A NEW APPROACH TO FLUOROSCOPY-BASED 3D KINEMATIC ANALYSIS OF THE SPINE BASED ON A PRIORI KNOWLEDGE AND NATURAL CONTRAINTS FROM CONTINUOUS MOTION OBSERVATION

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INTRODUCTION
A significant body of evidence has been compiled that connects pain causing disorders of the spine with altered kinematics [1], although very few studies have been able to accurately perform the fully dynamic and three dimensional analyses required to comprehensively explore these relationships. Optoelectronic-based measurements have yielded the majority of the available 3D dynamic data, but require surgically-implanted markers to be fixed to each measured vertebra to achieve high accuracy [1]. Similar fiducial-based radiographic methods also require a surgical procedure to facilitate measurement [2]. This limitation precludes the widespread use of these methods.

An alternative approach determines the 3D kinematic parameters by a comparison of fluoroscopic images and CT-derived data. This approach is generally entitled 2D/3D registration and there are a number of available methods in this class [3]. Current methodology forgoes challenging explicit image segmentation at the cost of computational speed. These methods may take over a minute to determine the position and orientation of a single bone in a single image, making multi-segment dynamic analyses cumbersome.

A fluoroscopy-based 3D kinematic measurement method was recently developed in our laboratory in order to better facilitate dynamic analyses of the spine by significantly reducing the analysis time. This method exploits a priori knowledge and natural kinematic constraints that arise from continuous motion observation. The objective of this study was to determine the accuracy and precision of measuring the kinematic parameters of a vertebra using this method.

METHODOLOGY
A vertebral model made of a synthetic bone material was attached to a precision micrometer rotation stage aligned to the imaging axes of a single fluoroscope (Figure 1). A single image was captured of the vertebra in a fixed orientation and then the vertebra was rotated by one degree about a single axis and the process repeated. The vertebra was imaged laterally for both flexion and lateral bending motions and then reattached to the rotation stage in an anterior view, where it was again imaged in sequential flexion and lateral bending motions. The fluoroscope was calibrated to determine its projection parameters and the inherent distortion characterized in order to correct each of the acquired images.

A 3D model of the vertebra was manually segmented from a CT scan of the vertebra using a commercial image segmentation package (Amira....). Using the projection parameters acquired during calibration, the 3D coordinates of a polygon surface model’s nodes were used to compute the projected boundary shapes of the vertebra covering all possible orientations in the test range at a resolution of 0.1°. The projected shapes were stored in two separate libraries for the lateral and anterior views.

The boundary shape of the vertebra in each of the collected images was determined by using a segmentation method specifically designed for our kinematic measurement system. This method uses information about the approximate position and orientation of the vertebra to improve the segmentation process (Figure 2).

![Figure 1](image1.png) A vertebral model is attached to a precision micrometer rotation stage that is aligned to the imaging axes of a fluoroscope.

![Figure 2](image2.png) Sample fluoroscopic images with marked Canny edge detection (above) and segmented with our new method (below).

The projected boundary shapes of the vertebra acquired from each of the fluoroscopic images was compared with the appropriate library using a distance metric and a targeted search strategy based on kinematic constraints. A single optimal match was determined using a minimal difference criterion and defined a corresponding set of orientation angles for the vertebra. These orientation angles were then corrected for perceived rotations due to translations parallel to the image plane of the fluoroscope and recorded.

RESULTS
The accuracy and precision of kinematic parameter recovery were characterized using mean error and standard deviation (SD) of the error in vertebral orientations derived from fluoroscopic images relative to the micrometer rotation stage (Table 1). The combined error for all trials was 0.07°±0.27° and the mean analysis time was 1.3 seconds per image.

**Table 1.** Accuracy and precision results for the best and worst axes from each of the four motion trials.

<table>
<thead>
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<th>View</th>
<th>Motion</th>
<th>Flexion</th>
<th>L. Bend.</th>
<th>Flexion</th>
<th>L. Bend.</th>
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<td>Lateral</td>
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<td>Lateral</td>
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<td>9°</td>
<td>17°</td>
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<td>Mean Error</td>
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<td>0°</td>
<td>0°</td>
<td>0°</td>
</tr>
<tr>
<td></td>
<td>SD of Error</td>
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<td>0.2°</td>
<td>0.2°</td>
<td>0.3°</td>
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<tr>
<td></td>
<td>Max Error</td>
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<td>0.5°</td>
<td>0.2°</td>
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DISCUSSION
The purpose of this study was to evaluate the accuracy of 3D kinematic parameter recovery using a recently developed fluoroscopy-based measurement system. This system was developed to exploit the a priori knowledge and natural kinematic constraints that arise from continuous motion observation in order to reduce the time required for multi-segment dynamic analyses. The results indicate that our kinematic errors are comparable with other registration methods while computation time is significantly reduced (e.g. kinematic analysis of two vertebrae, over 100 image frames would take 4-5 minutes instead of 200 minutes or more). Imaging synthetic bone material can not accurately represent in vivo situations, but the actual image quality in terms of the ability to acquire the vertebral boundaries is expected to be similar. In vitro cadaver trials are underway to further validate the methodology.

REFERENCES

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