A Non-Invasive Technique to Precisely Measure Three-Dimensional Vertebral Movement in the Lumbar Spine

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Introduction
It is difficult to accurately determine three-dimensional (3D) spine motion in vivo during physiological loading due to the inability to directly attach measurement equipment to individual vertebrae. Thus, radiographic techniques, including CT scans1 and biplane radiography2 have been developed to record static vertebral position. The major limitation of these techniques is the inability to measure vertebral movement during active motion. This limitation has been addressed by implanting markers into the vertebrae and tracking the markers using high-speed stereoradiography3. However, the necessity for implanted beads restricts the use of this technique to surgical patients. The objective of the present study was to evaluate a non-invasive technique to measure lumbar spine motion during dynamic motion.

Methods
Three to five 2 mm diameter beads were implanted into L3, L4, L5 and the pelvis in one male cadaver torso (T1 to mid-thigh; all bone and soft tissue intact). The torso was placed in a seated position within a biplane x-ray system and manipulated using ¼ inch metal rods passed laterally through the rib cage and obturator foramen. Biplane x-rays were collected at 60 frames per second using dual cardiac cine-angiography generators to produce high-powered (70kV, 250mA), pulsed (10 ms) x-rays. Images were recorded using 40 cm image intensifiers in series with high-resolution cameras (Phantom V10, Vision Research). Two trials each of flexion, lateral bending and axial twist were performed. Computed tomography (CT)-based 3D models4 of the lumbar vertebrae were placed into a proportionally identical virtual data collection system (Figure 1) and a computerized matching process reproduced bone location and orientation in 3D space. This process has been validated to track shoulder and knee joint movement during dynamic motion with accuracy of better than 1 mm in translation and 1 degree in rotation5,6.

Figure 1: The model-based tracking technique optimizes the correlation between edge-enhanced radiographic images (red in figure) and a ray-traced projection through the 3D CT reconstruction (green in figure).

Implanted beads were tracked in the distortion corrected radiographs as described previously1. All data were filtered at 5 Hz using a fourth-order, low-pass Butterworth filter. For each frame of every trial, relative translation and rotation between adjacent vertebrae was calculated using both the bead-based and the model-based tracking techniques. Additionally, disc height changes during lateral bending and minimum facet joint space during twists were calculated using both tracking techniques to determine if model-based tracking provided sufficient accuracy to investigate clinically relevant parameters. Agreement between the two systems was quantified by bias (average difference between methods over the entire trial) and precision (standard deviation of differences over the entire trial)5. One-sample, two tailed t-tests with alpha < 0.05 were used to test for bias in all cases.

Results
The total range of motion between the pelvic and L3 in flexion, lateral bending and axial twist was 3.0 deg. 10.0 deg. and 7.8 deg., respectively. Implanted beads were tracked with a precision between 0.05 mm and 0.11 mm, with no significant bias in any of the three motions tested. Precision for measuring relative translation and rotation was better than 0.32 mm and 0.43 deg, respectively (Table 1).

<table>
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<tr>
<th>L3/L4</th>
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<tbody>
<tr>
<td>Bias</td>
<td>Precision</td>
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<tr>
<td>-0.43*</td>
<td>0.26</td>
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<td>-0.21*</td>
<td>0.32</td>
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Table 1: Accuracy for relative translation (mm) and rotation (deg) between L3/L4 and L4/L5. (*) indicates significant bias.

Average bias and precision in disc height measures during the lateral bending trials was -0.04 mm and 0.27 mm, respectively (Figure 2). Average bias and precision in measuring the closest distance between facet joint surfaces during the axial twist trials was -0.47 mm and 0.19 mm, respectively.

Discussion
Model-based tracking accuracy is highly dependant on high quality radiographic images. This is especially problematic in the lumbar spine, given the large amount of tissue surrounding vertebrae. The high-powered generators used in this study provide superior image contrast and eliminate motion blur when recording active movement, unlike conventional c-arms.

The results of this study, showing sub-millimeter precision in all kinematic measurements, provide preliminary evidence that the model-based tracking technique is sufficiently accurate to investigate clinically relevant questions such as how disc height and facet joint space change during in vivo loading in both asymptomatic controls and symptomatic surgical and non-surgical patients.

References

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