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Short communication

Use of the alpha shape to quantify finite helical axis dispersion during simulated spine movements

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ABSTRACT

In biomechanical studies examining joint kinematics the most common measurement is range of motion (ROM), yet other techniques, such as the finite helical axis (FHA), may elucidate the changes in the 3D motion pathology more effectively. One of the deficiencies with the FHA technique is in quantifying the axes generated throughout a motion sequence. This study attempted to solve this issue *via* a computational geometric technique known as the alpha shape, which bounds a set of point data within a closed boundary similar to a convex hull. The purpose of this study was to use the alpha shape as an additional tool to visualize and quantify FHA dispersion between intact and injured cadaveric spine movements and compare these changes to the gold-standard ROM measurements. Flexion–extension, axial rotation, and lateral bending were simulated with five C5–C6 motion segments using a spinal loading simulator and Optotrak motion tracking system. Specimens were first tested intact followed by a simulated injury model. ROM and the FHAs were calculated post-hoc, with alpha shapes and convex hulls generated from the anatomic planar intercept points of the FHAs. While both ROM and the boundary shape areas increased with injury ($p < 0.05$), no consistent geometric trends in the alpha shape growth were identified. The alpha shape area was sensitive to the alpha value chosen and values examined below 2.5 created more than one closed boundary. Ultimately, the alpha shape presents as a useful technique to quantify sequences of joint kinematics described by scatter plots such as FHA intercept data.

1. Introduction

The helical axis is a widely adopted kinematic technique used to describe physiologic and pathologic spine motion (Anderst et al., 2015; Crawford et al., 2002; Ellingson and Nuckley, 2015; Metzger et al., 2010; Rousseau et al., 2006; Wachowski et al., 2009). Many studies have used either the finite (FHA) or instantaneous (IHA) helical axis to describe changes in a spinal motion segment's center of rotation (COR), as these measures have been found more sensitive than range of motion (ROM) for kinematic changes resulting from trauma, degeneration, or the application of instrumentation (Crawford, 2005; Mansour et al., 2004). Furthermore, with the development of many motion restoring spinal devices, the helical axis is frequently reported as a parameter of interest for evaluating the device efficacy (Niosi et al., 2006; Wachowski et al., 2013). Efforts have been undertaken to improve understanding of how the helical axis can be implemented in spinal kinematics (Crawford, 2006). However, the helical axes and CORs are typically only qualitatively reported, using 2D images of their migration on the motion segment (Ellingson and Nuckley, 2015; Kettler et al., 2004; Wachowski et al., 2010).

A potential improvement to further describe changes in spine motion would be to quantify the scatter in the axes generated from a motion sequence. In the elbow, Duck et al. quantified elbow instability based on the angular deviation of the generated screw displacement axes (equivalent to FHAs) from a simulated flexion motion with various pathologies (Duck et al., 2003). A similar approach could be useful for spine motion to define a boundary around the COR data in a given anatomic plane. One method to accomplish this is the alpha shape algorithm, a computational geometric technique used to envelop a finite set of points within a series of curves (Edelsbrunner et al., 1983). Similar to a convex hull, these geometric shapes can be thought of like an elastic band surrounding a set of points; however, the alpha shape's series of curves allows for a tighter boundary shape without the limitation of being entirely convex (Fig. 1). This algorithm requires a set of point data and an alpha value, which is used as a radius to define the outline shape of the point set. A smaller value of alpha will increase the detail of the shape by limiting the required distance between two points for an acceptable boundary edge; though below a certain alpha value, outlier points will be excluded and

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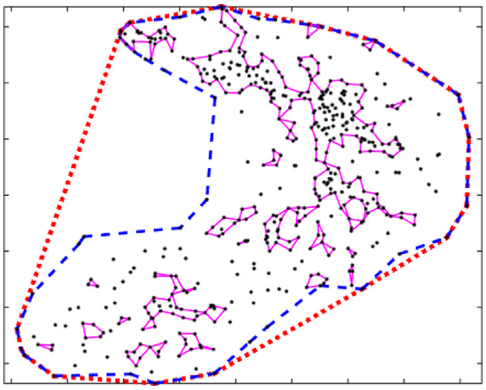

Fig. 1. Convex hull *versus* alpha shape comparison. Both the convex hull and alpha shape algorithm bound a set of points within a closed loop. The convex hull (shown in the dotted, red line) connects the most extreme points of the data set, whereas the alpha shape (dashed, blue line) is able to obtain a finer degree of detail (*i.e.,* identifying the inner curve) in the shape of the data set. In this case, the alpha shape more accurately quantifies the true area of the point set (110.6 mm^2) compared to the convex hull method (152.1 mm^2). Reducing the alpha value below a critical point will only consider very close points and can produce more than one closed boundary shape (solid, magenta lines). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

more than one closed shape may be generated (Fig. 1). An alpha value of infinity will generate a convex hull shape.

The purpose of this study was to investigate the applicability of the alpha shape to visualize and quantify dispersion in the FHAs generated during intact and injured simulated spinal movements as compared to changes in ROM. It was hypothesized that the alpha shape could identify the same quantitative differences in the motion segment kinematics as ROM.

2. Methods

Five fresh-frozen C4–C7 cadaveric cervical spine segments were used for this study (age: 74 ± 5 years). The C4–C5 and C6–C7 motion segments were fixed with screws to isolate motion to C5–C6. Each specimen was fixed within 2.5 cm thick, 10 cm diameter PVC rings using Denstone™ cement to hold the C4 and C7 vertebrae. Using a custom spinal loading simulator built off of an Instron materials testing machine (Instron 8874, Canton, MA), standardized flexibility testing was performed on each specimen (Wilke et al., 1998), with specimens loaded at a rate of 3°/s up to a target load of 1.5 Nm in pure bending. Specimens were cycled through flexion–extension, axial rotation, and lateral bending, with each motion repeated three times (data analysis used the final cycle). Kinematics were captured at 60 Hz using an Optotrak® Certus™ (Accuracy ≈ 0.1 mm, NDI, Waterloo, ON) with trackers attached to the C5 and C6 vertebrae and local coordinate systems created *via* digitization of anatomic landmarks (Rasoulinejad et al., 2012; Schmidt et al., 2009). A testing protocol was designed to assess the kinematic stability of the intact and injured states. First, the intact kinematics were collected for the three simulated movements. Subsequently, a standardized injury model for a unilateral facet perch was then induced in the right facet joint at C5–C6 of each specimen as the injured state (Nadeau et al., 2012). This injury model consisted of surgically sectioning both facet capsules, three-quarters of the annulus, and half of the ligamentum flavum, followed by rotating the disrupted specimen to the perched position.

Post-hoc analysis of the intact and injured states determined the total ROM of each complete movement (*i.e.,* maximum flexion to maximum extension) using custom-written LabVIEW™ software (National Instruments, Austin, TX). FHAs and their respective planar intercepts (*i.e., X, Y*, or $Z=0$ of the C6 frame of reference for lateral bending, flexion–extension, and axial rotation, respectively) were repeatedly calculated from the screw matrices determined from the pose information (*i.e.,* transformation matrix) of the C5 vertebra at two time points (McLachlin et al., 2014; Spoor and Veldpaus, 1980). Starting from the neutral position in each simulated movement, a loop was created in the LabVIEW software to evaluate each data point of pose information as an initial frame of a FHA and each subsequent data point as a possible second frame until a minimum rotation angle was met between the two time points (Ferreira et al., 2011). As such all pose data points throughout the movement were evaluated as initial frames, but FHAs were only considered valid once the angular selective inclusion criterion was met with a later data point. The minimum angle for the selective inclusion criteria was chosen post-hoc for each movement based on the total ROM of each specimen (McLachlin et al., 2014). With a step size of approximately 0.05° between each initial data point, this approach generated a large set of rotationally-consistent FHAs throughout the entire motion pathway for each movement.

Alpha shapes were then generated to envelope COR data points for each movement using MATLAB software (Mathworks, Natick, MA) and the function "alphavol," which was downloaded from the MATLAB File Exchange website. A series of alpha values (α) were compared from 0.3125 to infinity (*i.e.,* convex hull). Alpha shapes were quantified by determining both their area and number of closed boundary shapes generated. In addition to quantitative analysis, the alpha shapes for the intact and injured states of an alpha value of 2.5 were visualized over specimen-specific planar images of 3D bone models generated from segmented CT scans using Mimics software (Materialise, Leuven, Belgium). Statistical analyses were performed using SigmaStat software (Systat, Chicago, IL). Intact *versus* injured ROM, alpha shape area, and convex hull area were compared in a paired *t*-test ($\alpha = 0.05$).

3. Results

ROM between the intact and injured states increased for all three simulated movements ($p < 0.05$), with the largest increase seen in axial rotation (Table 1). Based on the intact ROM, the minimum rotation angle between data points for calculating FHAs was 2°, 3°, and 2° for axial rotation, flexion–extension, and lateral bending, respectively. Sensitivity analysis revealed a single, closed alpha shape was successfully created for the intact and injured states of each movement for all five specimens using an alpha value of 2.5 (Table 2). Data analysis of these alpha shapes and the convex hull shapes revealed an increase in area for all movements between the intact and injured states ($p < 0.05$) (Table 1). The alpha shapes ($\alpha = 2.5$) are shown for each specimen between the intact and injured states in Figs 2–4. Alpha values below 2.5 began to yield, in some specimens and simulated movements, alpha shapes with more than one closed boundary, which had a large impact on the alpha shape area (Table 2).

4. Discussion

The FHA is a widely reported biomechanical measure for describing changes in the COR of a joint (Anderst et al., 2015; Crawford et al., 2002; Kettler et al., 2004; Niosi et al., 2006; Rousseau et al., 2006), yet quantifying this scatter as a measure of joint kinematics is not common practice. In the current study, an advanced computational geometric algorithm known as the alpha shape was explored to calculate a wrapped boundary around the intercept points of the generated FHAs from simulated spine movements (*i.e.,* CORs) (Edelsbrunner et al., 1983). By defining the alpha shape area of these points, changes in cervical spine kinematics between the intact and injured states were identified. To the authors' knowledge, this is the first study to report on the changes in kinematics using the alpha shape of generated helical axes.

While both ROM and the boundary shape areas identified increase between the intact and injured states, there are potential benefits to consider the alpha shape algorithm as a measure of the kinematic stability of a spinal motion segment. A drawback to the ROM measurement is that only the extreme ends of motion in a single plane are identified (*i.e.,* how much rotation in the transverse plane occurs during simulated axial rotation). As such, it is challenging to use and interpret ROM of joint movements that do not occur in a single plane (Crawford, 2005). This is evident in the current results where a much larger increase in alpha shape area was found compared to ROM (339% *versus* 130%) between the lateral bending intact and injured states. This difference may be explained by the ability of the FHA to capture the coupled lateral bending motion in the cervical spine, where the corresponding alpha shapes in turn contain this information through increased

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