 distortion correction [21]. Measurement is virtually independent of distortion of the

258 radiographic image resulting from central projection, axial rotation, lateral tilt, and off-centre

259 position with an error for translation of between 0.4 and 0.8mm. Measurement of translation

260 was determined from the vertebral body centres, making it independent of rotation. Previous

261 QF studies have also shown that degrading the alignment by axially rotating it 10° out of

262 plane and inclining the X-ray beam inclined 10° inferiorly results in minimal loss of accuracy

263 in rotational studies [10]. Thus the technique should be sufficiently accurate to give useful

264 information about ranges and motion patterns. However, this technique is not thought to be

265 possible in scoliotic spines due to failure of image tracking.

266 This study found the current QF method to have fair to substantial repeatability for all levels

267 and directions using the current protocol. It also found acceptable accuracy *in vitro* for the

268 measurement of FCR location and translation during continuous spinal motion. Reliability

269 was mainly good, but at some levels and directions suggests that training and quality

270 assurance are needed when applying the measurement to comparisons between individuals

271 and reference standards [31].

272 The inter-observer y-error in determination of FCR in extension (5.67mm) and the intra-

273 observer ICC (0.644) for extension translation at L5-S1 point to a need for caution. Closer

274 inspection of the data revealed that the former was also greatest at L5-S1, where image

275 quality and consequently co-ordinate placement may be rendered problematical by the

276 super-imposition of the ilia and/or lack of perfect orthogonal alignment of the central X-ray

277 beam with the vertical axis of the vertebrae. Previous work found radiographic positioning to

278 be more important than tracking accuracy as a contributor to the variability in measurement

279 of angular position, but that this does not preclude high repeatability and accuracy of

280 measurement of rotation [19, 48]. However, for translation and FCR this may be more

281 critical.

282 FCR was once thought to be promising as a way of assessing abnormal loading during

283 intervertebral motion in patients [32, 33] but fell out of favour owing to high errors in

284 measurement and the intrinsic computational errors that occur when rotational range is low

285   [24, 34-36]. The suggestion that it might be used to measure stability has therefore also not

286   generally been taken up [14].   However, the present study has shown that despite the use

287   of continuous motion data, as is necessary in patient studies, greater accuracy was achieved

288   for determining the FCR (average error 0.3mm$_x$, 0.4mm$_y$) than was found in a previous study

289   with such a specimen that used stepped rotation positions (average error 2mm)[15].

290   The repeatability study utilised information from participants undergoing passive recumbent

291   and not weight bearing motion. It may be thought that weight bearing Information would have

292   been preferable to study the repeatability of translation and FCR measurement. However,

293   this would have meant irradiating additional participants to obtain the same data and

294   differences in motion patterns associated with weight bearing should not affect their

295   measurement.   Indeed, Wood concluded that the lateral decubitus position was superior for

296   the detection of instability in patients with spondylolisthesis and Yeager et al used these

297   interchangeably for their repeatability analysis of rotation and translation at pooled levels [37]

298   [5].

299   FCR, at least in the sagittal plane, could therefore be used to inform both patient care and

300   patient-specific mathematical models. However, further studies are needed to establish

301   normative *in vivo* reference standards at individual levels using QF. It would also be

302   beneficial to explore the effects of spinal geometry and muscle contraction on FCR location,

303   to add coronal plane validation and to confirm whether the FCR locus might be used to

304   assess relationships between structural change and the *in vivo* biomechanical performance

305   characteristics of discs under load. Finally, rotational cut-offs for accurately locating the FCR

306   should be revisited in the light of the greater standardisation offered by QF protocols.

307   Diagnostic advances in spine biomechanics have also been made using kinetic MRI [37-41]

308   and SPECT-CT imaging [42, 43].   However, although kinetic MRI locates points of

309   encroachment on neural tissues and SPECT-CT contributes to the identification of potential

310   sites of pain generation, neither can extract end-range or continuous inter-vertebral motion.

311   In addition, the radiation dosage from SPECT-CT is considerably larger than that of QF.

312   Improvements in repeatability and accuracy are ongoing requirements for any diagnostic

313   test, which means that reference standards will always be imperfect. Validation of QF will

314   therefore require that scientists and practitioners also examine the extent to which test

315   results are meaningful in practice [44]. This may be appreciated from patient register data. In

316   parallel with this, technology development should address any measurement deficiencies.

317   **Limitations**

318   Participants with a BMI over 31 or aged over 51 were excluded from the study and none had

319   osteoporosis, osteoarthritic change, vertebral deformities or curvatures; which may

320   precipitate tracking failures. In the accuracy study, the translation error was considerably

321   higher (2.10mm) in the translating specimen than in the fixed specimen (0.10mm).   This

322   may have been due to the resolution of the actuator motor in the latter (0.01mm), or by a

323   small amount of out of plane motion due to imperfections in the mechanical linkage of this

324   specimen. However, this discrepancy is well below the generally accepted cut-off of 4mm

325   for excessive translation [45-48].

326   Distortion that changes during motion is not correctable if the templates that track the images

327   from frame to frame do not change to accommodate it. In the future, this could be provided

328   by adaptations to the tracking codes [8]. The US versions of this technology image the upper

329   and lower lumbar levels separately to minimise out of plane images and ensure inclusion of

330   all lumbar levels. While this increases the X-ray dose, it also makes for better

331   reliability in the measurement of translation than was found here [5].

332   Future studies of accuracy and repeatability are needed to substantiate the present work.

333   These could use a larger number of examiners, a range of rotational angles for FCR

334   accuracy and a more elaborate calibration set up that combines rotation and translation. A

335   larger number of human participants would overcome the problem of low angles of rotation

336   and enable determination of the level by level repeatability of FCR location at 5° and above.

337   For example, poorer agreement was found at L5-S1 than other levels, possibly owing to

338   lower image quality resulting from superimposition of both ilia on the vertebral images.

339   **Conclusion**

340   Quantitative fluoroscopy was found to have a high level of accuracy as well as moderate to

341   substantial observer agreement and reliability for the measurement of FCR and translation.

342   Exceptions were in the reliability of measuring translation at L3-4 and agreement between

343   observers in locating the FCR in extension. The development of reference standards and

344   analysis quality assurance measures will be essential for optimal clinical use [6].

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Competing Interests

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Ethical Approval

References

[1] Deyo RA, McNeish, L.M., Cone, R.O. 3rd. Observer variability in the interpretation of lumbar spine radiographs. Arthritis and Rheumatism. 1985;1528:1066-70.

[2] Shaffer WO, Spratt, K. F., Weinstein, J. D., Lehmann, T. R., Goel, V . 1990 Volvo Award in Clinical Sciences: The Consistency and Accuracy of Roentgenograms for Measuring Sagittal Translation in the Lumbar Vertebral Motion Segment: An Experimental Model. Spine. 1990;15:741-50.

[3] Penning L, Wilmink, J.T., Van Woerden, H.H. Inability to prove instability: a critical appraisal of clinical-radiological flexion-extension studies in lumbar disc degeneration. Diagnostic Imaging in Clinical Medicine. 1984;53:186-92.

[4] Cakir B, Richter, M., Kafer, W., Wieser, M., Puhl, W., Schmidt, R. Evaluation of lumbar spine motion with dynamic x-ray: a reliability analysis. Spine. 2006;31:1258-64.

[5] Yeager MS, Cook DJ, Cheng BC. Reliability of computer-assisted lumbar intervertebral measurement using a novel vertebral motion analysis system. The Spine Journal. 2014;14:274-81.

[6] Leone A, Guglielmi, G., Cassar-Pullicino, V. N., Bonomo, L. Lumbar intervertebral instability: a review. Radiology. 2007;245:62-77.

[7] Breen AC, Allen, R., Morris, A. An image processing method for spine kinematics-preliminary studies. Clinical Biomechanics. 1988;3:5-10.

[8] Breen A.C., Teyhan DS, Mellor FE, Breen AC, Wong KWN, Deitz A. Measurement of InterVertebral Motion Using Quantitative Fluoroscopy: Report of an International Forum and Proposal for Use in the Assessment of Degenerative Disc Disease in the Lumbar Spine. Advances in Orthopaedics. 2012;2012.

[9] Mellor F.E., Thomas P, Thompson P, Breen AC. Proportional lumbar spine inter-vertebral motion patterns: A comparison of patients with chronic non-specific low back pain and healthy controls. European Spine Journal. 2014;23:2059-67.

[10] Breen A, Muggleton J, Mellor F. An objective spinal motion imaging assessment (OSMIA): reliability, accuracy and exposure data. BMC Musculoskeletal Disorders. 2006;7:1-10.

[11] Breen A, Mellor F, Breen A. Lumbar Intervertebral Motion in Vivo: A Preliminary Comparison of Recumbent and Weight Bearing Motion Patterns in Adult Males. Bone and Joint Journal. 2013;95-B.

[12] Branney J, Breen AC. Does inter-vertebral range of motion increase after spinal manipulation? A prospective cohort study. Chiropractic & Manual Therapies. 2014;22:24.

[13] Iguchi T, Kanemura, A., Kasahara, K., Sato, K., Kurihara, A., Yoshiya, S., Nishida, K., Miyamoto, H., Doita, M. Lumbar instability and clinical symptoms. Which is the more critical factor for symptoms: sagittal translation or segment angulation? J Spinal Disord Tech. 2004;17:284-90.

[14] Bogduk N, Amevo, B., Pearcy, M. A Biological basis for instantaneous centres of rotation of the vertebral column. Proc Instn Mech Engineers. 1995;209:177-83.

[15] Cerciello T, Romano, M., Bifulco, P., Cesarelli, M., Allen, R. Advanced template matching method for estimation of intervertebral kinematics of lumbar spine. Medical Engineering and Physics. 2011;33:1293-302.

[16] Wang S, Passias P, Li G, Li G, Wood K. Measurement of Vertebral Kinematics Using Noninvasive Image Matching Method-Validation and Application. Spine. 2008;33:E355-E61.

[17] Breen AC, Mick T, Phillips RB. Spinal Imaging and the Practice of Chiropractic. In: (ed) SH, editor. Principles and Practice of Chiropractic. Norwalk, Connecticut: Apple Lange; 1992. p. 391-412.

[18] Mellor FE, Thomas P, Breen AC. Quantitative fluoroscopy for investigating in vivo kinematics of the lumbar spine; radiation dose compared to lumbar spine radiographs with suggestions for further dose reduction. Radiography. 2014;In press.

[19] 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. 1991;16:562-71.

[20] Muggleton JM, Allen, R. Automatic location of vertebrae in digitised videofluoroscopic images of the lumbar spine. Medical Engineering & Physics. 1997;19:77-89.

453   [21] Frobin F, Brinckmann, P., Lievseth, G., Biggemann, M., Reikeras, O. Precision measurement of
454   segmental motion from flexion-extension radiographs of the lumbar spine. Clinical Biomechanics.
455   1996;11:457-65.
456   [22] McCane B, Abbott, J.H., King, T. On calculating the finite centre of rotation for rigid planar
457   motion. Medical Engineering and Physics. 2005;27:75-9.
458   [23] Bland JM, Altman, D.G. Statistical methods for assessing agreement between two methods of
459   clinical measurement. The Lancet. 1986:307-10.
460   [24] Pearcy M, Bogduk, N. Instantaneous axes of rotation of the lumbar intervertebral joint. Spine.
461   1988;13:1033-41.
462   [25] Shrout PE. Measurement reliability and agreement in psychiatry. Statistical Methods in Medical
463   Research. 1998;7:301-17.
464   [26] Landis JR, Koch, G.G. The Measurement of Observer Agreement for Categorical Data.
465   Biometrics. 1977;33:159-74.
466   [27] Pearcy MJ. Stereoradiography of lumbar spine motion. Acta Orthopaedica Scandinavica.
467   1985;56:1-45.
468   [28] Selvik G. Roentgen stereophotogrammetry: a method for the study of the kinematics of the
469   skeletal system. Acta Orthopaedica Scandinavica. 1989;232 (Suppl):1-51.
470   [29] Zuhlke T, Fine, J., Haughton, V.M., Anderson, P.A. Accuracy of Dynamic Computed Tomography
471   to Calculate Rotation Occurring at Lumbar Spinal Motion Segments. Spine. 2009;34:E215-E8.
472   [30] Meetings of Interest for Spine Physicians and Surgeons. SO - Spine July/August 1986;11(6):656-
473   657.
474   [31] Knottner J., Audige L, Brorson S, Donner A, Gajewski BJ, Hrobjartsson A, et al. Guidelines for
475   Reporting Reliability and Agreement Studies (GRRAS) were proposed. Journal of Clinical
476   Epidemiology. 2011;64:96-106.
477   [32] Gertzbein SD, Seligman, J., Holtby, K. Centrode patterns and segmental instability in
478   degenerative disc disease. Spine. 1985;10:257-61.
479   [33] Seligman JV, Gertzbein, S.D., Tile, M., Kapasouri, A. Computer analysis of spinal segment motion
480   in degenerative disc disease with and without axial loading. Spine. 1984;9:566-73.
481   [34] Panjabi MM. Centres and angles of rotation of body joints: a study of errors and optimization.
482   Journal of Biomechanics. 1979;12:911-20.
483   [35] Soudan K, Van Audekercke, R., Martens, M. Methods, difficulties and inaccuracies in the study
484   of human joint kinematics and pathokinematics by the instant axis concept, example: the knee joint.
485   Journal of Biomechanics. 1979;12:27-33.
486   [36] Panjabi MM, Goel, V.K., Takata, K. Physiologic strains in the lumbar spinal ligaments. Spine.
487   1982;7:192-203.
488   [37] Wood KB, Popp, C.A., Transfeldt, E.E., Geissele, A.E. Radiographic evaluation of instability in
489   spondylolisthesis. Spine. 1994;19:1697-703.
490   [38] Hirasawa Y, Bashir WA, Smith FW, Magnusson ML, Pope MH, Takahashi K. Postural Changes of
491   the Dural Sac in the Lumbar Spines of Asymptomatic Individuals Using Positional Stand-Up Magnetic
492   Resonance Imaging. Spine. 2007;32:E136-E40.
493   [39] Kong MH, Hymanson, H.J., Song, K.Y., Chin, D.K., Cho, Y.E., Yoon, D.H., Wang, J.C. Kinetic
494   magnetic resonance imaging analysis of abnormal segmental motionof the functional spine unit.
495   Journal of Neurosurgery: Spine. 2009;10:357-65.
496   [40] Tan Y, Aghdasi BG, Montgomery SR, Inoue H, Lu C, Wang JC. Kinetic magnetic resonance imaging
497   analysis of lumbar segmental mobility in patients without significant spondylosis. European Spine
498   Journal. 2012;21:2673-9.
499   [41] Lao L, Daubs MD, Scott TP, Lord EL, Cohen JR, Tin R, et al. Effect of Disc Degeneration on Lumbar
500   Segmental Mobility Analyzed by Kinetic Magnetic Resonance Imaging. Spine. 2015;40:316-22.
501   [42] Harisankar CNB, Mittal BR, Bhattacharya A, Singh P, Sen R. Utility of single photon emission
502   computed tomography/computed tomography imaging in evaluation of chronic low back pain.
503   Indian Journal of Nuclear Medicine. 2012;27:156-63.

504   [43] Matar HE, Navalkissoor S, Berovic M, Shetty R, Garlick N, Casey ATH, et al. Is hybrid imaging
505   (SPECT/CT) a useful adjunct in the management of suspected facet jonts arthropathy? International
506   Orthopaedics. 2013;37:865-70.
507   [44] Breen AC, Morris A. Lumbar Spine Instantaneous Centres of Rotation Determined by Digital
508   Video-floroscopy. Society for Back Pain Resarch Annual Scientific Meeting. St Mary's Hospital,
509   London1989.
510   [45] Dupuis PR, Yong-Hing, K., Cassidy, J.D., Kirkaldy-Willis, W.H. Radiologic diagnosis of degenerative
511   lumbar spinal instability. Spine. 1985;10:262-76.
512   [46] Boden SD, Wiesel, S.W. Lumbosacral segmental motion in normal individuals - have we been
513   measuring instability properly? Spine. 1990;15:571-6.
514   [47] Morgan FP, King, I. Primary instability of lumbar vetebrae as a common cause of low back pain.
515   Journal of Bone and Joint Surgery. 1957;39B:6-22.
516   [48] Hanley EN. The indications for lumbar spinal fusion with and without instrumentation. Spine.
517   1995;20:143S-53S.

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519

1 **Accuracy and repeatability of quantitative fluoroscopy for the measurement of sagittal**
2 **plane translation and finite centre of rotation in the lumbar spine**

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9

Abstract

Quantitative fluoroscopy (QF) was developed to measure intervertebral mechanics *in vivo* and has been found to have high repeatability and accuracy for the measurement of intervertebral rotations. However, sagittal plane translation and finite centre of rotation (FCR) are potential measures of stability but have not yet been fully validated for current QF. This study investigated the repeatability and accuracy of QF for measuring these variables. Repeatability was assessed from L2-S1 in 20 human volunteers. Accuracy was investigated using 10 consecutive measurements from each of two pairs of linked and instrumented dry human vertebrae as reference; one which tilted without translation and one which translated without tilt. The results found intra- and inter-observer repeatability for translation to be 1.1mm or less (SEM) with fair to substantial reliability (ICC 0.533-0.998). Intra-observer repeatability of FCR location for inter-vertebral rotations of 5° and above ranged from 1.5mm to 1.8mm (SEM) with moderate to substantial reliability (ICC 0.626-0.988). Inter-observer repeatability for FCR ranged from 1.2mm to 5.7mm, also with moderate to substantial reliability (ICC 0.621-0.878). Reliability was substantial (ICC>0.81) for 10/16 measures for translation and 5/8 for FCR location. Accuracy for translation was 0.1mm (fixed centre) and 2.2mm (moveable centre), with an FCR error of 0.3mm(x) and 0.4mm(y) (fixed centre). This technology was found to have a high level of accuracy and with a few exceptions, moderate to substantial repeatability for the measurement of translation and FCR from fluoroscopic motion sequences.

Introduction

The *In vivo* measurement of intervertebral motion in the lumbar spine in individuals has been progressing. This information has traditionally been obtained as displacement on flexion-extension radiographs, however, this has been consistently found to be prone to large errors and variability between observers [1-5]. The method also suffers from the inability to detect the true end-range during motion and lack of standardised measurement methods [6].

Studies of quantitative fluoroscopy (QF) for measuring lumbar spine intervertebral kinematics using continuous motion tracking began in the 1980s [7]. QF measures continuous intervertebral motion and extracts end of range measurement from wherever it occurs in the bending sequence, giving a radiation dose similar to a conventional radiographic examination [8, 9]. Various iterations have been found to have good repeatability and accuracy for measuring intervertebral rotations at lumbar and cervical levels [5, 9-12]. However, excessive translation is thought to be more closely associated with back symptoms [13]. Translation also affects the finite centre of rotation (FCR) and the latter is an expression of the distribution of loading between the disc and facets during upright flexion-extension motion [14]. It is also said that the centre of reaction force (CR) can be extrapolated from the FCR [14].

QF technology employs standardised image registration and analysis protocols with relatively straightforward and inexpensive hardware in contrast to specialist MR, CT or dual fluoroscopic systems which are not as readily available in hospital settings. However, the literature addressing the repeatability and accuracy of translation and FCR measurement from fluoroscopy is based on different techniques. For example, Cerciello et al determined the accuracy of measuring intervertebral rotation and FCR location in 2-D using stepped positions in a calibration specimen rather than from continuous motion [15]. Wang et al and Lin et al determined the accuracy of translation measurement in ovine specimens using 2D-3D dual fluoroscopic systems where the geometry was informed by magnetic resonance or CT-based vertebral models of the same participant rather than a calibrated reference [16, 17]. These studies also found excellent accuracy - and in the case of Wang et al good repeatability - for translation measurement. However, they involved greater radiation dose and expense, while Yeager et al found good repeatability for pooled vertebral levels using a less elaborate low-dose 2-D clinical QF system, but did not assess levels individually [5, 18].

The validation of QF technology for *in vivo* translation and FCR measurement from continuous motion sequences is therefore incomplete. The aim of this study was to determine the current accuracy and repeatability of 2-D QF for measuring lumbar inter-

66 vertebral translation and FCR location during motion using a standardised patient motion

67 protocol. This research involved the use of two calibrated human cadaveric specimens to

68 assess accuracy during sagittal plane motion in a prescribed pathway and repeatability in

69 twenty volunteers executing a standardised bending protocol.

70 **Methods**

71 *Accuracy study*

72 Two sets of dry cadaveric vertebral pairs were used to provide reference data. Specimen A

73 (Fig 1A) consisted of L4 and L5 vertebrae joined at their end-plate centres by a universal

74 joint 4mm high, representing a fixed centre of rotation with zero translation. Specimen B (Fig

75 1B) comprised of L3 and L4 vertebrae. These were joined at their end-plate centres by a

76 plastic linkage which allowed translation of the upper vertebra without rotation. It was driven

77 by an actuator motor and controller (Arduino Software Ltd. UK – resolution 0.01mm)

78 providing anterior to posterior translation across the lower vertebral end-plate during the

79 rotation.

80 Both specimens were mounted on rigid bases and positioned 15 cm from a motion frame

81 which incorporated a rotating disc (Fig 1 A and B). The central ray of a C-arm digital

82 fluoroscope (Siemens Arcadis Avantic – Siemens GMBH, Germany) was positioned so as to

83 pass through the centre of the disc space. A block of animal soft tissue was interposed

84 between the X-ray source, the models and the fluoroscope's image intensifier to degrade the

85 images by generating soft tissue scatter.

86   Fig 1A and B about here

87 The superior vertebra of specimen A was rotated to 18° of flexion and return representing an

88 arbitrary physiological maximum measured using a tilt sensor (Axminster instruments UK–

89 resolution +/- 0.002 degrees) [19]. This was done using a rod driven by a vertical rotating

90 disc embedded in a vertical motion frame (Fig 1A). It was controlled and driven by a laptop

91 computer using bespoke software (Daqfactory VSC – Heatherose Electronics Ltd. UK). The

92 superior vertebra of Specimen B was translated posteriorly across 50% of the lower

93 vertebral end-plate and back again. This was an arbitrary range designed to allow direct

94 comparison between the reference and index values, which should apply, within reason, no

95 matter how large or small the translation. Rotation was at 3°/sec and translation at

96 1.5mm/sec. These procedures were repeated 10 times for each specimen. Images were

97   recorded at 15 frames per second during the 10 sequences for each specimen.   All image

98   sequences were analysed by one trained observer.

99   *Repeatability study*

100   Data were obtained from a parallel study of twenty volunteers being examined for passive

101   recumbent lumbar motion [9]. These were recruited using the eligibility criteria described in

102   Table 1 and following a favourable opinion from the National Research Ethics Service (REC

103   reference 0/H0502/99).   Each participant was positioned in the lateral decubitus position on

104   a horizontal motion frame with the central ray of the fluoroscope positioned to pass through

105   the L4 vertebra (Fig 2). The inferior section of the motion frame was rotated through 40° of

106   flexion over a 12 second interval using the motion controller (Daqfactory VSC – Heatherose

107   Electronics Ltd, UK). This was immediately followed by 40° of extension. The effective

108   radiation dose for this procedure has been estimated as 0.24mSv [18].

109   Table 1 about here

110   Fig 2 about here

111   After transfer of images from the fluoroscope to an image processing workstation, two

112   trained observers (a senior radiographer and a medical physicist) analysed the same 40

113   image sequences for inter-observer repeatability (two sequences per participant for the 20

114   participants**).** Five repeated mark-ups of flexion and extension images of intervertebral

115   levels from L2-S1 took approximately 20 minutes. Observers were blinded to each other's

116   image registrations. The second observer also analysed each image sequence twice for

117   intra-observer repeatability.

118   *Kinematic data extraction*

119   The fluoroscopic sequences were transferred to a desktop computer and Image J (v 1.47 for

120   Windows OS) was used to separate the individual images from the digital sequences. The

121   images underwent user defined edge enhancement, after which templates were manually

122   placed five times around each vertebral body (L2–S1) in the first image. Bespoke software

123   written in Matlab (V R2007b, The Mathworks Inc.) used a cross-correlation method to obtain

124   automated frame to frame image tracking of the vertebral bodies in subsequent images [20].

125   Co-ordinates were placed on the vertebral body corners in the first image, linked to the

126   tracking templates and used to register the vertebrae in two dimensional space in each

127 frame. Tracking was verified for quality assurance by viewing all sequences and repeating
128 any tracking that failed.

129

130 The displacements between each pair of tracked positions were calculated using Distortion
131 Compensated Radiographic Analysis [21]. These were averaged over 25 registration
132 combinations and output as data series'. (Fig 3). Each data series was inspected for
133 tracking failure using video playback. Any failed tracking data were removed and if all
134 templates failed, the data were not used in the analysis.

135   Fig 3 about here

136 ***Translation calculation***

137 Frobins method [21] for calculating translation (shown in Figures 4 and 5 A & B) is based on
138 landmarks identified on the vertebral body 'corners'. Vertebral midlines (Fig. 4) are defined
139 as lines passing through the midpoints between corners 1-2 and 3-4 respectively.

140   Fig 4 about here

141 The average gradient and y axis crossover of the two midlines are calculated for a vertebral
142 pair. The resultant line is called the bisectrix and normally passes through the inter-vertebral
143 disc space.

144 Using the method depicted in Figure 5, a line is drawn from the centre of each vertebra to
145 the coinciding bisectrix. These lines intersect the bisectrix at 90 degrees to the bisectors'
146 gradient.

147   Fig 5 A and B about here

148 Translation was calculated as the distance along the bisectrix between the points at which
149 these two lines independently cross the bisectrix (Fig 5). To standardise this measurement
150 this is given as a proportion of the mean vertebral body depth of the superior vertebra, where
151 1 VBU (vertebral body unit) is the mean of the upper and lower vertebral body end plate
152 depth of the superior vertebra. For the *in vivo* studies VBUs were converted to millimetres
153 based on a standard vertebral depth of 35mm and for the specimens by their actual
154 measurement.

155 ***FCR calculation***

156   The FCR position and distance from the posterior superior corner of the inferior vertebral

157   body was calculated by finding the least squares solution between the four corners and the

158   corresponding co-ordinates on the subsequent image [22] (Fig 5 A and B).

159   The four corner reference template positions for two adjacent vertebrae were taken and re-

160   positioned so that the inferior vertebral position was superimposed. From these coordinate

161   positions, the centre of rotation between the two images was calculated by finding the least

162   squares solution between each of the four corners and their partners from the second image.

163   The least squares solution was taken as described by McCane et al [22] which gives the

164   Matlab script used to execute this calculation. The positions at which each of these least

165   squares solutions meet was taken as the FCR for those two vertebrae between those two

166   images. The axis of rotation was then displayed relative to the inferior vertebra in a pair as a

167   function of the four- corner template on the inferior vertebra. The superior-posterior corner of

168   the inferior vertebra was taken as the origin for this reference field where the X-axis is along

169   the template on the superior vertebral border and the Y-axis perpendicular to the X-axis

170   passing though the origin. The unit of distance used was the proportion of the average

171   vertebral body depth of superior vertebra (due to the non-uniform shape of the sacral

172   template) where the origin of this co-ordinate system is the anterior-superior corner of the

173   inferior vertebra.

174   FCR positional data were calculated at the maximum rotation angle between any two

175   template positions where the inter-vertebral angle was greater than 5 degrees as a cut-off -

176   as when intervertebral rotation interval decreases, the variation in FCR position increases.

177   This is a systematic error due to the way in which the FCR positions are calculated. FCR

178   was measured continuously between the first frame of the image sequence and the image

179   frame where angular rotation was at its maximum +/- 0.5°. The limit of +/- 0.5° was selected

180   as this was the increment through which the tracking templates rotated when calculating

181   vertebral body position within each image. The results were taken as the average position of

182   the FCR in X and Y co-ordinates over the 5 trackings.

183   Fig 6 A and B about here

184   **_Statistical analysis_**

185   For the accuracy study, 10 sets of markings were performed for each specimen. Measured

186   translation was compared with zero translation reference data in the fixed centre specimen

187   (end plate depth 28.77mm) and with translation across 50% of the inferior end plate (depth

188   34.66mm) in the moveable centre specimen. Disagreement was expressed as the root-

189   mean-square (RMS) differences between measured and reference values for both

190   translation and FCR. 95% limits of agreement (LoA) were calculated and expressed in VBU

191   [23].

192   For the repeatability studies, 4 intervertebral levels (L2-S1) were analysed for both flexion

193   and extension translation for each of the 20 participants. For FCR location, data were

194   removed from FCR analysis when rotation did not reach 5°. This range has been suggested

195   as the lowest over which intervertebral FCRs should be calculated from radiographs without

196   unacceptable error [24]. Therefore, in anticipation that not all levels would reach the

197   necessary 5°, the levels were pooled to give a maximum possible 80 observations for each

198   of flexion and extension. Intra and inter-observer reliability were expressed as intraclass

199   correlation coefficients ($ICC_{consistency}3,1$) using adjectives proposed by Shrout and Fleiss and

200   revised from the original scale of Landis and Koch [25, 26]. In the Shrout and Fleiss scale,

201   reliability as denoted by an ICC of 0.00-0.01 is considered as "virtually none", 0.11-0.40

202   "slight", 0.41-0.60 "fair", 0.61-0.80 "moderate" and 0.81-1.00 "substantial".

203   **Results**

204   *Accuracy*

205   The proportion of vertebral body depth that was translated in the moveable centre specimen

206   as measured by the actuator motor was 0.52 VBU (17.95mm). Table 2 shows the RMS

207   differences and 95% LoAs between the reference and measured translation and FCR

208   locations.

209   Table 2 about here

210   For the fixed centre of rotation specimen, the average discrepancy (RMS) in translation

211   range between reference and image data was 0.004 VBU (0.10mm) (LoA 0.01mm). For the

212   translating specimen, the discrepancy when the superior vertebra was translated across

213   50% of the end-plate of the lower one was 0.062 VBU (2.16mm) (LoA 0.52mm). For FCR,

214   the RMS x and y co-ordinate location differences between the reference and measured

215   locations in the fixed centre specimen were 0.009 VBU(x) or 0.25mm (LoA 1.30mm) and for

216   0.014 VBU(y) or 0.40mm (LoA 1.20mm). (Table 2). Bland-Altman plots for these are shown

217   in Fig 7 (A-D).

218   Fig 7 about here

219

220 *Repeatability*

221 The participant sample was made up of 9 females and 11 males aged 26 to 46 (mean age
222 35.7, SD 7.20). Their mean body mass index was 24.71 (SD 2.22).

223 Between 6 and 14 observations for each level in the 20 subjects were visible and tracked
224 successfully for translation. Not all levels and directions were visible or trackable in all
225 subjects. Artefacts due to the movement of bowel gas across images and tall patients
226 whose upper vertebral levels did not fit the image field) were the main causes of this. Intra
227 and inter-observer repeatability for each intervertebral level are shown in Table 3. All levels
228 and directions showed at least fair agreement and reliability. The best agreement was
229 between observers at L2-3 in extension (SEM=0.17mm) and the worst within observers at
230 L5-S1 in extension (SEM=1.14mm). The best reliability was within observers at L2-3 in
231 flexion ((ICC=0.998 (0.958-0.997)) and the worst within observers at L3-4 in flexion
232 ((ICC=0.533 (0.406-0.849)).

233   Table 3 about here

234 Repeatability results for FCR are shown in Table 4. Five degrees of rotation was reached by
235 30 intervertebral pairs. For both translation and FCR location, within observer disagreement
236 did not exceed 2mm for either flexion or extension. Inter-observer disagreement was high
237 for FCRy in extension (5.67mm). All directions otherwise showed moderate to substantial
238 reliability, the smallest ICC being 0.621 (0.429-0.813) for FCRx flexion between observers.

239   Table 4 about here

240 **Discussion**

241 Where mechanical impairment of intervertebral motion in the spine is at issue, its assessment
242 will depend on the availability of technology with which to perform standardised
243 measurements in patients during motion and to provide reference values and error estimates
244 for the various parameters. This study is the first to assess the accuracy and level by level
245 repeatability of the measurement of sagittal plane translation and FCR location from moving
246 vertebral images using low dose 2-D QF. Its results indicate where the current strengths
247 and weaknesses in the technique lie when reporting results of patient studies to clinicians.

248 The accuracy of techniques for radiographic measurement of intervertebral kinematics has
249 been determined using calibration models for roentgen stereophotogrammetry, (which
250 although highly invasive, is sometimes considered the gold standard), biplanar radiography

251 and QF [10, 15, 27, 28]. In this study, idealised conditions were also avoided by degrading
252 the images with animal soft tissue and in the upright position, although It is not uncommon
253 for such studies to be undertaken with no loading or in an animal model with no tissue
254 degradation [16, 29, 30]

255 In this study, we compensated for radiographic image distortion using distortion-
256 compensated roentgen analysis and used an image intensifier that incorporated automatic
257 distortion correction [21]. Measurement is virtually independent of distortion of the
258 radiographic image resulting from central projection, axial rotation, lateral tilt, and off-centre
259 position with an error for translation of between 0.4 and 0.8mm. Measurement of translation
260 was determined from the vertebral body centres, making it independent of rotation. Previous
261 QF studies have also shown that degrading the alignment by axially rotating it 10° out of
262 plane and inclining the X-ray beam inclined 10° inferiorly results in minimal loss of accuracy
263 in rotational studies [10]. Thus the technique should be sufficiently accurate to give useful
264 information about ranges and motion patterns. However, this technique is not thought to be
265 possible in scoliotic spines due to failure of image tracking.

266 This study found the current QF method to have fair to substantial repeatability for all levels
267 and directions using the current protocol. It also found acceptable accuracy *in vitro* for the
268 measurement of FCR location and translation during continuous spinal motion. Reliability
269 was mainly good, but at some levels and directions suggests that training and quality
270 assurance are needed when applying the measurement to comparisons between individuals
271 and reference standards [31].

272 The inter-observer y-error in determination of FCR in extension (5.67mm) and the intra-
273 observer ICC (0.644) for extension translation at L5-S1 point to a need for caution. Closer
274 inspection of the data revealed that the former was also greatest at L5-S1, where image
275 quality and consequently co-ordinate placement may be rendered problematical by the
276 super-imposition of the ilia and/or lack of perfect orthogonal alignment of the central X-ray
277 beam with the vertical axis of the vertebrae. Previous work found radiographic positioning to
278 be more important than tracking accuracy as a contributor to the variability in measurement
279 of angular position, but that this does not preclude high repeatability and accuracy of
280 measurement of rotation [19, 48]. However, for translation and FCR this may be more
281 critical.

282 FCR was once thought to be promising as a way of assessing abnormal loading during
283 intervertebral motion in patients [32, 33] but fell out of favour owing to high errors in
284 measurement and the intrinsic computational errors that occur when rotational range is low

285   [24, 34-36]. The suggestion that it might be used to measure stability has therefore also not

286   generally been taken up [14].   However, the present study has shown that despite the use

287   of continuous motion data, as is necessary in patient studies, greater accuracy was achieved

288   for determining the FCR (average error $0.3mm_x$, $0.4mm_y$) than was found in a previous study

289   with such a specimen that used stepped rotation positions (average error 2mm)[15].

290   The repeatability study utilised information from participants undergoing passive recumbent

291   and not weight bearing motion. It may be thought that weight bearing Information would have

292   been preferable to study the repeatability of translation and FCR measurement. However,

293   this would have meant irradiating additional participants to obtain the same data and

294   differences in motion patterns associated with weight bearing should not affect their

295   measurement.   Indeed, Wood concluded that the lateral decubitus position was superior for

296   the detection of instability in patients with spondylolisthesis and Yeager et al used these

297   interchangeably for their repeatability analysis of rotation and translation at pooled levels [37]

298   [5].

299   FCR, at least in the sagittal plane, could therefore be used to inform both patient care and

300   patient-specific mathematical models. However, further studies are needed to establish

301   normative *in vivo* reference standards at individual levels using QF. It would also be

302   beneficial to explore the effects of spinal geometry and muscle contraction on FCR location,

303   to add coronal plane validation and to confirm whether the FCR locus might be used to

304   assess relationships between structural change and the *in vivo* biomechanical performance

305   characteristics of discs under load. Finally, rotational cut-offs for accurately locating the FCR

306   should be revisited in the light of the greater standardisation offered by QF protocols.

307   Diagnostic advances in spine biomechanics have also been made using kinetic MRI [37-41]

308   and SPECT-CT imaging [42, 43].   However, although kinetic MRI locates points of

309   encroachment on neural tissues and SPECT-CT contributes to the identification of potential

310   sites of pain generation, neither can extract end-range or continuous inter-vertebral motion.

311   In addition, the radiation dosage from SPECT-CT is considerably larger than that of QF.

312   Improvements in repeatability and accuracy are ongoing requirements for any diagnostic

313   test, which means that reference standards will always be imperfect. Validation of QF will

314   therefore require that scientists and practitioners also examine the extent to which test

315   results are meaningful in practice [44]. This may be appreciated from patient register data. In

316   parallel with this, technology development should address any measurement deficiencies.

317   **Limitations**

318   Participants with a BMI over 31 or aged over 51 were excluded from the study and none had

319   osteoporosis, osteoarthritic change, vertebral deformities or curvatures; which may

320   precipitate tracking failures. In the accuracy study, the translation error was considerably

321   higher (2.10mm) in the translating specimen than in the fixed specimen (0.10mm). This

322   may have been due to the resolution of the actuator motor in the latter (0.01mm), or by a

323   small amount of out of plane motion due to imperfections in the mechanical linkage of this

324   specimen. However, this discrepancy is well below the generally accepted cut-off of 4mm

325   for excessive translation [45-48].

326   Distortion that changes during motion is not correctable if the templates that track the images

327   from frame to frame do not change to accommodate it. In the future, this could be provided

328   by adaptations to the tracking codes [8]. The US versions of this technology image the upper

329   and lower lumbar levels separately to minimise out of plane images and ensure inclusion of

330   all lumbar levels. While this increases the X-ray dose, it also makes for better

331   reliability in the measurement of translation than was found here [5].

332   Future studies of accuracy and repeatability are needed to substantiate the present work.

333   These could use a larger number of examiners, a range of rotational angles for FCR

334   accuracy and a more elaborate calibration set up that combines rotation and translation. A

335   larger number of human participants would overcome the problem of low angles of rotation

336   and enable determination of the level by level repeatability of FCR location at 5° and above.

337   For example, poorer agreement was found at L5-S1 than other levels, possibly owing to

338   lower image quality resulting from superimposition of both ilia on the vertebral images.

339   **Conclusion**

340   Quantitative fluoroscopy was found to have a high level of accuracy as well as moderate to

341   substantial observer agreement and reliability for the measurement of FCR and translation.

342   Exceptions were in the reliability of measuring translation at L3-4 and agreement between

343   observers in locating the FCR in extension. The development of reference standards and

344   analysis quality assurance measures will be essential for optimal clinical use [6].

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Acknowledgements

References

[1] Deyo RA, McNeish, L.M., Cone, R.O. 3rd. Observer variability in the interpretation of lumbar spine radiographs. Arthritis and Rheumatism. 1985;1528:1066-70.

[2] Shaffer WO, Spratt, K. F., Weinstein, J. D., Lehmann, T. R., Goel, V . 1990 Volvo Award in Clinical Sciences: The Consistency and Accuracy of Roentgenograms for Measuring Sagittal Translation in the Lumbar Vertebral Motion Segment: An Experimental Model. Spine. 1990;15:741-50.

[3] Penning L, Wilmink, J.T., Van Woerden, H.H. Inability to prove instability: a critical appraisal of clinical-radiological flexion-extension studies in lumbar disc degeneration. Diagnostic Imaging in Clinical Medicine. 1984;53:186-92.

[4] Cakir B, Richter, M., Kafer, W., Wieser, M., Puhl, W., Schmidt, R. Evaluation of lumbar spine motion with dynamic x-ray: a reliability analysis. Spine. 2006;31:1258-64.

[5] Yeager MS, Cook DJ, Cheng BC. Reliability of computer-assisted lumbar intervertebral measurement using a novel vertebral motion analysis system. The Spine Journal. 2014;14:274-81.

[6] Leone A, Guglielmi, G., Cassar-Pullicino, V. N., Bonomo, L. Lumbar intervertebral instability: a review. Radiology. 2007;245:62-77.

[7] Breen AC, Allen, R., Morris, A. An image processing method for spine kinematics-preliminary studies. Clinical Biomechanics. 1988;3:5-10.

[8] Breen A.C., Teyhan DS, Mellor FE, Breen AC, Wong KWN, Deitz A. Measurement of InterVertebral Motion Using Quantitative Fluoroscopy: Report of an International Forum and Proposal for Use in the Assessment of Degenerative Disc Disease in the Lumbar Spine. Advances in Orthopaedics. 2012;2012.

[9] Mellor F.E., Thomas P, Thompson P, Breen AC. Proportional lumbar spine inter-vertebral motion patterns: A comparison of patients with chronic non-specific low back pain and healthy controls. European Spine Journal. 2014;23:2059-67.

[10] Breen A, Muggleton J, Mellor F. An objective spinal motion imaging assessment (OSMIA): reliability, accuracy and exposure data. BMC Musculoskeletal Disorders. 2006;7:1-10.

[11] Breen A, Mellor F, Breen A. Lumbar Intervertebral Motion in Vivo: A Preliminary Comparison of Recumbent and Weight Bearing Motion Patterns in Adult Males. Bone and Joint Journal. 2013;95-B.

[12] Branney J, Breen AC. Does inter-vertebral range of motion increase after spinal manipulation? A prospective cohort study. Chiropractic & Manual Therapies. 2014;22:24.

[13] Iguchi T, Kanemura, A., Kasahara, K., Sato, K., Kurihara, A., Yoshiya, S., Nishida, K., Miyamoto, H., Doita, M. Lumbar instability and clinical symptoms. Which is the more critical factor for symptoms: sagittal translation or segment angulation? J Spinal Disord Tech. 2004;17:284-90.

[14] Bogduk N, Amevo, B., Pearcy, M. A Biological basis for instantaneous centres of rotation of the vertebral column. Proc Instn Mech Engineers. 1995;209:177-83.

[15] Cerciello T, Romano, M., Bifulco, P., Cesarelli, M., Allen, R. Advanced template matching method for estimation of intervertebral kinematics of lumbar spine. Medical Engineering and Physics. 2011;33:1293-302.

[16] Wang S, Passias P, Li G, Li G, Wood K. Measurement of Vertebral Kinematics Using Noninvasive Image Matching Method-Validation and Application. Spine. 2008;33:E355-E61.

[17] Breen AC, Mick T, Phillips RB. Spinal Imaging and the Practice of Chiropractic. In: (ed) SH, editor. Principles and Practice of Chiropractic. Norwalk, Connecticut: Apple Lange; 1992. p. 391-412.

[18] Mellor FE, Thomas P, Breen AC. Quantitative fluoroscopy for investigating in vivo kinematics of the lumbar spine; radiation dose compared to lumbar spine radiographs with suggestions for further dose reduction. Radiography. 2014;In press.

[19] 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. 1991;16:562-71.

[20] Muggleton JM, Allen, R. Automatic location of vertebrae in digitised videofluoroscopic images of the lumbar spine. Medical Engineering & Physics. 1997;19:77-89.

453   [21] Frobin F, Brinckmann, P., Lievseth, G., Biggemann, M., Reikeras, O. Precision measurement of
454   segmental motion from flexion-extension radiographs of the lumbar spine. Clinical Biomechanics.
455   1996;11:457-65.
456   [22] McCane B, Abbott, J.H., King, T. On calculating the finite centre of rotation for rigid planar
457   motion. Medical Engineering and Physics. 2005;27:75-9.
458   [23] Bland JM, Altman, D.G. Statistical methods for assessing agreement between two methods of
459   clinical measurement. The Lancet. 1986:307-10.
460   [24] Pearcy M, Bogduk, N. Instantaneous axes of rotation of the lumbar intervertebral joint. Spine.
461   1988;13:1033-41.
462   [25] Shrout PE. Measurement reliability and agreement in psychiatry. Statistical Methods in Medical
463   Research. 1998;7:301-17.
464   [26] Landis JR, Koch, G.G. The Measurement of Observer Agreement for Categorical Data.
465   Biometrics. 1977;33:159-74.
466   [27] Pearcy MJ. Stereoradiography of lumbar spine motion. Acta Orthopaedica Scandinavica.
467   1985;56:1-45.
468   [28] Selvik G. Roentgen stereophotogrammetry: a method for the study of the kinematics of the
469   skeletal system. Acta Orthopaedica Scandinavica. 1989;232 (Suppl):1-51.
470   [29] Zuhlke T, Fine, J., Haughton, V.M., Anderson, P.A. Accuracy of Dynamic Computed Tomography
471   to Calculate Rotation Occurring at Lumbar Spinal Motion Segments. Spine. 2009;34:E215-E8.
472   [30] Meetings of Interest for Spine Physicians and Surgeons. SO - Spine July/August 1986;11(6):656-
473   657.
474   [31] Knottner J., Audige L, Brorson S, Donner A, Gajewski BJ, Hrobjartsson A, et al. Guidelines for
475   Reporting Reliability and Agreement Studies (GRRAS) were proposed. Journal of Clinical
476   Epidemiology. 2011;64:96-106.
477   [32] Gertzbein SD, Seligman, J., Holtby, K. Centrode patterns and segmental instability in
478   degenerative disc disease. Spine. 1985;10:257-61.
479   [33] Seligman JV, Gertzbein, S.D., Tile, M., Kapasouri, A. Computer analysis of spinal segment motion
480   in degenerative disc disease with and without axial loading. Spine. 1984;9:566-73.
481   [34] Panjabi MM. Centres and angles of rotation of body joints: a study of errors and optimization.
482   Journal of Biomechanics. 1979;12:911-20.
483   [35] Soudan K, Van Audekercke, R., Martens, M. Methods, difficulties and inaccuracies in the study
484   of human joint kinematics and pathokinematics by the instant axis concept, example: the knee joint.
485   Journal of Biomechanics. 1979;12:27-33.
486   [36] Panjabi MM, Goel, V.K., Takata, K. Physiologic strains in the lumbar spinal ligaments. Spine.
487   1982;7:192-203.
488   [37] Wood KB, Popp, C.A., Transfeldt, E.E., Geissele, A.E. Radiographic evaluation of instability in
489   spondylolisthesis. Spine. 1994;19:1697-703.
490   [38] Hirasawa Y, Bashir WA, Smith FW, Magnusson ML, Pope MH, Takahashi K. Postural Changes of
491   the Dural Sac in the Lumbar Spines of Asymptomatic Individuals Using Positional Stand-Up Magnetic
492   Resonance Imaging. Spine. 2007;32:E136-E40.
493   [39] Kong MH, Hymanson, H.J., Song, K.Y., Chin, D.K., Cho, Y.E., Yoon, D.H., Wang, J.C. Kinetic
494   magnetic resonance imaging analysis of abnormal segmental motionof the functional spine unit.
495   Journal of Neurosurgery: Spine. 2009;10:357-65.
496   [40] Tan Y, Aghdasi BG, Montgomery SR, Inoue H, Lu C, Wang JC. Kinetic magnetic resonance imaging
497   analysis of lumbar segmental mobility in patients without significant spondylosis. European Spine
498   Journal. 2012;21:2673-9.
499   [41] Lao L, Daubs MD, Scott TP, Lord EL, Cohen JR, Tin R, et al. Effect of Disc Degeneration on Lumbar
500   Segmental Mobility Analyzed by Kinetic Magnetic Resonance Imaging. Spine. 2015;40:316-22.
501   [42] Harisankar CNB, Mittal BR, Bhattacharya A, Singh P, Sen R. Utility of single photon emission
502   computed tomography/computed tomography imaging in evaluation of chronic low back pain.
503   Indian Journal of Nuclear Medicine. 2012;27:156-63.

504   [43] Matar HE, Navalkissoor S, Berovic M, Shetty R, Garlick N, Casey ATH, et al. Is hybrid imaging
505   (SPECT/CT) a useful adjunct in the management of suspected facet jonts arthropathy? International
506   Orthopaedics. 2013;37:865-70.
507   [44] Breen AC, Morris A. Lumbar Spine Instantaneous Centres of Rotation Determined by Digital
508   Video-floroscopy. Society for Back Pain Resarch Annual Scientific Meeting. St Mary's Hospital,
509   London1989.
510   [45] Dupuis PR, Yong-Hing, K., Cassidy, J.D., Kirkaldy-Willis, W.H. Radiologic diagnosis of degenerative
511   lumbar spinal instability. Spine. 1985;10:262-76.
512   [46] Boden SD, Wiesel, S.W. Lumbosacral segmental motion in normal individuals - have we been
513   measuring instability properly? Spine. 1990;15:571-6.
514   [47] Morgan FP, King, I. Primary instability of lumbar vetebrae as a common cause of low back pain.
515   Journal of Bone and Joint Surgery. 1957;39B:6-22.
516   [48] Hanley EN. The indications for lumbar spinal fusion with and without instrumentation. Spine.
517   1995;20:143S-53S.

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Figure legends

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Figure

Figure

4

Midline

1

3

Bisectrix

4'

2

1'

Midline

'2'

3'

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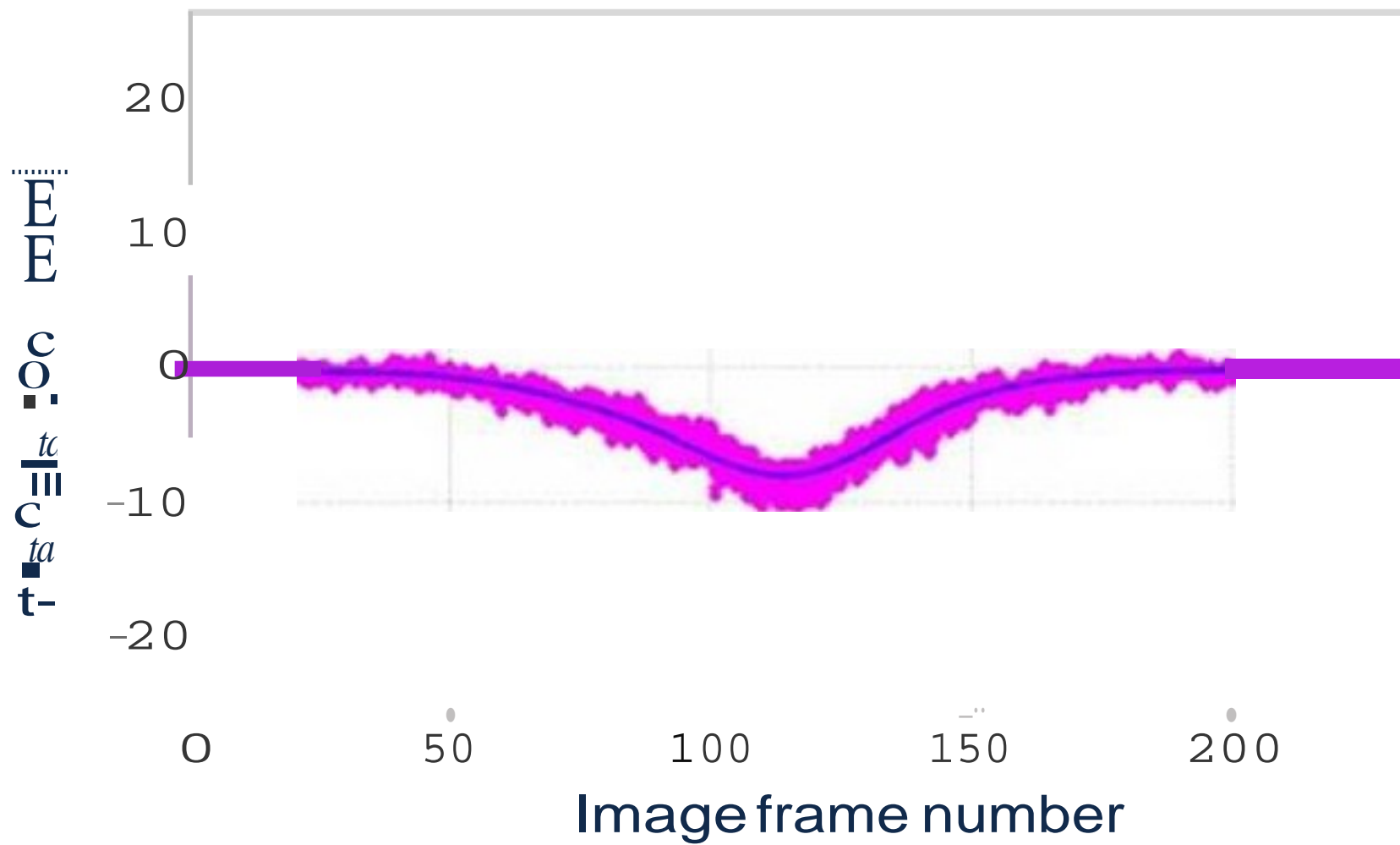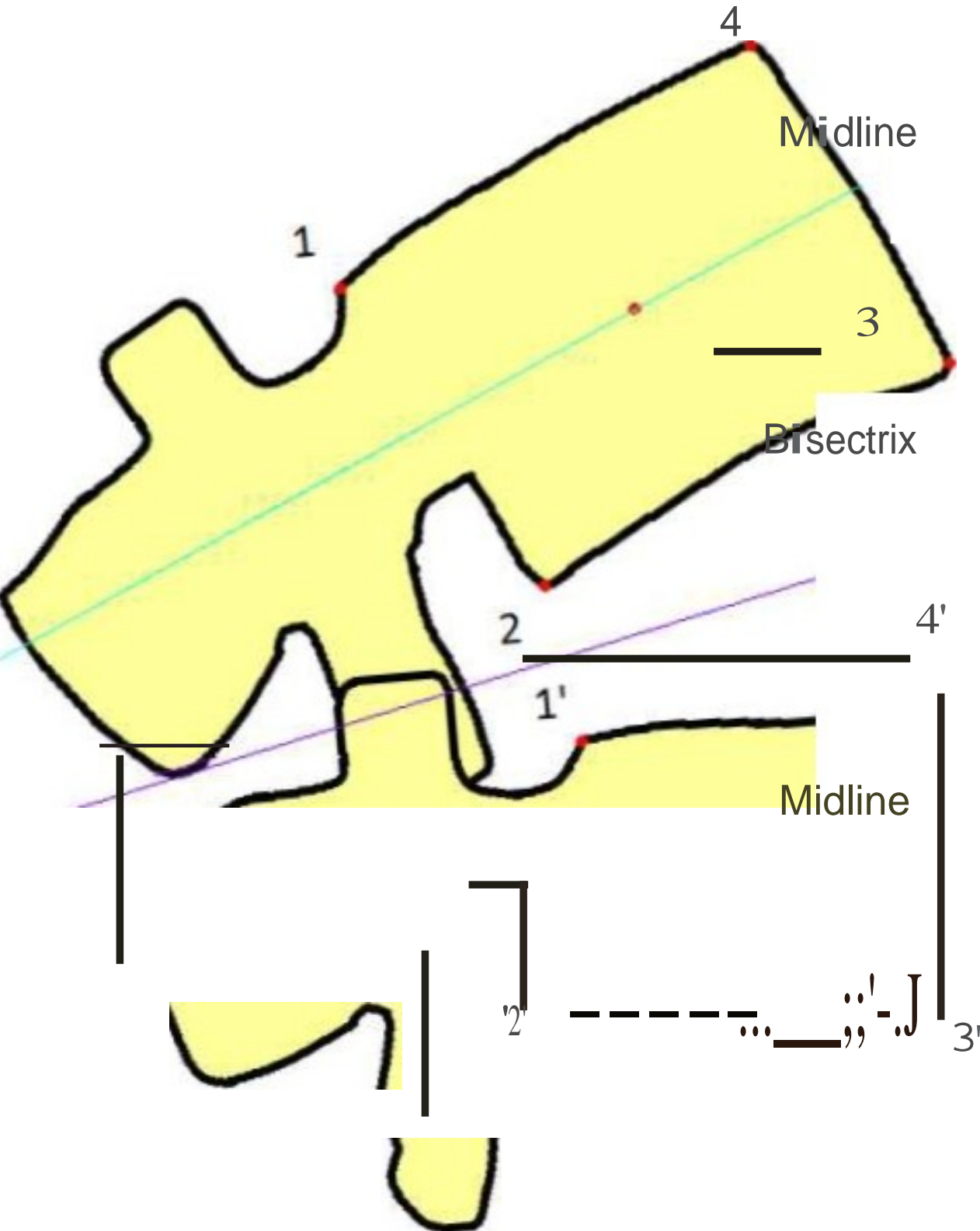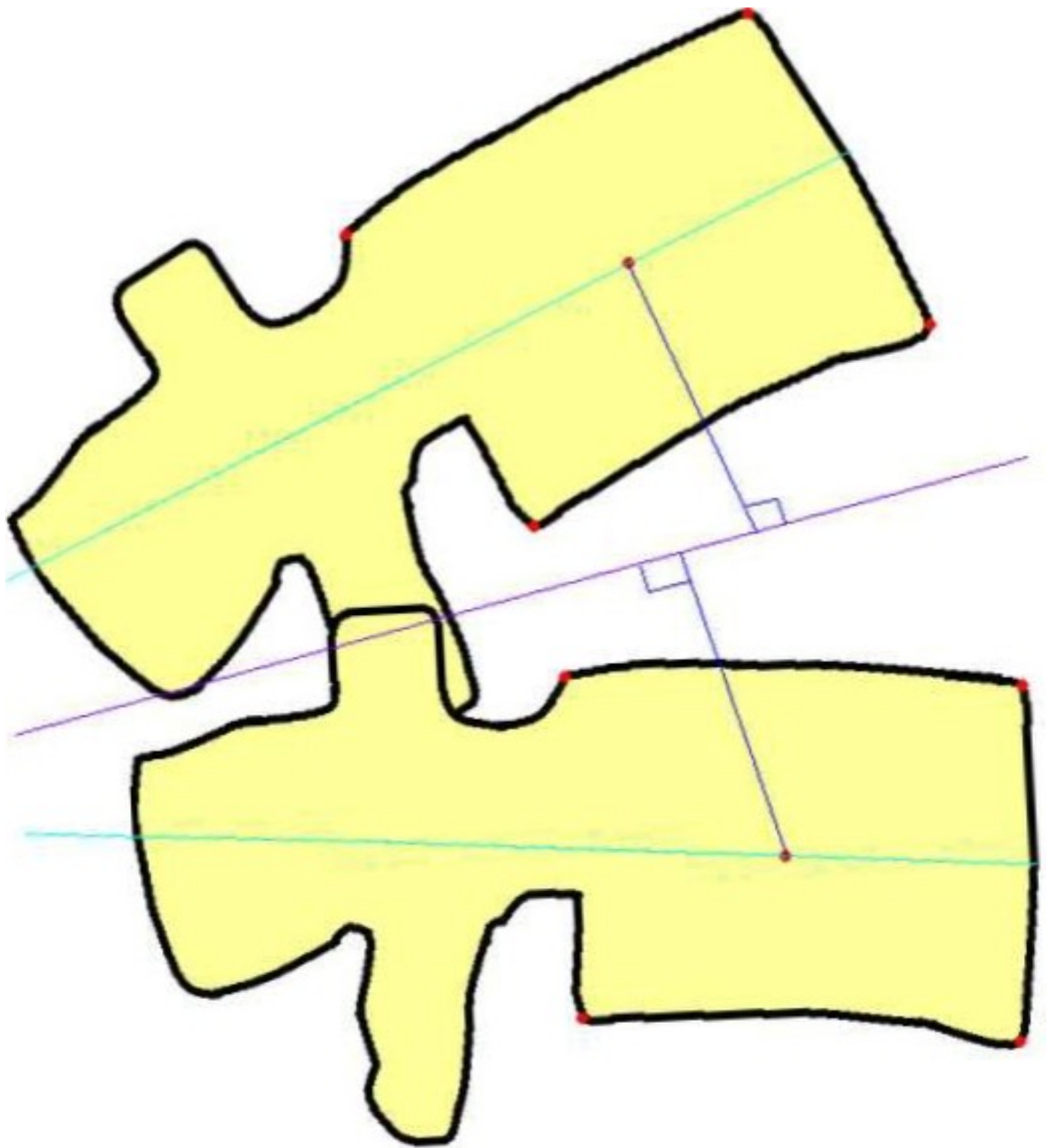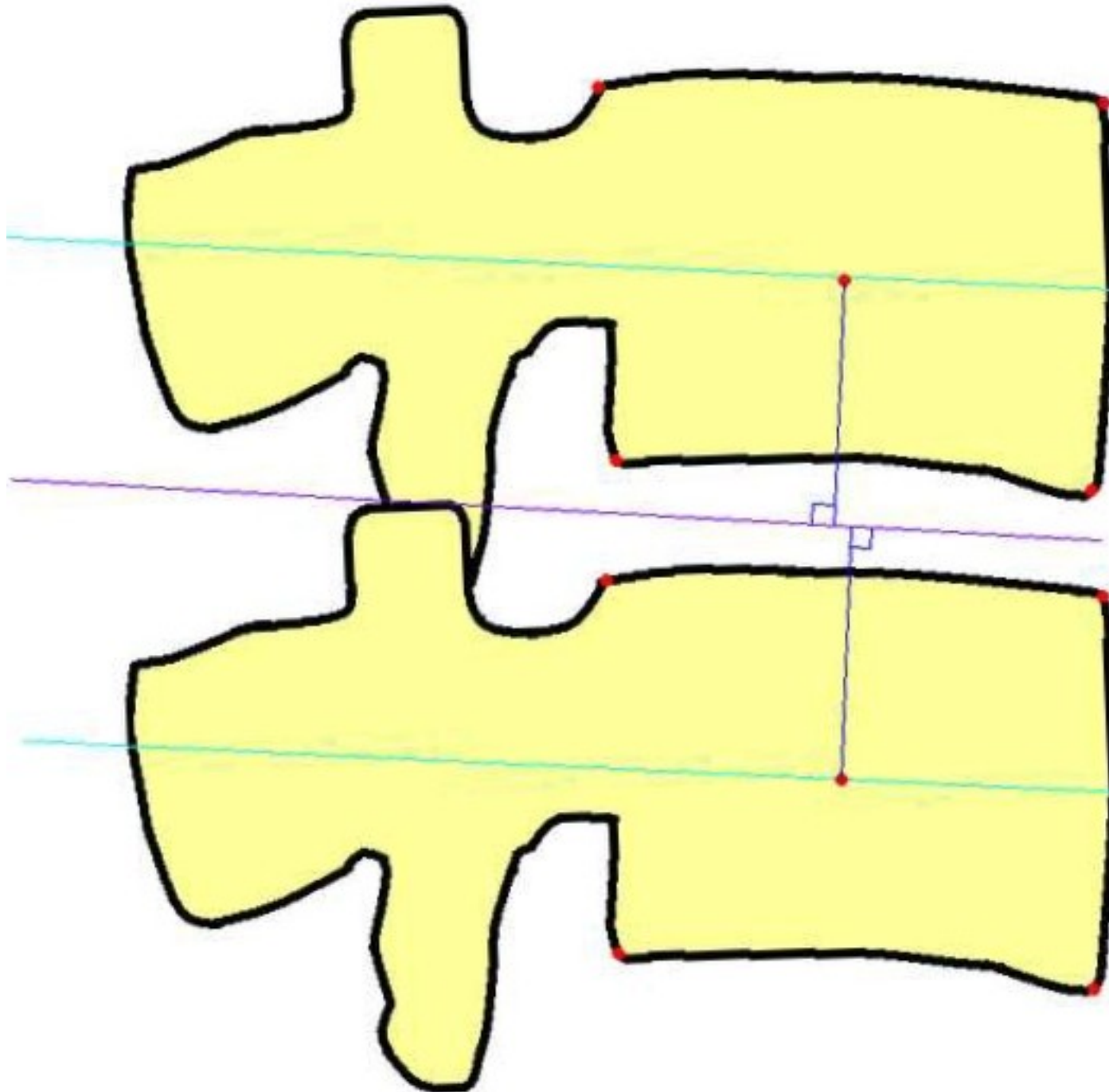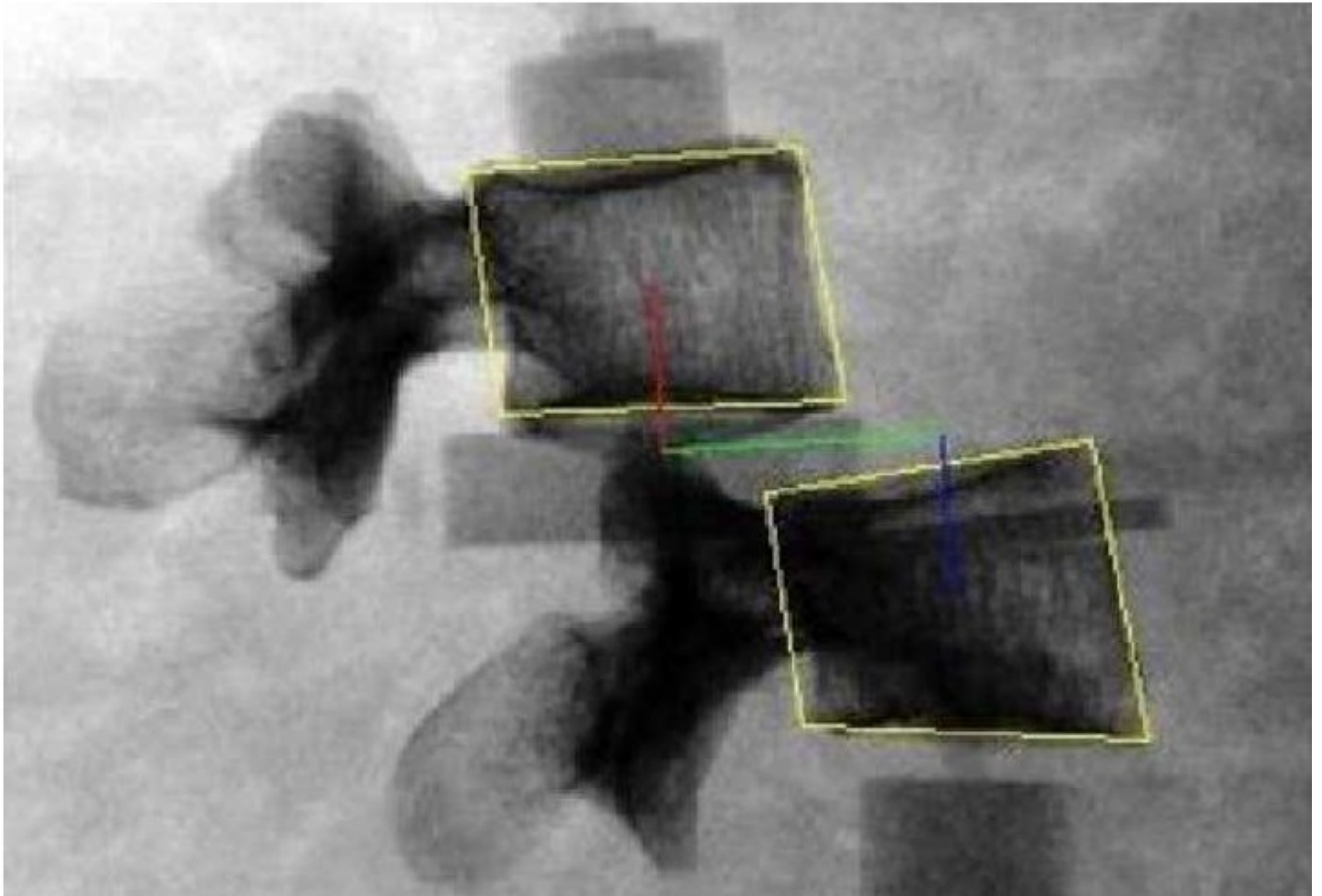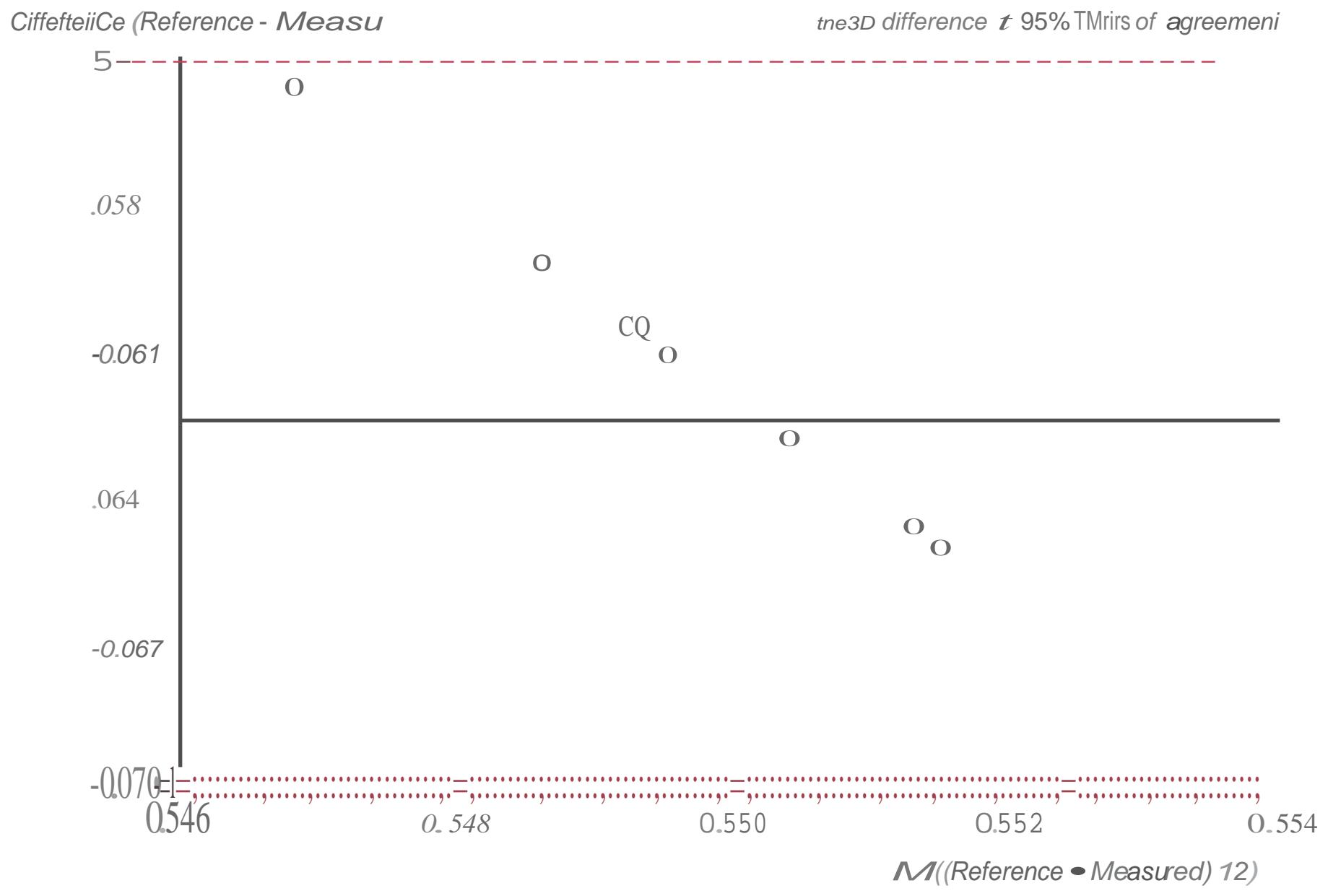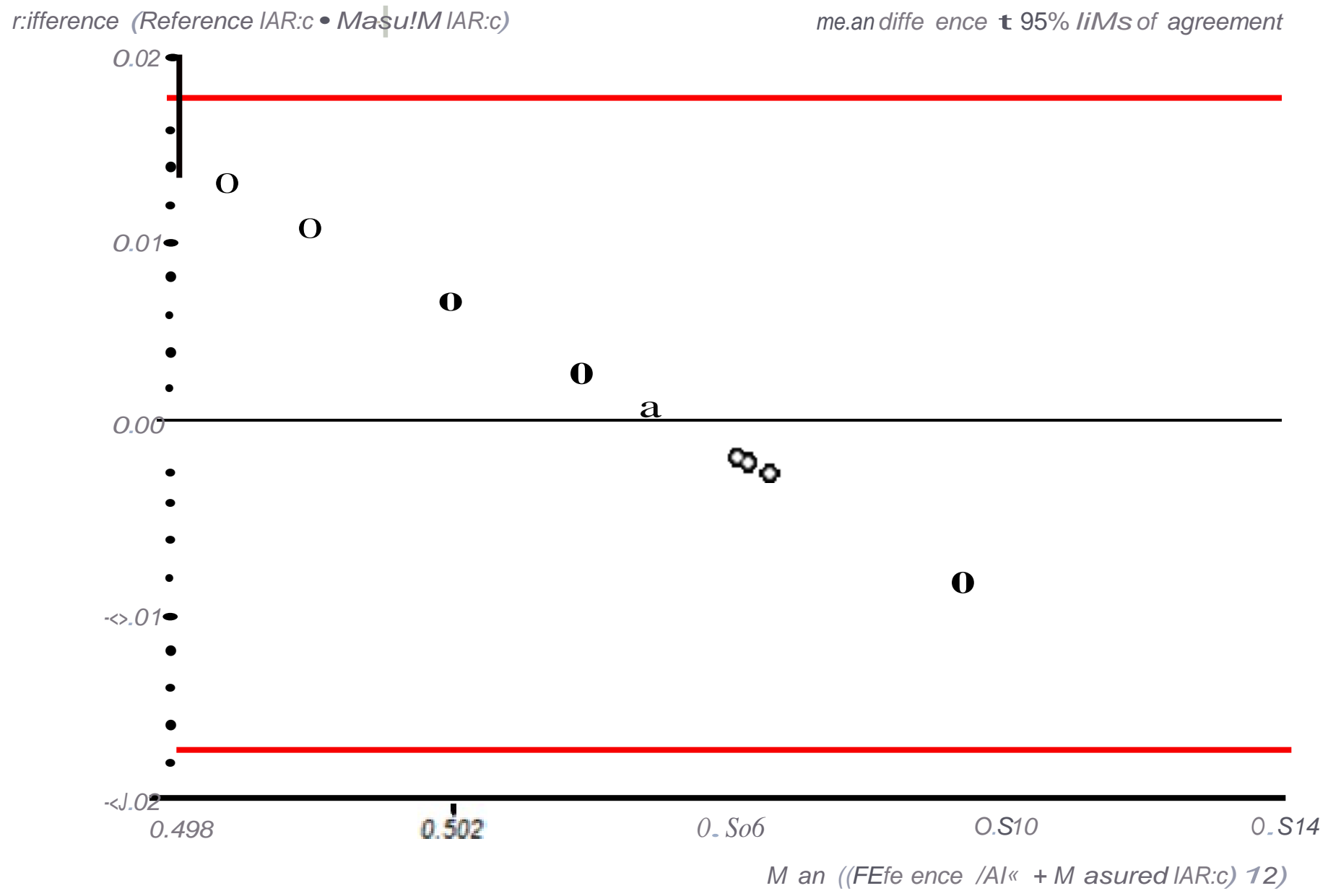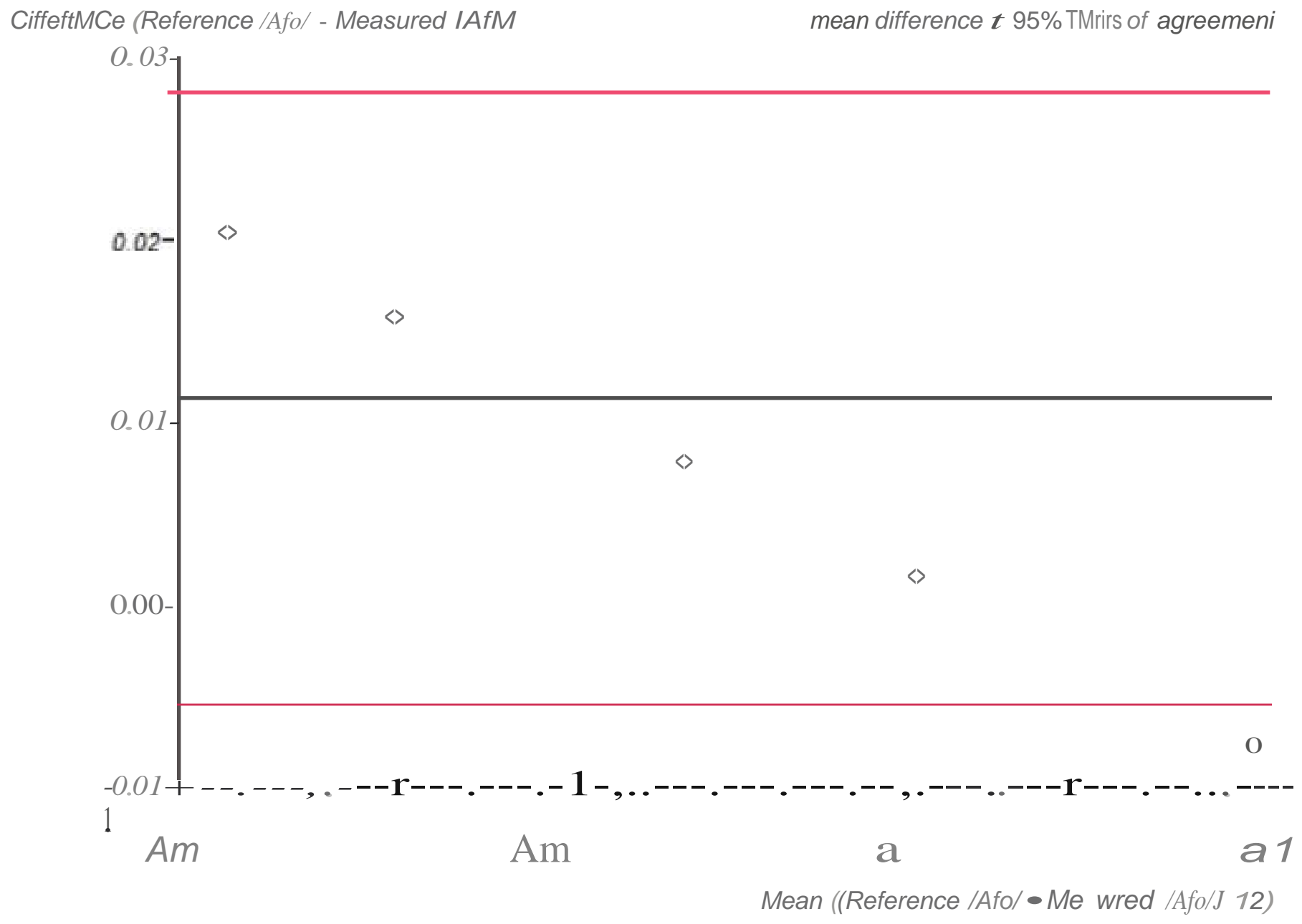
Table

Tables

Table 1. Participant inclusion and exclusion criteria for repeatability study

Inclusion criteria	Exclusion criteria
Male and female. Age 21–51 years. Able to understand written information. Willing to participate> Able to freely give informed consent. Menstruation within last 28 days, or evidence of contraceptive use, or sterility (females). Consent to GP being informed of inclusion in study. Able to tolerate 80 degrees of flexion–extension passive trunk motion	Pregnancy Mental illness Poor understanding of English Recent abdominal or pelvic surgery. Previous mid-lumbar spinal surgery Body mass index (BMI)>31 Medical radiation exposure in the past 2 years with a dose of greater than 8 mSv (defined as CT scan of chest, abdomen or pelvis or interventional procedures under radiological control, i.e. angiography). Current involvement in any other research study. Hyper-mobility syndrome Pathology such as fracture, infection, neoplasm. Spinal stenosis. Spondyolisthesis. Radicular pain. Litigation or compensation pending

Table 2. RMS differences between reference and measured translation and FCR locations

	Fixed specimen			Translating specimen		
	VBU	mm	95% LoA (VBU)	VBU	mm	95% LoA (VBU)
Translation	0.004	0.10	0.001 to 0.006	0.062	2.16	0.055 to 0.070
IARx	0.009	0.25	-0.017 to 0.018	_	_	_
IARy	0.014	0.40	-0.028 to 0.005	_	_	_

Table 3. Intra and interobserver repeatability of translation by level and direction

| | Flexion | | | | | | | Extension | | | | | | |
| | Intraobserver | | | Interobserver | | | | Intraobserver | | | Interobserver | | |
Level	n	SEM (mm)	ICC (95%CI)	n	SEM (mm)	ICC (95%CI)	n	SEM (mm)	ICC (95%CI)	n	SEM (mm)	ICC (95%CI)
L2-3	11	0.18	0.988 (0.958-0.997)	11	0.51	0.865 (0.499-0.964)	7	0.21	0.935 (0.671-0.989)	6	0.17	0.932 (0.514-0.990)
L3-4	14	0.43	0.533 (0.406-0.849)	14	0.46	0.570 (-0.339-0.862)	13	0.40	0.742 (0.185-0.920)	12	0.35	0.809 (0.337-0.945)
L4-5	11	0.39	0.853 (0.483-0.947)	11	0.62	0.700 (-0.115-0.919)	10	0.56	0.899 (0.619-0.975)	7	0.65	0.916 (0.512-0.982)
L5-S1	13	0.77	0.828 (0.456-0.947)	12	0.75	0.844 (0.458-0.955)	10	1.14	0.644 (-0.344-0.910)	8	0.64	0.910 (0.553-0.931)

Table 4. Intra and interobserver repeatability of FCR location (pooled data)

| | | Flexion | | | | | | | Extension | | | | |
| | | Intraobserver | | | Interobserver | | | Intraobserver | | | Interobserver | |
	n	SEM (mm)	ICC (95%CI)	n	SEM (mm)	ICC (95%CI)	n	SEM (mm)	ICC (95%CI)	n	SEM (mm)	ICC (95%CI)
IARx	30	1.72	0.816 (0.678-0.953)	24	2.03	0.621 (0.429-0.813)	21	1 82	0.852 (0.680-1)	21	1.19	0.876 (0.727-1)
IARy	30	1.75	0.626 (0.421-0.830)	24	1.86	0.690 (0.497-0.882)	21	1 51	0.999 (0.833-1)	21	5.67	0.878 (0.659-1)