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INJURY BIOMECHANICS RESEARCH
Proceedings of the Thirty-First International Workshop

Centers of Rotation for the Upper Cervical Spine: Methodology and Preliminary Data

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This paper has not been screened for accuracy nor refereed by any body of scientific peers and should not be referenced in the open literature.

ABSTRACT

During complex loading, bending moments within the cervical spine are frequently calculated at the center of rotation (COR) for a particular joint. The COR location is often inexact as it is described by an anatomical feature whose location is poorly identified using conventional imaging or superficial anatomic landmarks. The most important example is the use of the occipital condyles as the COR and reference landmark for flexion and extension bending moment within the upper cervical spine and in anthropomorphic testing devices (ATDs). Although upper cervical neck moments are calculated about the occipital condyles, the condyles and the COR for the human upper cervical spine have not been quantitatively located, particularly with respect to other known cranial landmarks. In this study, ten upper cervical spine specimens were tested in both flexion and extension at pure moment increments of approximately 0.5 N-m to determine CORs of the upper cervical spine. Using digital images recorded at each moment increment, the location of tracking markers attached to the C1 and C2 vertebrae were determined. These marker locations were used to determine the CORs for O-C2 and O-C1 motion segments using Reuleaux's method (Panjabi et al., 1982). Following the biomechanical testing, cranial landmarks, including the occipital condyles, were identified and digitized in 3D-space using a MicroScribe 3Dx with Immersion Inscribe3 software. Other landmarks digitized included the external auditory meatus, infraorbital foramen, zygion, nasion, foramen magnum, and the Frankfort plane. For each specimen, motion segment COR and head center of gravity (CG) were plotted on a reference digital image and the digitized cranial landmarks were registered and plotted on the same image. Preliminary results showed the CORs of O-C1 for a majority of the specimens were superior to the condyles and the O-C2 CORs were inferior to the condyles in flexion. The CORs of O-C1 were anterior to the CORs of O-C2 in both flexion and extension. This approach allowed qualitative and quantitative comparison between the upper cervical spine COR and commonly referenced cranial landmarks.

INTRODUCTION

IN anthropomorphic testing devices (ATDs), the load cell for the upper neck is placed at the occipital condyles, where the center of rotation (COR) for the upper cervical spine is believed to be located. The location of the COR plays an important role in neck moment sensitivity because movement of the COR significantly affects calculated neck moment due to the large resultant forces that occur during head impact. Several challenges emerge when one attempts to rigorously measure the upper neck moment. One difficulty is that the occipital condyles have not been quantitatively located (Hubbard et al., 1973, Byars et al., 1970, Butler, 1992). A second difficulty is that few studies have measured the COR at the O-C1 joint. The COR of the upper cervical spine has been located near or cranial and dorsal to the occipital condyles (Van Mameran et al., 1992, Lang, 1993). Additionally, the unique anatomy of this joint is poorly described and is difficult to accurately measure and reference the COR. As a result, the normal location of the COR is not known (Amevo et al., 1991, Bogduk et al., 1995).

Past studies have measured the COR through the use of lateral radiographs from volunteers. The COR was calculated graphically by tracing the vertebrae and specifying landmarks in order to employ the perpendicular bisector method (Amevo et al., 1991). Other studies used computer assisted methods to hand digitize vertebral landmarks and then calculated the COR mathematically (Panjabi et al., 1982). Experimental limitations with these techniques have been tracing errors (Van Mameran et al., 1992, Amevo et al., 1991), inter-observer and intra-observer errors (Amevo et al., 1991), significant errors for small changes in angle, and repeatability in locating the same anatomical landmark (Panjabi et al., 1982).

The purpose of this study is to describe the anatomy and position of the condyles using direct measurement. In addition, this study will also provide quantitative data on the COR of O-C2 and O-C1 using pure bending tests and image tracking software. The CORs will be co-registered with the digitized cranial landmarks and digital images.

METHODS

Ten male upper cervical spine specimens were tested in flexion and extension. Of these ten, all have been anatomically digitized and two have their CORs calculated for the O-C1 and O-C2 motion segments. Each specimen was tested in both flexion and extension at pure moment load steps of 0.5 N-m up to 4 N-m. The head was inverted and supported by a halo. Two markers were mounted to the C1 vertebra to track the motion of the O-C1 joint. C2 markers were mounted to a rigid moment arm to track O-C2 motion (Figure 1) (Nightingale et al., 2002). An image was recorded at each load increment to capture movement of the mounted markers. Since the distance between the C2 markers was known, the number of pixels per millimeter was determined for the images of each specimen.

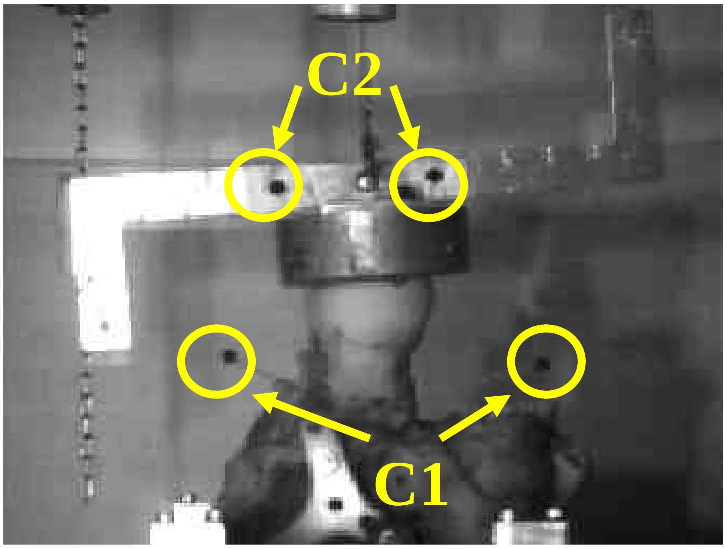


Figure 1: Mounted markers were used to track C1 and C2 motion.

Following disarticulation of the skull from the cervical spine, cranial landmarks were digitized using a MicroScribe 3Dx with Immersion3 software (Immersion, San Jose, CA). The specimen was digitized while still in the halo to ensure that it was in the same orientation as it was during testing. Using the base plate as the reference frame, the nasion, external auditory meatus (EAM), infraorbital foramen (IOF), and zygion were digitized. The sagittal plane was digitized by outlining the profile of the nose with the digitizing pen, the Frankfort plane was the line digitized from the EAM to IOF, and the foramen magnum was digitized along its inside perimeter. The surface of the occipital condyles was digitized by first outlining the perimeter and then sampling a point cloud on the articular surface. This digitized data, reported in mm, was then co-registered onto the testing image using Matlab, with the EAM as the origin (Figure 2).

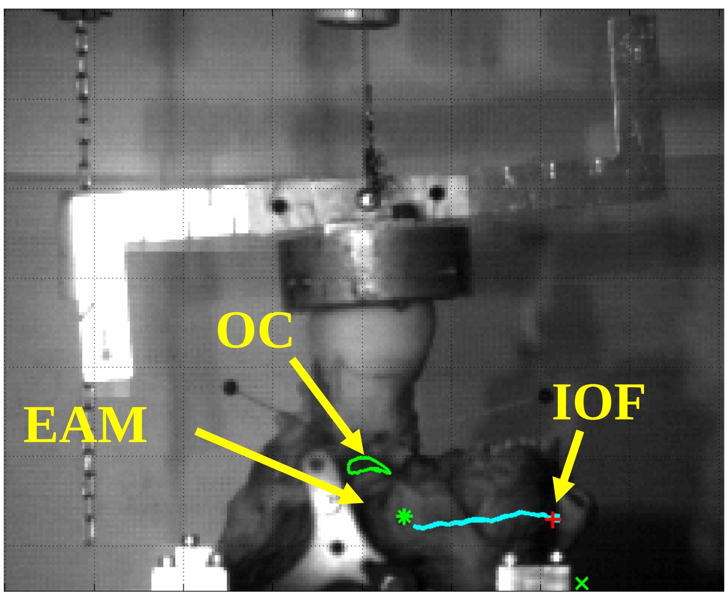


Figure 2: Anatomic landmarks derived from dissection are located on the digital image allowing for identification of the infraorbital (IOF), the external auditory meatus (EAM), and the occipital condyles

(OC). Center of rotation data from the bending test can then be quantitatively reported with respect to these anatomic landmarks.

The marker locations for C1 and C2 were tracked from the bending images using Image Express Motion Plus (SAI, Utica, NY). The COR were calculated for each image with Reuleaux's method as described by Panjabi et al. (1982):

$$X_c = \frac{(Z_4 - Z_3)E - (Z_2 - Z_1)F}{2G} \quad (1)$$

$$Z_c = \frac{(X_2 - X_1)E - (X_4 - X_3)F}{2G} \quad (2)$$

where,

$$E = X_2^2 - X_1^2 + Z_2^2 - Z_1^2$$
$$F = X_4^2 - X_3^2 + Z_4^2 - Z_3^2$$
$$G = (X_2 - X_1)(Z_4 - Z_3) - (X_4 - X_3)(Z_2 - Z_1)$$

The variables (X_1 , Z_1) and (X_2 , Z_2) represent the initial positions of the left and right markers, respectively. Likewise, (X_3 , Z_3) and (X_4 , Z_4) are the left and right marker positions after one increment of moment is applied. The COR was calculated using this formulation at each moment increment for O-C1 and O-C2 in both flexion and extension. These values were plotted on the same image as the cranial landmarks.

A representative point was defined about which the moments were calculated. This point was defined by averaging the most anterior coordinate of the articular surface with the most posterior coordinate of the articular surface. Flexion COR coordinates for O-C1 were averaged, then subtracted from the occipital condyle position. The coordinates for the extension COR were also averaged and subtracted from the condyles. Student t-tests were used to compare the positions of the coordinates in flexion and extension for O-C1. The same procedure was followed for O-C2 motion. Statistical significance was defined as $p < 0.05$.

Of the ten specimens, the one with the best image resolution and the one with the worst resolution were chosen to determine how the resolution affected standard deviations in the COR calculation. Ten trials were conducted on each, where the markers were tracked and their positions recorded. CORs were calculated, averaged, and had their standard deviations determined for each trial.

RESULTS

The COR calculated for the O-C1 joint of Specimen 1 showed that the extension COR was slightly more superior than the flexion COR (Figure 3). Extension COR was more anterior to the condyles (Table 1). There was a significant difference found in the x and z directions ($p < 0.001$) between extension and flexion. The CORs for the O-C2 extension were also more superior than those in flexion, with a significant difference found only in the z direction ($p < 0.001$) and not the x ($p = 0.88$) (Figure 4). The flexion COR is inferior to the occipital condyles (Table 1).

An anatomical variant was found while digitizing Specimen 2 (Figure 5). Each occipital condyle was found to contain two distinct surfaces. This anatomic variant occurred in 30% of the specimens. O-C1 flexion and extension CORs are superior to the condyles (Table 1). However, the CORs calculated for O-C1 flexion are on the posterior side of the condyles, while extension CORs remain on the anterior portion (Figure 6). Student t-tests yielded a significant difference for x and z directions ($p < 0.001$). Calculations for O-C2 motion showed flexion and extension CORs on the anterior portion of the condyles (Figure 7). A significant difference was found in the x direction with $p < 0.001$.

The specimen with the best resolution (0.7642 pixels/mm) had a standard deviation of 3.6×10^{-6} mm, while the specimen with the worst (1.040 pixels/mm) had a standard of 1.832 mm.

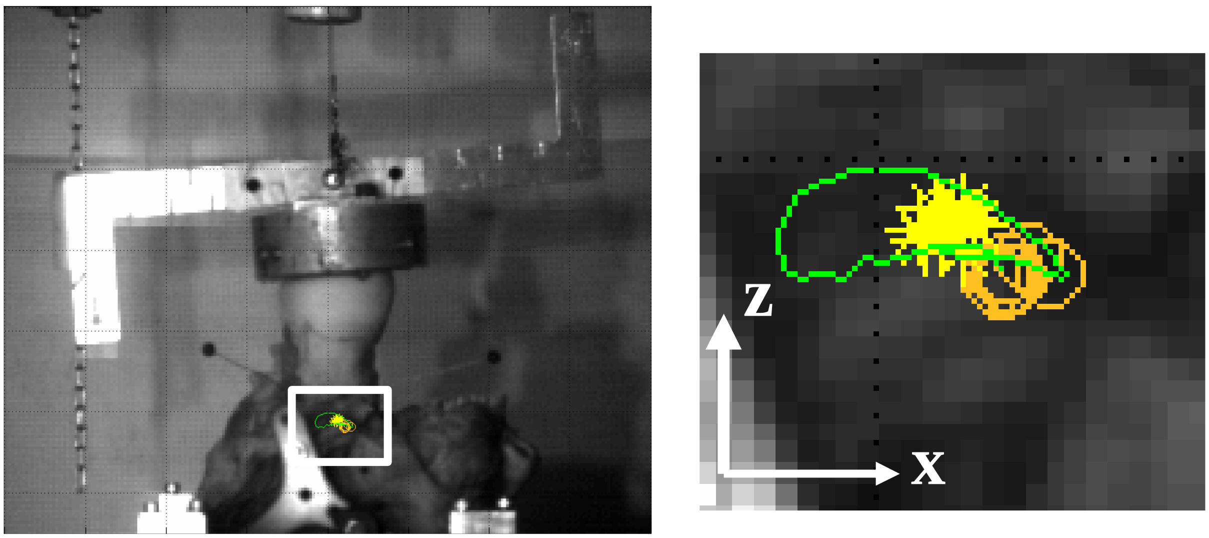


Figure 3: (Left) Entire image of specimen in the frame. (Right) Detailed image of the left occipital condyle of Specimen 1, showing O-C1 COR for flexion (yellow stars) and extension (orange circles).

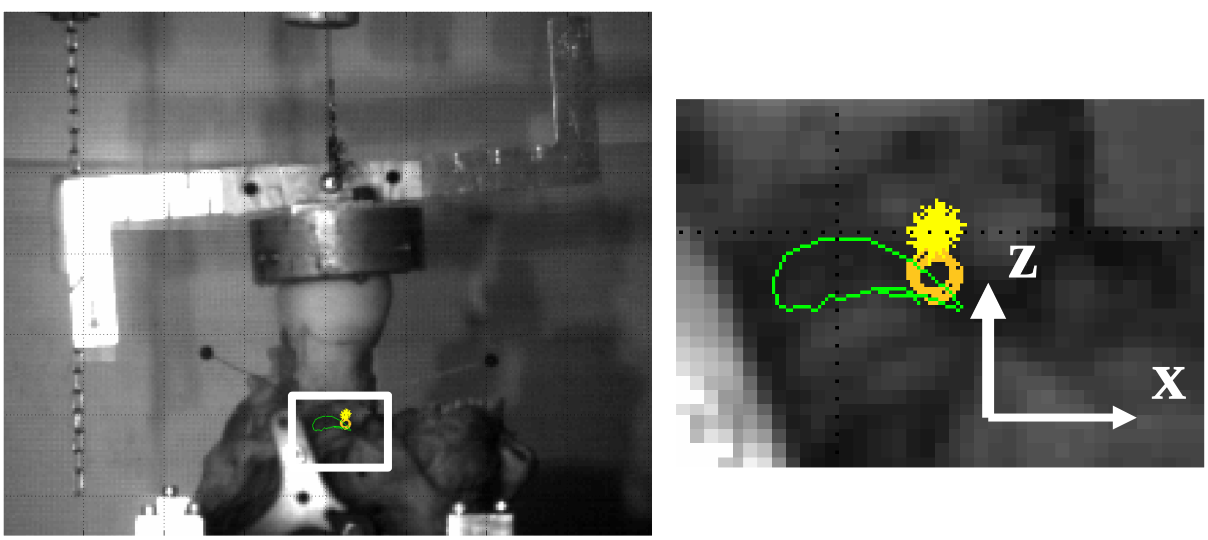


Figure 4: (Left) Entire image of specimen in the frame. (Right) Detailed image of the left occipital condyle of Specimen 1, showing O-C2 COR for flexion (yellow stars) and extension (orange circles).

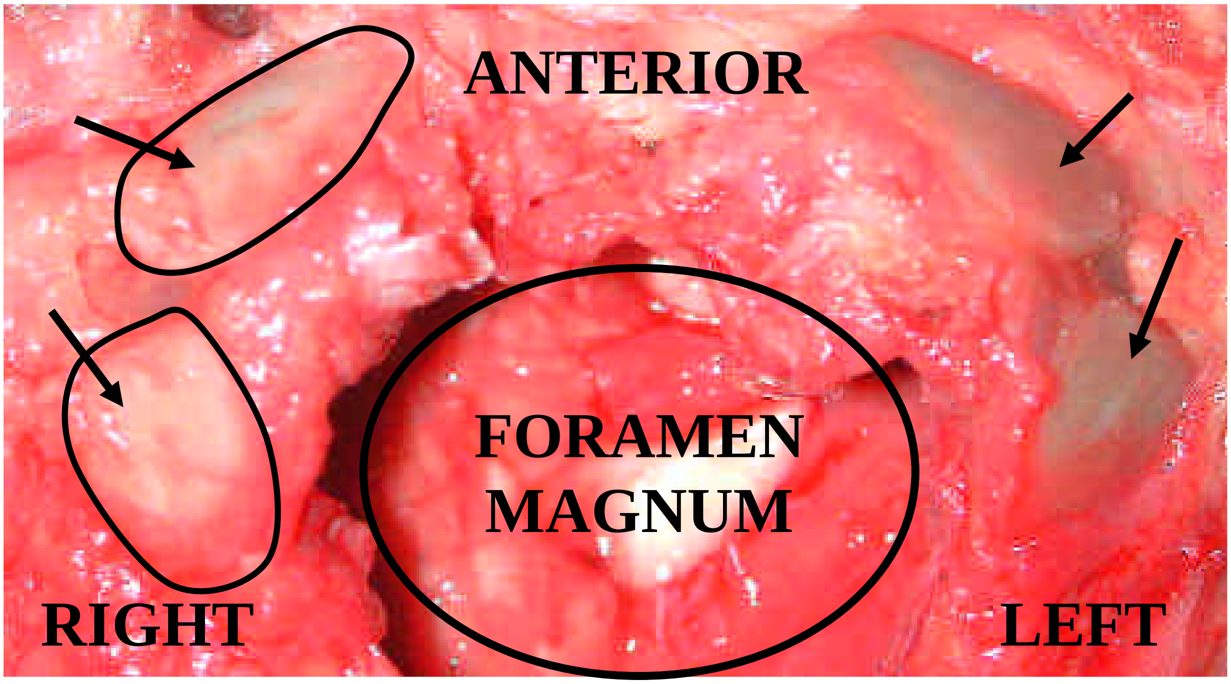


Figure 5: The base of skull of Specimen 2. The arrows identify the condylar facet double (Berry, 1975, Berry and Berry, 1967, Corruccini, R.S., 1974, Kellock et al., 1970)

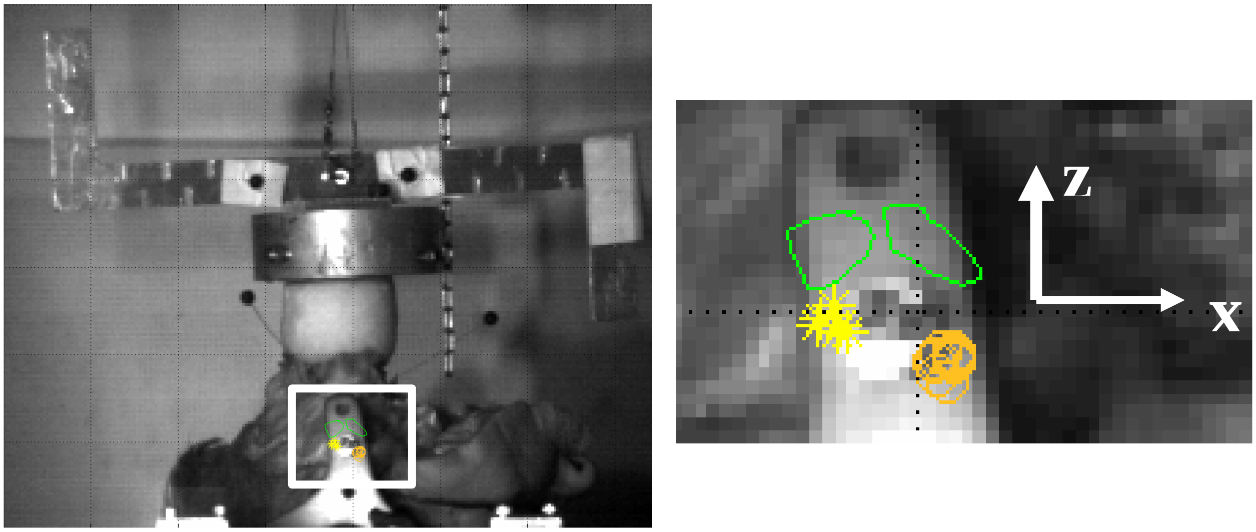
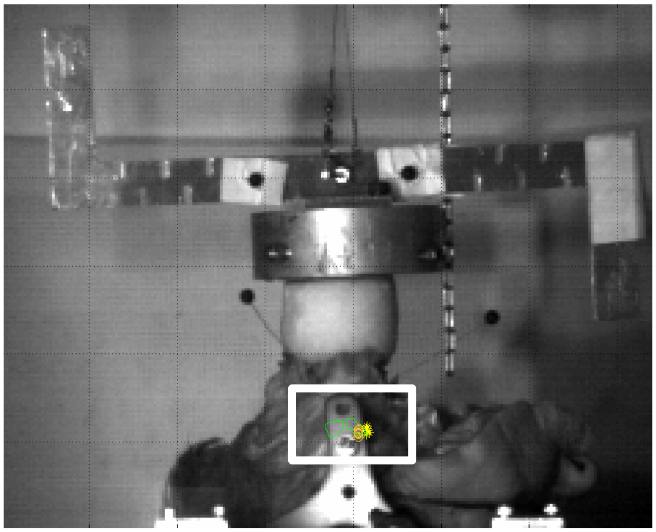


Figure 6: (Left) Entire image of specimen in frame. (Right) Detailed image of the divided articular surface of Specimen 2, showing O-C1 COR for flexion (yellow stars) and extension (orange circles).



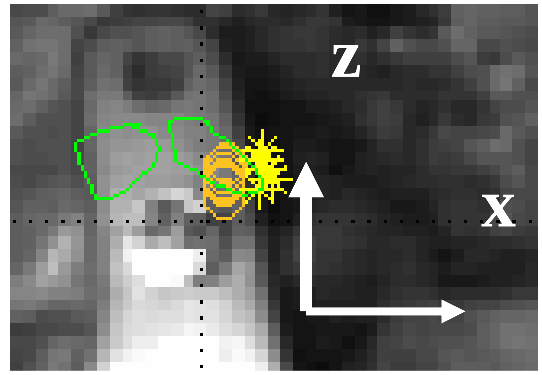


Figure 7: (Left) Entire image of specimen in frame. (Right) Detailed image of the divided articular surface of Specimen 2, showing O-C2 COR for flexion (yellow stars) and extension (orange circles).

Table 1. COR Locations (± Standard Deviations) Relative To The Center Of The Occipital Condyle

Specimen	Segment	Motion	x (mm)	z (mm)
1	O-C1	Flexion	2.1 ± 1.4*	2.4 ± 1.2*
		Extension	7.5 ± 1.5*	-1.5 ± 0.6*
	O-C2	Flexion	8.5 ± 0.7	8.0 ± 0.8*
		Extension	8.5 ± 0.4	2.4 ± 0.6*
2	O-C1	Flexion	-6.4 ± 1.4*	-9.0 ± 1.2*
		Extension	7.6 ± 1.0*	-13.7 ± 1.3*
	O-C2	Flexion	12.1 ± 0.6*	-0.6 ± 1.7*
		Extension	7.0 ± 1.0*	-2.0 ± 1.3*

* *Indicates a significant difference between flexion and extension ($p < 0.001$)*

DISCUSSION

In prior studies, approximations of the location of the occipital condyles have been made, but their exact location was not measured directly (Hubbard et al., 1973, Byars et al., 1970, Butler, 1992). The COR for the upper neck has been difficult to measure in the past due to its unique anatomy (Amevo et al., 1991, Bogduk et al., 1995). For these reasons, upper neck moment measurements are challenging, therefore the OC and the upper cervical CORs need to be quantitatively located with respect to each other and other known cranial landmarks.

Limitations found in this study include the two dimensional methodology, the accuracy of the digitization systems, and the repeatability of the image tracking software. Since Reuleaux's method of determining the COR is only applicable for planar motion, the equations cannot be used to determine a third coordinate if a 3D camera system is used. More importantly, the affect of any out of plane rotations, if they occurred, is unknown. Thus, the location of the COR with respect to the medial-lateral (y) axis has not been examined in the current study. Camera resolution affected the repeatability of the tracking software and therefore the error of the calculated COR. On the specimen with the best resolution (0.7642 pixels/mm), the standard deviation found on O-C1 and O-C2 was 3.6×10^{-6} mm. The specimen with the worst resolution (1.040 pixels/mm) had a standard deviation of 1.832 mm. Poorer image resolution creates significant challenges for the image software and appears to be responsible for the significantly larger variance. The Microscribe 3Dx had an error of ± 0.22 mm, so when the distance between the cranial landmarks and the CORs are determined, both errors must be taken into account.

As the moment was increased in flexion and then extension, the COR did not vary significantly, with relatively small standard deviations ranging from 0.6 mm to 1.7 mm. Interestingly, significant differences were seen between the flexion and extension CORs despite the small distances measured. Completion of the study and additional analysis of data will determine if these small but significant differences impact the calculated neck moment.

Further work is needed to define the geometric location of the occipital condyles more accurately, perhaps by determining the centroid of its area. The marker locations of O-C1 and O-C2 can be useful in calculating the COR of C1-C2. They will allow us to calculate the rotation of C1 relative to C2. Once that is found, Reuleaux's method can be used to calculate the COR for the segment. The technique presented in this study can be applied to the lower cervical spine to study its motion as well. The lower motion segments were tested using the same rigid moment arm with digitizing markers to track motion. However, reliable landmarks on the lower cervical spine will have to be identified in order to relate the CORs calculated.

Thirty percent of the specimens in this study had a condylar facet double (Berry, 1975, Berry et al., 1967, Corruccini, 1974, Kellock et al., 1970). In the Berry et al. study, this anomaly was found in less then 1% of the 585 skulls observed. The importance and frequency of this variation should be investigated further.

CONCLUSIONS

This study has enabled us to define a location of the occipital condyles, accurately calculate the COR for O-C1 and O-C2, and then determine the location of the COR relative to the condyles. It has been shown that the COR does not vary significantly with moment; and while the CORs for flexion and extension are significantly different, the distance between the two CORs is small. Completion of the data analysis will define this difference and allow for a quantitative understanding of its impact on calculated upper cervical bending moment.

ACKNOWLEDGEMENTS

The Injury and Orthopedic Biomechanics Laboratory at Duke University thanks the Department of Transportation, National Highway Traffic Safety Administration for its generous and longstanding commitment to this research (Contract No. DTNH22-94-Y-07133).

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DISCUSSION

PAPER: **Centers of Rotation for the Upper Cervical Spine: Methodology and Preliminary Data**

PRESENTER: ***Danielle Ottaviano, Duke University***

QUESTION: *Guy Nusholtz, Daimler/Chrysler*
It looks like your CORs are revolving at times, or they're moving as you pass the trajectory. Did I read the data correctly?

ANSWER: There's clouds. I don't--I haven't actually seen the progression through each load increment. Is that what you mean?

Q: Yeah. It looks--There are clouds in the diagram.

A: Right.

Q: But it looks like they're moving around quite a bit. Did you just--Are you just choosing the condyles and looking at how those move, or are you trying to calculate a center of rotation?

A: Calculate a center of rotation. I took the average. I guess I didn't say that. I'm sorry. I took the average center of rotation and I referenced that to the condyles.

Q: Okay. So you're looking--So the con--So the center of rotation is projected away from that, from the condyles. It's not exactly at it.

A: Right. Correct.

Q: And is that--How do you--How are you defining the center of rotation? Is that a minimum rotation? Is it a center in absent space or is it a center with respect to something else? Since your center is moving--

A: Yes.

Q: It's only--It's only a center at that point in time.

A: Right.

Q: Did you try to find the minimum, a center which has a minimum motion?

A: No, I haven't.

Q: As you move it through the whole, the whole rotation so it's actually a center in which you're actually moving around.

A: No, I haven't done that yet.

Q: Okay. Thank you.

Q: *Erik Takhounts, National Highway Traffic Safety Administration*

Danielle, very nice research. I have a small question for you.

A: Sure.

Q: I was wondering if you thought about how muscle activation. When you activate muscles so there will be inter-vertebral or extra-vertebral, there's probably going to be some constraints in the relative motion in both C1 and the C1/C2. I was wondering: How would you think--I know that you haven't done this yet!--that would affect your center of rotation?

A: I actually--No. I haven't thought about that. I only--I've only done two of them, so I haven't really gotten any further.

Q: That'll be interesting to know in the future.

A: I agree.