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# Technical Note: Determining and Displaying the Instantaneous Axis of Rotation of the Spine

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**Abstract** The instantaneous axis of rotation (IAR) is a parameter that is desirable to study in evaluating spinal motion in the normal condition and after arthroplasty. When high-precision optical data are collected during in vitro experimentation, high-precision IARs can be calculated in two or three dimensions. These IARs then must be represented on an image of spinal anatomy. Methods for calculating high-precision IARs and accurately overlaying them on the anatomy are described. The overlay method requires a graph of the IARs and key virtual landmarks transformed into a fixed local coordinate system of the spinal motion segment being studied. The anatomical image and graph are merged, and landmarks are synchronized by rotating the image and resizing the graph.

Keywords: instantaneous axis of rotation (IAR)

## Introduction

Currently, there is great enthusiasm in spine surgery for intervertebral disc prostheses as an alternative to fusion, with an increasing number of devices being introduced to the market in the past few years. In discussing and evaluating the designs and efficacy of these devices, researchers and clinicians often refer to the location of the axis of rotation. It is theoretically desirable that, after insertion of a disc prosthesis, the axis of rotation should be located at the same position as it would be in the normal spine. By maintaining the correct location of the axis of rotation, the facet joints would slide efficiently across each other and loads would be distributed appropriately at the level replaced and at the adjacent levels. Conversely, if the disc prosthesis forces an incorrect location of the axis of rotation, the facet joints may interact pathologically, leading to facet hypertrophy, spontaneous fusion or other unwanted outcomes.

Although it is seemingly a very important parameter to quantify for full understanding of the spinal motion segment—second in importance after the range of motion(1)—some authors have referenced locations of the axis of rotation summarized for a small number of samples from literature that is somewhat dated.(2-3) Other researchers have used 2-D radiographs rather than 3-D optical tracking systems to calculate imprecise planar approximations of the axis of rotation.(4-6) Planar approximations from radiographic projections lack accuracy because it is unknown whether the two planar views are exact planar projections or slightly oblique views. Furthermore, the planar method of approximating the axis of rotation (method of Reuleaux) does not use to its advantage the consideration that the points studied are part of a rigid body and should not be able to move relative to each other.(7)

In this paper, a method for quantifying the axis of rotation using known vector techniques and modern high-precision motion analysis data is presented. The novelty of this method is the usage of virtual landmarks to map the location of the axis of rotation onto the spinal anatomy.

## Methods

The method presented assumes that three-dimensional rigid body data are collected from one of many commercially-available motion analysis systems. A few of such systems are Optotrak and Polaris (Northern Digital, Waterloo, Ontario, Canada), Flock of Birds (Ascension Technology Corporation, Burlington, VT) and Peak Motus (Peak Vicon, Lake Forest, CA). It is assumed that 3-D marker position data are collected from the moving vertebra and the vertebra below it from at least three markers per vertebra (to define rigid bodies). The method presented requires alignment of the tracking coordinates to the anatomical coordinate system of the spinal motion segment being studied, identification and tracking of key virtual points on the anatomy during movement of the motion segment and an image representing the anatomy on which the axis of rotation is to be plotted. After these three requirements are satisfied, the axis of rotation is easily plotted in two dimensions or (less easily) displayed in three dimensions.

### Transformation to the Anatomical Coordinate System

For quantifying the axis of rotation at a particular motion segment, movement of the upper vertebra of the motion segment must be quantified relative to movement of the lower vertebra of that motion segment. That is, all data must be transformed such that the lower vertebra appears to be fixed at every frame and the upper vertebra appears to move relative to it. This transformation is easily accomplished using standard rigid body techniques.(8) Essentially, in the neutral position, the locations of the optical markers on the lower vertebra are stored, then at every subsequent frame, the current positions of the optical markers on the lower vertebra are transformed to match the stored positions.

In addition to "fixing" the lower vertebra of the motion segment, the data should be transformed such that they are not in the coordinate system of the cameras or another arbitrary coordinate system, but instead are in the coordinate system of the upper vertebra of the motion segment of interest established while that vertebra is in its upright neutral posture. A method for achieving the desired coordinate system transformation was previously published.(9) Briefly, this method requires that the researcher identify four virtual landmarks on the anatomy of the vertebra of interest relative to the physical optical markers. A digitizing probe, which can be custom built or purchased as an accessory to some optical systems, is the most convenient instrument for achieving this goal. The digitizing probe has optical markers embedded in it in a known configuration for which the tracking system knows the precise position of the probe's tip. After identifying the landmarks, the left and right lateral points are used to establish the lateral (x) axis and the anterior and posterior points are used to establish the orientations of the rostrocaudal (y) and anteroposterior (z) axes about the lateral axis. Once the transformation is achieved for the vertebra in its neutral posture, the transformation (not the marker locations) is stored and applied to every frame of data during movement. Each frame then represents movement of the upper vertebra of the motion segment away from its neutral position relative to the vertebra below it in a coordinate system where the xy plane is the true coronal plane, the xz plane is the true transverse plane and the yz plane is the true sagittal plane.

### Identification of Key Virtual Points

To accurately map the axis of rotation onto the anatomy, it is necessary to identify meaningful anatomical landmarks that will subsequently be easily visualized on the image of the spine. The four landmarks that are identified for the purpose of aligning the anatomical coordinate system of the motion segment to be studied can also serve this purpose. Additional points may be needed for unambiguous positioning of the image. It is often advantageous to use metallic landmarks if a radiograph is to be used as the image for overlay since the borders of metallic objects are clearer than those of bony landmarks on the X-ray film. For example, metal pins may be inserted in bone above and below the level studied, or articulations on the metal fixtures in which specimens are plotted may serve as landmarks. Identification of more virtual points improves the accuracy of the technique. If the landmarks used for mapping are attached to the vertebra that will be moving or to adjacent rigid bodies (eg, the plotting fixtures at distal ends of the specimen), then it is necessary that these landmarks be identified while all joints of the spine are in the same posture as the image to be used for mapping.

**Table 1. Formulae for coordinates where the helical axis crosses the plane of interest**

| Plane of intersection | Formulae |
|---|---|
| Midsagittal (x=0) | $y_o = s_y - s_x(n_y/n_x)$<br>$z_o = s_z - s_x(n_z/n_x)$ |
| Transverse (y=0) | $x_o = s_x - s_y(n_x/n_y)$<br>$z_o = s_z - s_y(n_z/n_y)$ |
| Coronal (z=0) | $x_o = s_x - s_z(n_x/n_z)$<br>$y_o = s_y - s_z(n_y/n_z)$ |

### Image of the Anatomy

For mapping of the axis of rotation on to the anatomy, an accurate representation is necessary. For two-dimensional representations, a photograph, radiograph or drawing of the spine in the plane of interest is needed. Of these three options, a radiograph is preferred because it is anatomically accurate, quickly obtained and clearly shows the positional relationships between vertebral body, facets and disc. For three-dimensional representations, a computer-assisted drawing (CAD) model, computed tomographic reconstruction or other three-dimensional representation of the motion segment is needed.

### Computation of the Instantaneous Axis

Given two frames of data with the 3-D coordinates of three or more landmarks, an accurate vector method has been described that provides the position, angle about and translation along the finite helical axis of motion required to achieve the motion.(7, 10) Some software has been posted to the Internet containing the algorithms referenced (for example, see http://www.isbweb.org). It has been observed that smoothing of the data using a moving average (± 10 points) improves the consistency of the calculated helical axes (unpublished). Ignoring the angle of rotation about the helical axis and translation along the helical axis, the finite helical axis of motion is the same as the three-dimensional instantaneous axis of rotation between the two frames of data. By calculating where this axis intersects the plane of interest, a two-dimensional instantaneous center of rotation can be determined. Usually, the plane of interest would be the midsagittal plane during flexion or extension, a coronal plane (eg, coronal slice through the anteroposterior center of the intervertebral disc) for lateral bending and a transverse plane (eg, transverse slice through the rostrocaudal center of the disc) for axial rotation. The coordinate locations where the three-dimensional axis intersects the plane of interest are calculated from the unit vector describing the orientation of

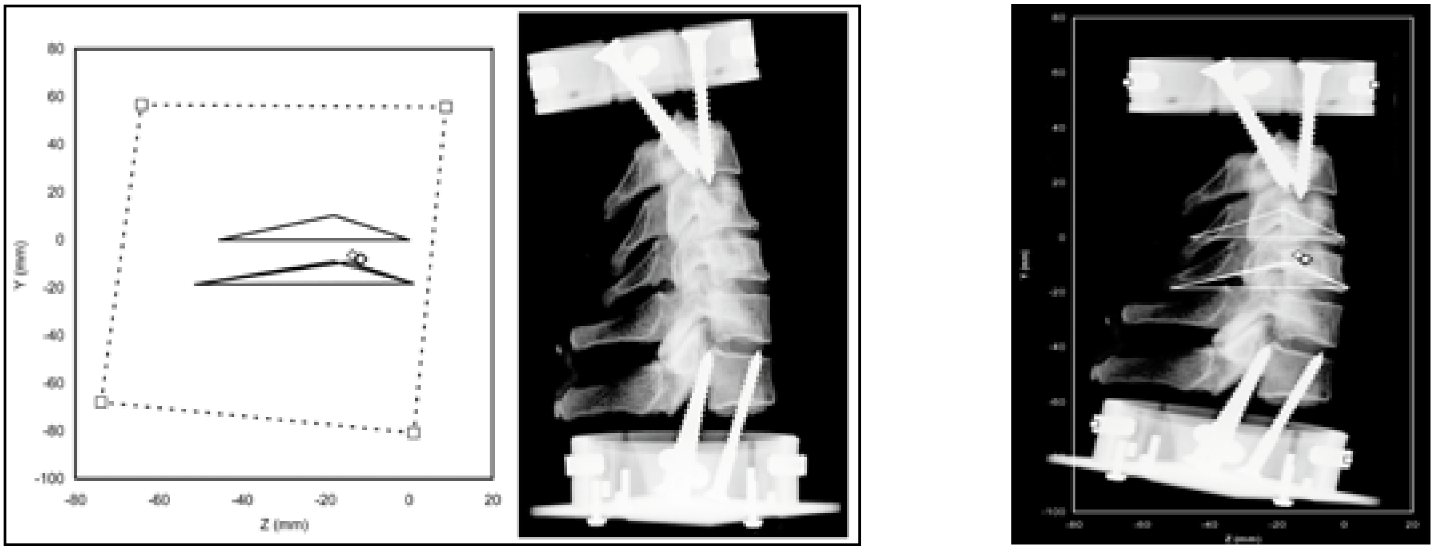

Figure 1A.

Figure 1B.

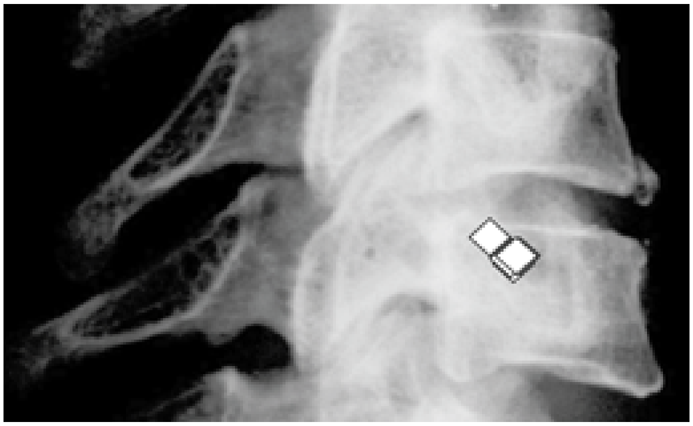

Figure 1C.

**Figure 1A-C.** Combination of graphical axis of rotation and landmarks with image of the anatomy. **1A.** Graph is created (in this case using Microsoft Excel) with numerical indices but arbitrary sizing and an X-ray image of the anatomy on which the graph is to be overlaid is imported into the graphing software. Plotted on the graph are the locations of the axis of rotation in ~1° intervals during flexion (6 nodes plotted), locations of the anterior, posterior, left and right landmarks on C5 and C6, and the locations of the anterior and posterior ends of the bolts on the top and bottom fixtures (connected by dashed lines). **1B.** After importing, the X-ray image is rotated and the graph is resized horizontally and vertically until the landmarks overlay the corresponding points on the image. The aspect ratio of the image is unaltered. **1C.** After overlay is complete, the area of interest is magnified, showing clearly the location of the C5-C6 axis of rotation in the posterior half of the vertebral body slightly below the disc space.

the helical axis, n, and the vector from the origin to the closest point on the helical axis, s (**Table 1**).

One caveat for effective calculation of the axis of rotation from this method is that the finite helical axis should only be calculated from frames of data with adequate angular separation. Typically, a filter increments frames, checking the angular separation (eg, Euler angle, Tilt-twist angle (11), or “helical angle” / “attitude vector” (12), until it exceeds a minimum user-specified amount such as 0.5°.(13)

Another caveat is that axes of rotation that are not close to being perpendicular to the plane of 2-D representation should be excluded. Such behavior occurs if there is significant angular coupling of the joint. If these nonperpendicular axes of rotation are included in analysis, they can lead to confusion since they may intersect the plane of interest at one location but then intersect a nearby parallel plane (like an adjacent computed tomography slice with a similar anatomic representation) at a significantly different location. A reasonable cutoff for filtering data is to exclude axes greater than 30° from perpendicular to the plane of interest. If much of the data set falls outside this angle, it may not be appropriate to represent the axis of rotation in 2-D and a 3-D representation should be used instead. The off-perpendicular angle is simply the arccosine of the component of the helical axis unit vector n that is expected to be nearly perpendicular to the plane. For example, to calculate the angle, θ, between the x-axis and the axis of rotation during flexion-extension, the formula is: $\theta = \cos^{-1}(n_x)$

## Combination of Components

Necessary components for plotting the axis of rotation are the neutral position of landmarks, the coordinates of the axis of rotation and an image on which to plot the axis. The neutral position of the landmarks should be in the same coordinate system as the coordinates of the axis of rotation. The image can be in an arbitrary coordinate system and scale, but there should be no distortion of the image (aspect ratio maintained).

In 2-D, these components can be combined using graphing software such as Microsoft Excel. Axis of rotation and landmark coordinates are plotted and then the image of the spine is inserted into the graphing software (**Figure 1A**). Then, the graph is resized and the image or graph is rotated until the landmarks overlay their corresponding positions on the anatomical representation (**Figure 1B**). After overlay is achieved, the region of interest can be magnified and landmark data discarded (**Figure 1C**). 3-D representation follows a similar algorithm, but software must allow resizing of the 3-D volume of landmarks and axes of rotation and rotation of the 3-D image or data in all three coordinate axes to allow appropriate overlay.

## Conclusions

Although axes of rotation are often described in the literature, there is little information on how they are calculated and displayed during spinal motion. This paper provides one possible algorithm for performing this task. This technique has been used successfully in many in vitro studies of spinal kinematics.(14-20) It should be understood that the accuracy of overlaying axes of rotation onto the correct anatomical position can vary depending on the number of virtual landmarks that are taken as data points and the ability to discern these points accurately on the anatomical image.

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### Editor's Comments

The quantitative mention of the IAR in clinical or experimental studies is inconsistent and based on a variety of techniques. The technique, in fact, as Dr. Crawford points out, is often not presented or referenced. Crawford has presented a viable relatively simple alternative. He points out its limitations and provides an assessment of the literature regarding this arena. Accuracy is limited regardless of technique employed. Dr Crawford has eloquently and correctly portrayed what is known in this arena and has provided a reasonable strategy for the determination of the IAR. For this he is to be congratulated.

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