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

Alexander Breen[a], Alan Breen[b,*]

[a] Institute for Musculoskeletal Research and Clinical Implementation, Anglo-European College of Chiropractic, 13-15 Parkwood Road, Bournemouth, Dorset BH5 2DF, UK

[b] School of Design Engineering and Computing, Bournemouth University, Talbot Campus, Poole, Dorset BH12 5BB, UK

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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 1.1 mm 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 1.5 mm to 1.8 mm (SEM) with moderate to substantial reliability (ICC 0.626–0.988). Inter-observer repeatability for FCR ranged from 1.2 mm to 5.7 mm, 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 0.1 mm (fixed centre) and 2.2 mm (moveable centre), with an FCR error of 0.3 mm(x) and 0.4 mm(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.

1. 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

* Corresponding author. Tel.: +44 1202 436275; fax: +44 1202 436268.
E-mail address: imrci.abreen@aecc.ac.uk (A. Breen).

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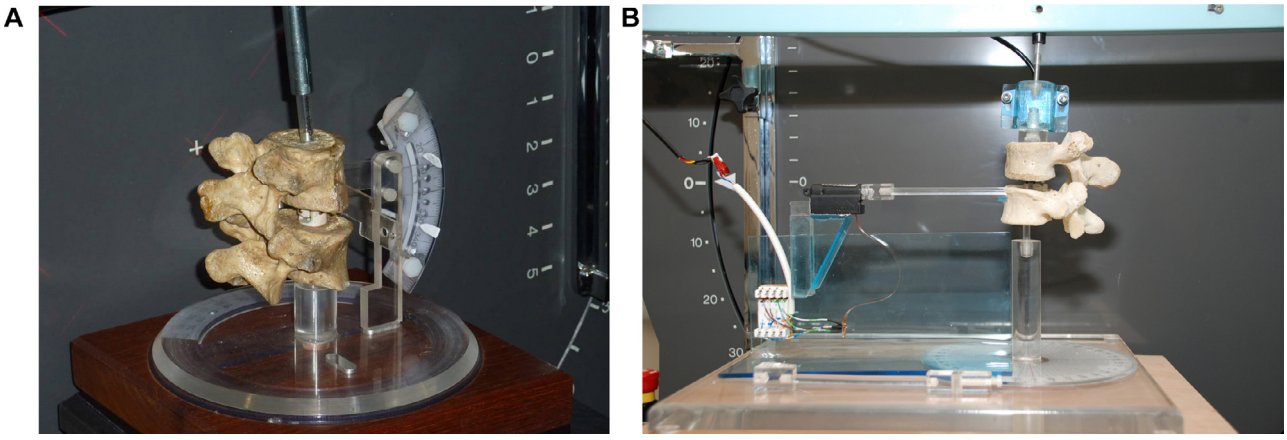

Fig. 1. Lumbar intervertebral motion specimens. (A) Fixed centre specimen. (B) Movable centre specimen.

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 intervertebral translation and FCR location during motion using a standardised patient motion protocol. This research involved the use of two calibrated human cadaveric specimens to assess accuracy during sagittal plane motion in a prescribed pathway and repeatability in 20 volunteers executing a standardised bending protocol.

2. Methods

2.1. Accuracy study

Two sets of dry cadaveric vertebral pairs were used to provide reference data. Specimen A (Fig. 1A) consisted of L4 and L5 vertebrae joined at their end-plate centres by a universal joint 4 mm high, representing a fixed centre of rotation with zero translation. Specimen B (Fig. 1B) comprised of L3 and L4 vertebrae. These were joined at their end-plate centres by a plastic linkage which allowed translation of the upper vertebra without rotation. It was driven by an actuator motor and controller (Arduino Software Ltd., UK—resolution 0.01 mm) providing anterior to posterior translation across the lower vertebral end-plate during the rotation.

Both specimens were mounted on rigid bases and positioned 15 cm from a motion frame which incorporated a rotating disc (Fig. 1A and B). The central ray of a C-arm digital fluoroscope (Siemens Arcadis Avantic—Siemens GMBH, Germany) was positioned so as to pass through the centre of the disc space. A block of animal soft tissue was interposed between the X-ray source, the models and the fluoroscope's image intensifier to degrade the images by generating soft tissue scatter.

The superior vertebra of specimen A was rotated to 18° of flexion and return representing an arbitrary physiological maximum measured using a tilt sensor (Axminster instruments UK—resolution ±0.002°) [19]. This was done using a rod driven by a vertical rotating disc embedded in a vertical motion frame (Fig. 1A). It was controlled and driven by a laptop computer using bespoke software (Daqfactory VSC—Heatherose Electronics Ltd., UK). The superior vertebra of Specimen B was translated posteriorly across 50% of the lower vertebral end-plate and back again. This was an arbitrary range designed to allow direct comparison between the reference and index values, which should apply, within reason, no matter how large or small the translation. Rotation was at 3°/s and translation at 1.5 mm/s. These procedures were repeated 10 times for each specimen. Images were recorded at 15 frames per second during the 10 sequences for each specimen. All image sequences were analysed by one trained observer.

2.2. Repeatability study

Data were obtained from a parallel study of twenty volunteers being examined for passive recumbent lumbar motion [9]. These were recruited using the eligibility criteria described in Table 1 and following a favourable opinion from the National Research Ethics Service (REC reference 0/H0502/99). Each participant was positioned in the lateral decubitus position on a horizontal motion frame with the central ray of the fluoroscope positioned to pass through the L4 vertebra (Fig. 2). The inferior section of the motion frame was rotated through 40° of flexion over a 12 s interval using the motion controller (Daqfactory VSC—Heatherose Electronics Ltd., UK). This was immediately followed by 40° of extension. The effective radiation dose for this procedure has been estimated as 0.24 mSv [18].

After transfer of images from the fluoroscope to an image processing workstation, two trained observers (a senior radiographer and a medical physicist) analysed the same 40 image sequences for inter-observer repeatability (two sequences per participant for the 20 participants). Five repeated mark-ups of flexion and extension images of intervertebral levels from L2-S1 took approximately 20 min. Observers were blinded to each other's image registrations. The second observer also analysed each image sequence twice for intra-observer repeatability.

2.3. Kinematic data extraction

The fluoroscopic sequences were transferred to a desktop computer and Image J (v 1.47 for Windows OS) was used to separate the individual images from the digital sequences. The images underwent user defined edge enhancement, after which templates were manually placed five times around each vertebral body (L2-S1) in the first image. Bespoke software written in Matlab (V R2007b, The Mathworks Inc.) used a cross-correlation method to obtain automated frame to frame image tracking of the vertebral bodies in subsequent images [20]. Co-ordinates were placed on