Biomechanical evaluation of the craniovertebral junction after unilateral joint-sparing condylectomy: implications for the far lateral approach revisited

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OBJECTIVE The far lateral transcondylar approach to the ventral foramen magnum requires partial resection of the occipital condyle. Early biomechanical studies suggest that occipitocervical (OC) fusion should be considered if 50% of the condyle is resected. In clinical practice, however, a joint-sparing condylectomy has often been employed without the need for OC fusion. The biomechanics of the joint-sparing technique have not been reported. Authors of the present study hypothesized that the clinically relevant joint-sparing condylectomy would result in added stability of the craniovertebral junction as compared with earlier reports.

METHODS Multidirectional in vitro flexibility tests were performed using a robotic spine-testing system on 7 fresh cadaveric spines to assess the effect of sequential unilateral joint-sparing condylectomy (25%, 50%, 75%, 100%) in comparison with the intact state by using cardinal direction and coupled moments combined with a simulated head weight "follower load."

RESULTS The percent change in range of motion following sequential condylectomy as compared with the intact state was 5.2%, 8.1%, 12.0%, and 27.5% in flexion-extension (FE); 8.4%, 14.7%, 39.1%, and 80.2% in lateral bending (LB); and 24.4%, 31.5%, 49.9%, and 141.1% in axial rotation (AR). Only values at 100% condylectomy were statistically significant ($p < 0.05$). With coupled motions, however, –3.9%, 6.6%, 35.8%, and 142.4% increases in AR+F and 27.3%, 32.7%, 77.5%, and 175.5% increases in AR+E were found. Values for 75% and 100% condyle resection were statistically significant in AR+E.

CONCLUSIONS When tested in the traditional cardinal directions, a 50% joint-sparing condylectomy did not significantly increase motion. However, removing 75% of the condyle may necessitate fusion, as a statistically significant increase in motion was found when E was coupled with AR. Clinical correlation is ultimately needed to determine the need for OC fusion.

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KEY WORDS occipital condylectomy; biomechanics; skull base surgery; spine; far lateral approach; occipitocervical fusion; spinal instability

ANTERIOR and anterolateral lesions at the craniovertebral junction (CVJ) pose a surgical challenge to neurosurgeons given the lesions' proximity to critical neurovascular structures. Initial attempts to address such lesions from a traditional midline suboccipital craniectomy resulted in high morbidity and mortality.^{14,22,38,40} Over the last several decades, alternative approaches have been developed to address these lesions more safely.^{1–3,5–13,15–19,21,23–26,29,30,32–37,44}

In 1978, Seeger first proposed removing the condyle to access the ventral foramen magnum from a more lateral approach.³⁴ Since then, many reports in the literature have described the far lateral transcondylar and extreme lateral approaches.^{1–3,6,7,11,16,23,30,33,36,37,44} As these approaches became more commonplace, questions arose regarding the stability of the CVJ after condylectomy. In 1999, Vishteh et al. performed a biomechanical analysis of the CVJ after unilateral condylectomy.⁴¹ They found that removing 50%

ABBREVIATIONS AR = axial rotation; CVJ = craniovertebral junction; FE = flexion-extension; HWL = head weight load; LB = lateral bending; O = occiput; OC = occipitocervical; ROM = range of motion; SOC+C1 = suboccipital craniectomy with C-1 laminectomy.

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or more of the condyle resulted in significantly increased mobility in flexion-extension (FE), lateral bending (LB), and axial rotation (AR). They concluded that occipitocervical (OC) fusion should be considered after resecting 50% or more of the condyle.

Anatomical studies have demonstrated that, on average, the hypoglossal canal divides the condyle in half along its longitudinal axis.^{4,27,28} Consequently, the hypoglossal canal has been used as a surgical landmark to approximate resection of 50% of the condyle. In practice, however, fusion after resection of the condyle up to the hypoglossal canal has frequently not been necessary. This clinical experience creates discordance with previous biomechanical findings. The reason for this may be 2-fold. First, because the transcondylar approach has been used and refined over time, many authors believe that the superomedial portion of the condyle obstructs visualization of the clivus and that the removal of only this portion is necessary to access most lesions of the CVJ. Condylectomy performed in a prior study by Vishteh et al. included resection of the occiput (O)–C1 joint.⁴¹ Second, the results of this prior biomechanical study have not been confirmed. The authors used a quasi-static testing model that employed cables and pulleys. A biomechanical study employing dynamic testing controlled by robotics could yield different results. Therefore, we sought to assess the stability of the O–C1 and C1–2 joints after unilateral joint-sparing condylectomy (25%, 50%, 75%, 100%) in comparison with the intact state by using a simulated head weight, follower load, and coupled motions. We hypothesized that the joint-sparing condylectomy would result in added stability of the CVJ as compared with earlier reports.

Methods

Cadaveric Specimens

Seven fresh-frozen, unembalmed, human cadaveric specimens, O–C7, free from any craniocervical pathology were used. Specimens were obtained from donors 40–75 years of age at the time of death. Donors were screened for any history of cancer or rheumatoid disease. Occipitocervical radiographs of the specimens were reviewed to rule out any traumatic injuries, fusion, prior surgery, or major deformity. The cranium was transected just above a line drawn from the supraorbital rim to the inion, and all soft tissues and musculature were removed while preserving all joint capsules and spinal ligaments. We placed 1.5-mm titanium microscrews in various points along the O to serve as skull fiducial markers. Volumetric CT scanning (1.0 mm) of all specimens was performed for input into stereotactic navigation software (Medtronic StealthStation S7). Specimens were warmed to room temperature, and all testing for a given specimen was performed on a single day to avoid repeated freezing and thawing. Specimens were moistened with saline as needed to prevent drying during testing.

Biomechanical Testing

In vitro intact flexibility tests were conducted using a 6-axis robotic spine-testing system (KR16, Kuka Robotics). A 6-axis force-moment sensor (Delta/SI-330–30, ATI

Industrial Automation) was used to measure the applied loads and provide feedback for the robot, which was controlled with simVITRO software (Cleveland Clinic). For this study, the system applied a constant 40-N force for head weight simulation, followed by 3 loading and unloading cycles of continuous moment (± 1.5 Nm) to simulate FE, LB, and AR. The system also simulated coupled motions involving AR with E (AR+E) and AR with F (AR+F) using ± 1.5 -Nm magnitudes. The vertical force vector was applied in the direction of gravity regardless of the orientation of the spine. This constant vertical force was used to simulate head weight load (HWL) during cervical spine motion. The specimens were preconditioned to minimize viscoelastic effects.

Range of motion (ROM) at the O–C1 and C1–2 levels was determined from the final loading cycle for each specimen. The relative vertebral motion was captured using an optoelectronic camera system (Optotrak, Northern Digital Inc.). Infrared motion sensors were placed on the O and the vertebral bodies of C-1 and C-2 (Fig. 1). Anatomical landmarks were then digitized to define the coordinate systems and capture relative vertebral kinematics per International Society of Biomechanics standards.⁴³

FIG. 1. Testing setup. The specimen is rigidly fixed at the O and C-3. A navigation reference frame is rigidly fixed to the O, and titanium micro-screw fiducial markers are registered. Optoelectric sensors are placed in the O, C-1, and C-2 to record relative ROM. A 6-axis robotic spine-testing system was used to apply head weight simulation and loading and unloading cycles of continuous moment. Figure is available in color online only.

FIG. 2. **A:** Sagittal CT demonstrating occipital condyle anatomy with a rectangular main body (green) and concave articular surface (red). **B:** View of the foramen magnum. Yellow indicates the area of unilateral suboccipital craniectomy. Each condyle was divided into 4 quadrants along the anatomical transverse axis. Dotted lines indicate approximate location and course of the hypoglossal canal (HC). Figure is available in color online only.

Surgical Conditions

First, the specimens were tested in the intact state in all planes of motion under a constant HWL. After intact testing, the following surgical conditions were sequentially performed on each specimen: unilateral suboccipital craniectomy with C-1 laminectomy (SOC+C1) and 25%, 50%, 75%, and 100% joint-sparing condyle resections. Cranial navigational software was used to create a condyle resection plan. The condyle was divided into 2 components: a rectangular body and a concave articulating portion. The intersection of these 2 components was defined by a line drawn from the junction of the vertical and concave portions of the condyle at its anterior and posterior aspects (Fig. 2A). The body of the condyle was divided into 4 segments along the anatomical transverse axis (Fig. 2B). Using a 2-mm diamond bur, segmental condylectomy was performed, sparing the concave articulating portion of the condyle, with the extent of the condylectomy guided by navigation (Fig. 3). With removal of the condyle body, even a 25% condylectomy, there was often very little functional attachment of the joint capsule on the posterior portion of the occipital condyle. Multidirectional flexibility testing was repeated after each sequential surgical condition. In this manner, each specimen served as its own control to account for interspecimen differences in baseline ROM.

Statistical Analysis

Mean relative ROM was compared among groups using repeated-measures ANOVA. Post hoc Tukey-Kramer analysis was used for multiple comparisons between groups. A p value < 0.05 was considered statistically significant. Mean values are expressed with their standard deviations.

Results

Intact State and C-1 Laminectomy

The mean ROM at the OC junction in FE, LB, and AR was $24.8^\circ \pm 10.1^\circ$, $6.7^\circ \pm 2.3^\circ$, and $6.9^\circ \pm 3.9^\circ$, respectively.

Coupled AR+E resulted in a mean ROM of $7.4^\circ \pm 4.2^\circ$. Coupled AR+F resulted in a mean ROM of $5.6^\circ \pm 2.5^\circ$. Unilateral SOC+C1 resulted in no statistically significant changes (Table 1).

Sequential Joint-Sparing Condylectomy

Twenty-five percent condylectomy resulted in non-significant changes in ROM in all cardinal and coupled directions. Compared with the intact condition, AR+E showed the largest absolute increase (2.1°). Mean ROM changed by only 1.3° , 0.6° , 1.7° , and -0.2° in FE, LB, AR, and AR+F. With 50% resection of the unilateral condyle, AR+E showed a marginal increase by an additional 0.4° . As compared with the previous condition, 50% condylectomy resulted in a negligible change in all directions: 0.7° , 0.4° , 0.5° , and 0.5° in FE, LB, AR, and AR+F, respectively.

With 75% condylectomy, the change in absolute ROM in each cardinal direction was larger than with prior surgical conditions: 1.0° , 1.6° , 1.3° , 1.7° , and 3.3° in FE, LB, AR, AR+F, and AR+E, respectively. The change in AR+E was statistically significant ($p = 0.04$). The 2.6° increase in ROM in LB as compared with the intact state was not significant ($p = 0.07$); however, the increase was significant when evaluating LB ROM over O–C2 ($p = 0.02$; Table 2). Although changes in other directions were not statistically significant, these increases were found to be 1.3–3.3 times larger than increases in ROM recorded after prior surgical conditions. As expected, there were large changes in ROM following 100% condylectomy in cardinal and coupled directions (Fig. 4).

C1–2 Stability

The mean ROM in FE, LB, AR, AR+F, and AR+E was 12.0° , 4.9° , 65.4° , 64.8° , and 63.5° , respectively. There were no statistically significant changes in the ROM at C1–2 following each surgical procedure (Table 3).

Measurement Variability

Across all specimens and conditions, at the distinct

FIG. 3. Stereotactically guided joint-sparing condylectomy. Navigation plan (**A and B**) demonstrating 25% (green), 50% (red), and 75% (blue) resection lines. Navigation pointer on the lateral margin (**C**) and the medial margin (**D**) of the 25% condylar resection line. Blue dotted lines in the photographs (**C and D**) indicate the posterior O-C1 joint line. Figure is available in color online only.

quasi-static loading region of interest, the root-mean-square errors between the prescribed and actual loads were 2.1 N, 9.4 N, 2.9 N, 0.08 Nm, 0.04 Nm, and 0.08 Nm in the posterior, compression, lateral, AR, FE, and LB degrees of freedom.

Discussion

We investigated the kinematics of the OC junction following sequential joint-sparing condylectomy and found statistically significant increases in coupled ROM at the 75% condyle resection. Authors of an early biomechanical study found that condylectomy extending into the OC joint resulted in statistically increased FE ROM at the 25% condylectomy and larger increases in all cardinal directions after a 50% condylectomy.³⁶ They concluded that OC fusion should be considered following 50% condyle resection. However, in an attempt to avoid iatrogenic

instability requiring OC fusion, many surgeons perform condylectomy sparing the OC joint.^{18,19,39} We hypothesized that a joint-sparing technique would result in added stability at this degree of condyle resection.

In a prior study, Vishteh et al. found statistically significant increases in FE (15.3%), LB (40.8%), and AR (28.1%) after resecting 50% of the condyle.⁴¹ We found smaller overall increases (8.1%, 14.7%, and 31.5%, respectively), which were not statistically significant. This finding suggests that the joint-sparing condylectomy provides biomechanically relevant additional stability to the OC joint. In contrast to the conclusion of Vishteh et al., our data suggest that OC fusion is unlikely to be necessary when 50% of the condyle has been removed using the joint-sparing technique. At 75% condyle resection, there appeared to be meaningful increases in ROM in LB (39.1%), but they were not significant ($p = 0.07$). However, when analyzing

TABLE 1. Occiput–C1 mean ROM in primary and coupled movements across various surgical conditions

Direction	Intact	SOC+C1	Condyle Resection			
			25%	50%	75%	100%
FE	24.8° ± 10.1°	24.7° ± 8.4° –0.4% (0.49)	26.1° ± 7.9° 5.2% (0.40)	26.8° ± 8.1° 8.1% (0.34)	27.8° ± 8.9° 12.0% (0.28)	31.6° ± 10.9° 27.5% (0.12)
LB	6.7° ± 2.3°	6.7° ± 2.9° –0.9% (0.48)	7.3° ± 2.8° 8.4% (0.35)	7.7° ± 2.7° 14.7% (0.24)	9.3° ± 3.8° 39.1% (0.07)	12.1° ± 5.1° 80.2% (0.01)
AR	6.9° ± 3.9°	7.9° ± 4.0° 13.6% (0.34)	8.6° ± 3.6° 24.4% (0.23)	9.1° ± 4.0° 31.5% (0.18)	10.4° ± 5.1° 49.9% (0.11)	16.7° ± 6.6° 141.1% (<0.01)
AR+F	5.6° ± 2.5°	6.2° ± 2.3° 10.9% (0.33)	5.4° ± 2.6° –3.9% (0.44)	5.9° ± 2.8° 6.6% (0.41)	7.6° ± 4.1° 35.8% (0.17)	13.5° ± 6.0° 142.4% (<0.01)
AR+E	7.4° ± 4.2°	8.9° ± 5.7° 20.2% (0.31)	9.5° ± 4.7° 27.3% (0.24)	9.9° ± 4.8° 32.7% (0.20)	13.2° ± 5.6° 77.5% (0.04)	20.5° ± 10.2° 175.5% (0.01)

Values reflect mean ROM ± standard deviation (first line) and the percentage change in ROM with associated p values in parentheses (second line) for each surgical condition. Boldface type indicates statistical significance ($p < 0.05$) as compared to the intact state.

the ROM over O–C2, there was a significant increase ($p = 0.02$) in LB after 75% resection. There also appeared to be a meaningful increase in AR (49.9%) after 75% resection, but it was not significant ($p = 0.11$), probably because of power limitation. The importance of testing coupled motions was evident at this extent of condyle resection. We found a statistically significant 77.5% increase in AR+E ($p = 0.04$) following 75% condyle resection. Our results indicated that in using a joint-sparing technique, the OC joint may require fusion when 75% of the condyle is resected.

The differences in our results compared with those of the prior biomechanical study by Vishteh et al. are likely multifactorial.⁴¹ First, the joint-sparing condylectomy retains the entire OC joint surface and as much capsule as possible. Clinically, surgeons often resect the condyle to the hypoglossal canal without the need for OC fusion. Retention of this joint surface likely provides added stability as we have seen in biomechanical studies addressing partial joint resection following cervical foraminotomy. The study by Zdeblick et al. demonstrates that it is not until resection of 75% of the facet (in addition to laminectomy) that statistically significant increases in segmental displacement are seen.⁴⁵ The saddle-shaped geometry of

the OC joint may constrain translation to a greater extent compared with the subaxial cervical spine. Therefore, it is not surprising to find similar if not slightly greater tolerance for osseous and capsular disruption at the OC joint. Second, we used a simulated head weight, which biomechanically is a constant 40-N load directed vertically independent of neck position. It likely loads facet joints, especially those with horizontal orientation such as the OC joint, adding to stability in a clinically relevant manner. It is worth noting that our baseline ROM in the intact specimens was similar to those in prior studies.^{31,41,42} We found the mean ROM at O–C1 for FE, LB, and AR to be 24.8°, 6.7°, and 6.9°. The mean and range of ROM in 4 prior studies were 25° (23°–28°), 7.3° (5°–10°), and 9.8° (6°–14°).^{20,31,41,42}

There are several important limitations to this study. First, we must acknowledge that the nomenclature for the percentage of resection does not represent the true volumetric percentage resection of the condyle. Radiographic volumetric analysis after each sequential resection was not feasible. If one divides the condyle into a superior rectangular body and an inferior concave articulating portion (Fig. 2), the percentage of condyle resection, as reported

TABLE 2. Occiput–C2 mean ROM in primary and coupled movements across various surgical conditions

Direction	Intact	SOC+C1	Condyle Resection			
			25%	50%	75%	100%
FE	37.9° ± 11.1°	38.9° ± 9.4° 2.5% (0.44)	40.8° ± 9.8° 7.6% (0.31)	41.5° ± 9.7° 9.5% (0.27)	42.5° ± 9.9° 12.1% (0.22)	45.2° ± 12.3° 19.1% (0.14)
LB	15.3° ± 3.0°	16.0° ± 2.4° 4.4% (0.34)	15.3° ± 1.6° 0.0% (0.50)	15.8° ± 2.1° 2.8% (0.38)	19.6° ± 3.7° 27.9% (0.02)	27.6° ± 6.6° 80.1% (<0.01)
AR	78.5° ± 11.9°	79.2° ± 12.1° 0.9% (0.46)	82.4° ± 12.4° 5.0% (0.28)	83.6° ± 12.3° 6.5% (0.22)	85.8° ± 12.9° 9.3% (0.15)	92.6° ± 14.3° 18.0% (0.03)
AR+F	75.8° ± 10.8°	77.4° ± 11.8° 2.1% (0.40)	78.7° ± 11.1° 3.9% (0.31)	79.5° ± 11.0° 4.8% (0.27)	82.0° ± 12.4° 8.1% (0.17)	89.6° ± 15.9° 18.2% (0.04)
AR+E	75.6° ± 11.5°	76.4° ± 11.6° 1.0% (0.45)	79.2° ± 11.8° 4.7% (0.29)	80.0° ± 11.8° 5.8% (0.25)	82.9° ± 11.9° 9.7% (0.13)	92.6° ± 16.4° 22.5% (0.02)

Values reflect mean ROM ± standard deviation (first line) and percentage change in ROM with associated p values in parentheses (second line) for each surgical condition. Boldface type indicates statistical significance ($p < 0.05$) as compared to the intact state.

FIG. 4. Occiput–C1 mean ROM (% change compared with intact state) in cardinal (**A**) and coupled (**B**) movements across various surgical conditions. Asterisks indicate statistical significance compared with the intact state.

TABLE 3. C1–2 mean ROM in primary and coupled movements across various surgical conditions

Direction	Intact	SOC+C1	Condyle Resection			
			25%	50%	75%	100%
FE	12.0° ± 4.3°	12.2° ± 3.7° 1.8% (0.46)	13.5° ± 2.4° 12.7% (0.22)	13.7° ± 2.6° 14.4% (0.19)	13.7° ± 2.9° 15.0% (0.19)	12.9° ± 3.8° 8.2% (0.33)
LB	4.9° ± 2.9°	5.2° ± 3.1° 5.5% (0.44)	5.2° ± 2.3° 6.4% (0.41)	5.3° ± 2.2° 7.9% (0.39)	5.8° ± 2.0° 18.1% (0.26)	6.4° ± 2.3° 31.8% (0.14)
AR	65.4° ± 9.0°	62.8° ± 11.8° -4.0% (0.35)	66.7° ± 8.8° 2.0% (0.41)	69.9° ± 9.9° 6.8% (0.23)	70.9° ± 9.9° 8.4% (0.18)	71.9° ± 9.8° 9.9% (0.14)
AR+F	64.8° ± 13.3°	63.6° ± 19.6° -1.8% (0.45)	69.6° ± 11.1° 7.4% (0.26)	70.2° ± 10.8° 8.4% (0.23)	71.3° ± 10.8° 10.1% (0.19)	74.2° ± 10.4° 14.5% (0.09)
AR+E	63.5° ± 10.4°	61.3° ± 17.5° -3.4% (0.40)	67.2° ± 8.7° 5.9% (0.26)	67.8° ± 8.7° 6.9% (0.22)	68.8° ± 8.4° 8.4% (0.18)	70.6° ± 10.3° 11.2% (0.13)

Values reflect mean ROM ± standard deviation (first line) and percentage change in ROM with associated p values in parentheses (second line) for each surgical condition. There were no statistically significant changes in the ROM at C1–2 following each surgical procedure.

in our study, refers to the percentage of the superior rectangular body. Clinically, this portion of the condyle can be easily divided into 4 quadrants on an axial CT scan, and the degree of condyle resected intraoperatively can be estimated by neuronavigation. Second, while we have used standard validated biomechanical techniques, a cadaveric (nonhealing) model is limited in that we only test for acute instability and cannot assess the effect of repeated cyclical loading and unloading that, coupled with postsurgery biological remodeling, may affect ROM and contribute to chronic instability. Moreover, chronic instability may pose a greater problem with higher degrees of condylectomy (for example, 75%) given the narrow column of bone that connects the occiput to the articulating surface of the condyle. Third, we have compared our results of the joint-sparing technique with those in similar prior biomechanical studies in which the joint was not spared. With additional resources, repeating the same study with the non-joint-sparing technique would allow more direct comparison of relative stability between these techniques and account for differences in the testing setup. Lastly, although we have compared our results to prior studies, there are no precise numerical ROM cutoffs for instability. Therefore, our results must be cautiously interpreted, and clinical symptoms must be evaluated to further assess for any signs of instability.

Conclusions

Results of this study suggest that in using a joint-sparing technique, up to 75% of the condyle can be removed without significant biomechanical instability at the O–C1 joint necessitating fusion. Condylectomy did not result in any significant instability at C1–2. These results must be interpreted in the context of the study limitations and clinical symptoms.

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Author Contributions

Conception and design: Kshetty. Acquisition of data: Kshetty, Healy, Colbrunn, Beckler. Analysis and interpretation of data: Kshetty, Healy, Colbrunn. Drafting the article: Kshetty. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Kshetty. Study supervision: Benzel, Recinos.

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