Biomechanical analysis of screw constructs for atlantoaxial fixation in cadavers: a systematic review and meta-analysis

Jerry Y. Du, BS, Alexander Aichmair, MD, Janina Kueper, Timothy Wright, PhD, and Darren R. Lebl, MD

Spine and Scoliosis Surgery, Hospital for Special Surgery, Weill Cornell Medical College, New York, New York

OBJECT The unique and complex biomechanics of the atlantoaxial junction make the treatment of C1–2 instability a challenge. Several screw-based constructs have been developed for atlantoaxial fixation. The biomechanical properties of these constructs have been assessed in numerous cadaver studies. The purpose of this study was to systematically review the literature on the biomechanical stability achieved using various C1–2 screw constructs and to perform a meta-analysis of the available data.

METHODS A systematic search of PubMed through July 1, 2013, was conducted using the following key words and Boolean operators: “atlanto [all fields]” AND “axial [all fields]” OR “C1–C2” AND “biomechanic.” Cadaveric studies on atlantoaxial fixation using screw constructs were included. Data were collected on instability models, fixation techniques, and range of motion (ROM). Forest plots were constructed to summarize the data and compare the biomechanical stability achieved.

RESULTS Fifteen articles met the inclusion criteria. An average (± SD) of 7.4 ± 1.8 cadaveric specimens were used in each study (range 5–12). The most common injury models were odontoidectomy (53.3%) and cervical ligament transection (26.7%). The most common spinal motion segments potted for motion analysis were occiput–C4 (46.7%) and occiput–C3 (33.3%). Four screw constructs (C1 lateral mass–C2 pedicle screw [C1LM–C2PS], C1–2 transarticular screw [C1–C2TA], C1 lateral mass–C2 translaminar screw [C1LM–C2TL], and C1 lateral mass–C2 pars screw [C1LM–C2 pars]) were assessed for biomechanical stability in axial rotation, flexion/extension, and lateral bending, for a total of 12 analyses. The C1LM–C2TL construct did not achieve significant lateral bending stabilization (p = 0.70). All the other analyses showed significant stabilization (p < 0.001 for each analysis). Significant heterogeneity was found among the reported stabilities achieved in the analyses (p < 0.001; I² > 80% for all significant analyses). The C1LM–C2 pars construct achieved significantly less axial rotation stability (average ROM 36.27° [95% CI 34.22°–38.33°]) than the 3 other constructs (p < 0.001; C1LM–C2PS average ROM 49.26° [95% CI 47.66°–50.87°], C1–C2TA average ROM 47.63° [95% CI 45.22°–50.04°], and C1LM–C2TL average ROM 53.26° [95% CI 49.91°–56.61°]) and significantly more flexion/extension stability (average ROM 13.45° [95% CI 10.53°–16.37°]) than the 3 other constructs (p < 0.001; C1LM–C2PS average ROM 9.02° [95% CI 8.25°–9.80°], C1–C2TA average ROM 7.39° [95% CI 5.60°–9.17°], and C1LM–C2TL average ROM 7.81° [95% CI 6.93°–8.69°]). The C1–C2TA (average ROM 5.49° [95% CI 3.89°–7.09°]) and C1LM–C2 pars (average ROM 4.21° [95% CI 2.19°–6.24°]) constructs achieved significantly more lateral bending stability than the other constructs (p < 0.001; C1LM–C2PS average ROM 1.51° [95% CI 1.23°–1.78°], C1LM–C2TL average ROM 0.07° [95% CI −0.44° to 0.29°]).

CONCLUSIONS Meta-analysis of the existing literature showed that all constructs provided significant stabilization in all axes of rotation, except for the C1LM–C2TL construct in lateral bending. There were significant differences in stabilization achieved in each axis of motion by the various screw constructs. These results underline the various strengths and weaknesses in biomechanical stabilization of different screw constructs. There was significant heterogeneity in the data reported across the studies. Standardized spinal motion segment configuration and injury models may provide more consistent and reliable results.

http://thejns.org/doi/abs/10.3171/2014.10.SPINE13805

KEY WORDS atlantoaxial fixation; C1–2 fixation; screw construct; cervical spine; biomechanics; stability

ABBREVIATIONS C1–C2TA = C1–2 transarticular screw; C1LM–C2PS = C1 lateral mass–C2 pedicle screw; C1LM–C2TL = C1 lateral mass–C2 translaminar screw; C1LM–C2 pars = C1 lateral mass–C2 pars screw; CI = confidence interval; ROM = range of motion.


INCLUDE WHEN CITING Published online December 5, 2014; DOI: 10.3171/2014.10.SPINE13805.

DISCLOSURE The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.
The atlantoaxial joint has complex biomechanical properties as a result of its unique anatomy, which provides high levels of mobility. The absence of an intervertebral disc between the C-1 and C-2 vertebrae and associated anatomy is unique, with stability provided largely by the transverse, alar, and apical ligaments in association with the joints’ articular and osseous structures. A variety of degenerative conditions, previous cervical surgery, congenital anomalies, and trauma may result in atlantoaxial instability. The techniques for fixation to restore stability and prevent potentially life-threatening neurological deterioration have progressed rapidly in recent years.

Posterior wiring and graft techniques, such as the Gallie, Brooks-Jenkins, and Sonntag techniques, have been used for many decades to achieve arthrodesis. The use of screw constructs for atlantoaxial fixation has emerged as a popular alternative. The technique described by Jeanneret and Magerl involves placing a transarticular screw through the C1–2 articular surfaces. Other screw constructs for atlantoaxial fixation include the Goel-Harms C1 lateral mass–C2 pedicle screw construct, the Wright C1 lateral mass–C2 translaminar (C1LM–C2TL) screw construct, and the C1 lateral mass–C2 (C1LM–C2) pars screw construct. An anterior approach for transarticular screws has also been described. Figures diagramming the various screw constructs are shown in Figs. 1–4.

In addition to distinct clinical indications, there are unique biomechanical properties to each screw construct that have been investigated using cadaveric models in various studies. To our knowledge, there has not been a systematic analysis of the biomechanical stability achieved by these various screw constructs in achieving atlantoaxial arthrodesis and preventing potentially life-threatening neurological sequelae. The purpose of this study was to systematically review the literature using cadaveric models to study the biomechanical stability achieved by various C1–2 screw constructs and to perform a meta-analysis on available data.

Methods

Literature Search

A systematic literature search using PubMed through July 1, 2013, was performed. The Boolean operators and search terms used are presented in Table 1. Biomechanical studies on atlantoaxial fixation using cadavers were identified. Abstracts of articles written in the English language were reviewed. The exclusion criteria and article-inclusion process are presented in Table 2. Clinical studies, animal studies, imaging studies, studies on intact and injury biomechanics without fixation, occiput fixation studies, and odontoplasty studies were excluded. Meta-analyses, systematic reviews, and review articles were also excluded. In addition, a total of 16 duplicate abstracts were identified and excluded.

Abstracts from a total of 209 articles from the primary literature search were individually reviewed, and 20 articles (10.0%) met the inclusion criteria. The full texts of the included papers were then retrieved and examined. Three studies that did not assess range of motion (ROM) and 2 studies that assessed screw constructs with additional fixation techniques were excluded, leaving a total of 15 studies (7.2%) included in this review.

Data extracted from the full text of the included articles were injury model, number of cadaveric specimens, cervical vertebral levels used in motion segment configuration, intact ROM, screw constructs, and postinjury/postinstrumentation ROM. ROM was reported in terms of 3 axes of rotation (flexion/extension, right and left axial rotation, and right and left lateral bending).

Statistical Analysis

Meta-analyses were performed using the inverse-variance procedure. The biomechanical stability achieved by the screw construct for each axis of rotation was defined as the difference in ROM between the intact spine and the injured spine with instrumentation. Biomechanical stability of the screw constructs was assessed using the z statistic, with a p value < 0.05 considered significant. Forest
Fig. 2. Schematic of screw placements in atlantoaxial fixation: C1–C2TA construct. Copyright Cynthia Conklin. Published with permission. Figure is available in color online only.

Fig. 3. Schematic of screw placements in atlantoaxial fixation: C1LM–C2TL construct. Copyright Cynthia Conklin. Published with permission. Figure is available in color online only.

Fig. 4. Schematic of screw placements in atlantoaxial fixation: C1LM–C2 pars screw construct. Copyright Cynthia Conklin. Published with permission. Figure is available in color online only.
plots were created, and average ROM reductions and 95% confidence intervals (CIs) were reported. Heterogeneity in reported stability among the studies was evaluated by the chi-square test and I² statistic. Significant heterogeneity was defined as a chi-square p value < 0.5 or an I² statistic ≥ 50%, which indicates that the differences in reported stability among the studies were a result of more than sampling error. The differences in stability achieved among the constructs for each axis of rotation were evaluated by the chi-square test. Possible publication bias was assessed using funnel plots, because studies with positive results are more likely to be published than those with negative results. Statistical analyses were performed using Review Manager (version 5.2, the Cochrane Collaboration).

**Results**

**Cadaveric Model Characteristics**

Fifteen articles were assessed (Table 3). Fixation procedures were performed on a total of 134 cadaveric specimens, with an average (± SD) of 7.4 ± 1.8 specimens per study (range 5–12). The spinal levels of the cadavers potted were occiput–C2 (n = 7), C1–2 (n = 10), occiput–C3 (n = 38), occiput–C4 (n = 57), and occiput–C5 (n = 12). The injury models used to simulate instability were odontoidectomy (53.3%), transection of cervical ligaments (26.7%), and other (20.0%). Primary injury models were assessed (Table 2). Secondary literature exclusions

**TABLE 2. Secondary literature exclusions**

<table>
<thead>
<tr>
<th>Exclusion Criteria</th>
<th>No. Excluded</th>
<th>No. Remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary literature search</td>
<td>NA</td>
<td>209</td>
</tr>
<tr>
<td>Article not in English</td>
<td>29</td>
<td>180</td>
</tr>
<tr>
<td>Irrelevant topic (animal, imaging, or clinical study)</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Intact biomechanics</td>
<td>27</td>
<td>73</td>
</tr>
<tr>
<td>Injury biomechanics</td>
<td>11</td>
<td>62</td>
</tr>
<tr>
<td>Meta-analysis, systematic review, or review article</td>
<td>6</td>
<td>56</td>
</tr>
<tr>
<td>Occiput fixation</td>
<td>17</td>
<td>39</td>
</tr>
<tr>
<td>Duplicate article</td>
<td>16</td>
<td>23</td>
</tr>
<tr>
<td>Odontoidoplasty</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>Did not assess ROM</td>
<td>3</td>
<td>17</td>
</tr>
<tr>
<td>Assessed nonscrew or hybrid construct</td>
<td>2</td>
<td>15</td>
</tr>
</tbody>
</table>

NA = not applicable.

C2 pedicle screw (C1LM–C2PS [n = 10]), C1LM–C2TL (n = 3), and C1LM–C2 pars (n = 3) constructs. Anterior-approach transarticular screw and C1 lateral mass–C3 lateral mass screw constructs were excluded from the meta-analysis because each technique was reported only once in the included articles. Unilateral screw constructs and hybrid screw constructs inserted using different techniques on the contralateral sides were also excluded.

**Axial Rotation**

A meta-analysis assessing the effect of each surgical fixation technique on axial rotation showed significant biomechanical stabilization in all 4 construct types (p < 0.001 for each construct). There was significant heterogeneity in reported stabilization among studies that assessed the C1LM–C2PS construct (p < 0.001; I² = 90%), the C1–C2TA construct (p < 0.001; I² = 96%), and the C1LM–C2TL construct (p < 0.001; I² = 83%). There was marginal heterogeneity among the studies that assessed the C1LM–C2 pars construct (p = 0.11; I² = 54%). The C1LM–C2 pars construct achieved significantly less stability in axial rotation (average ROM 36.27° [95% CI 34.22°–38.33°]) than the 3 other constructs (p < 0.001; C1LM–C2PS average ROM 49.26° [95% CI 47.66°–50.87°], C1–C2TA average ROM 47.63° [95% CI 45.22°–50.04°], and C1LM–C2TL average ROM 53.26° [95% CI 49.91°–56.61°]). The meta-analysis of fixation of axial rotation for the 4 screw construct types is summarized in a forest plot in Fig. 5.

**Flexion/Extension**

A meta-analysis assessing the effect of each surgical fixation technique on flexion/extension showed significant biomechanical stabilization in all 4 construct types (p < 0.001 for each construct). There was significant heterogeneity in the reported stabilization among studies that assessed the C1LM–C2PS construct (p < 0.001; I² = 81%). The C1LM–C2 pars construct achieved significantly more stability in flexion/extension (average ROM 13.45° [95% CI 10.53°–16.37°]) than the 3 other constructs (p < 0.001; C1LM–C2PS average ROM 9.02° [95% CI 8.25°–9.80°], C1–C2TA average ROM 7.39° [95% CI 5.60°–9.17°], and C1LM–C2TL average ROM 7.81° [95% CI 6.93°–8.69°]). The meta-analysis of fixation of flexion/extension for the 4 screw construct types is summarized in a forest plot in Fig. 6.

**Lateral Bending**

A meta-analysis assessing the effect of each surgical fixation technique on lateral bending showed significant biomechanical stabilization for the C1LM–C2PS (p < 0.001), C1–C2TA (p < 0.001), and C1LM–C2 pars (p < 0.001) constructs but not the C1LM–C2TL construct (p = 0.70). There was significant heterogeneity in the reported stabilization among the studies that assessed the C1LM–C2PS (p < 0.001; I² = 96%) and C1LM–C2TL constructs (p < 0.001; I² = 86%). There was marginal heterogeneity for the C1LM–C2 pars construct (p = 0.07; I² = 61%). The C1–C2TA (average ROM 5.29° [95% CI 3.89°–7.09°]) and C1LM–C2 pars (average ROM 4.21° [95% CI 2.19°–
### TABLE 3. Literature review

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>Injury Model</th>
<th>Spinal Level (no. of specimens)</th>
<th>Intact Spine ROM*</th>
<th>Screw Construct</th>
<th>Injured Spine ROM* w/ Instrumentation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Axial Rotation</td>
<td>Flexion/Extension</td>
<td>Lateral Bending</td>
</tr>
<tr>
<td>Lehman et al., 2012†</td>
<td>Odontoidectomy</td>
<td>Oc–C3 (10)</td>
<td>62.9 ± 7.9</td>
<td>17.4 ± 3.5</td>
<td>3.6 ± 2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Robertson et al., 2012</td>
<td>Odontoidectomy</td>
<td>Oc–C4 (6)</td>
<td>67.3 ± 13.8</td>
<td>14.1 ± 2.9</td>
<td>1.8 ± 1.1</td>
</tr>
<tr>
<td>Sim et al., 2011</td>
<td>Odontoidectomy &amp; ligament transection</td>
<td>Oc–C3 (7)</td>
<td>47.5 ± 9.6</td>
<td>10.6 ± 1.2</td>
<td>1.6 ± 0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Park et al., 2011</td>
<td>Odontoidectomy &amp; C1–2 facetectomy</td>
<td>Oc–C2 (7)</td>
<td>52.0 ± 17.54</td>
<td>14.5 ± 4.08</td>
<td>5.91 ± 4.11</td>
</tr>
<tr>
<td>Brasiliense et al., 2010</td>
<td>Odontoidectomy</td>
<td>Oc–C4 (7)</td>
<td>36.9 ± 2.8</td>
<td>18.5 ± 4.3</td>
<td>2.3 ± 1.0</td>
</tr>
<tr>
<td>Li et al., 2010</td>
<td>Ligament transection</td>
<td>Oc–C4 (6)</td>
<td>44.19 ± 4.34</td>
<td>17.78 ± 3.78</td>
<td>9.56 ± 1.2</td>
</tr>
<tr>
<td>Elgafy et al., 2010†</td>
<td>Odontoidectomy</td>
<td>Oc–C4 (9)</td>
<td>38 ± 12</td>
<td>21 ± 10</td>
<td>11 ± 7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guo et al., 2009§</td>
<td>Ligament transection</td>
<td>Oc–C4 (8)</td>
<td>72.1</td>
<td>22.3</td>
<td>12.1</td>
</tr>
<tr>
<td>Rocha et al., 2009†</td>
<td>Instrumentation hyperrotation to create subluxation</td>
<td>Oc–C3 (7)</td>
<td>60 ± 10</td>
<td>16 ± 4</td>
<td>9 ± 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ma et al., 2009†</td>
<td>Odontoidectomy</td>
<td>Oc–C5 (12)</td>
<td>57 ± 4</td>
<td>19 ± 5</td>
<td>9 ± 4</td>
</tr>
<tr>
<td>Dmitriev et al., 2009†</td>
<td>Odontoidectomy</td>
<td>Oc–C4 (7)</td>
<td>56 ± 12</td>
<td>20 ± 9</td>
<td>21 ± 11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kelly et al., 2008†</td>
<td>Odontoidectomy</td>
<td>Oc–C4 (7)</td>
<td>45 ± 8.5</td>
<td>30 ± 9.0</td>
<td>11 ± 6.4</td>
</tr>
<tr>
<td>Kuroki et al., 2005</td>
<td>Ligament transection</td>
<td>Oc–C3 (5)</td>
<td>45.48 ± 11.40</td>
<td>14.78 ± 4.36</td>
<td>4.53 ± 2.84</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(continued)
6.24°) constructs achieved more biomechanical stability in lateral bending than the other constructs (p < 0.001; C1LM-C2PS average ROM 1.51° [95% CI 1.23–1.78°] and C1LM-C2TL average ROM −0.07° [95% CI −0.44° to 0.29°]). The meta-analysis of fixation of lateral bending for the 4 screw construct types is summarized in a forest plot in Fig. 7.

Publication Bias

Funnel plots for axial rotation, flexion/extension, and lateral bending are presented in Fig. 8. Although there is a high degree of heterogeneity, there does not seem to be publication bias in axial rotation (Fig. 8A) or flexion/extension (Fig. 8B). The funnel plot for lateral bending demonstrated potential publication bias, because the studies tended to cluster to the right (i.e., more stabilization achieved) (Fig. 8C).

Discussion

The meta-analysis performed on 4 screw constructs for atlantoaxial fixation revealed that each method resulted in significant biomechanical stabilization of axial rotation and flexion/extension of the C1–2 motion segment. Of the 4 constructs, only the C1LM–C2TL construct did not achieve significant stabilization in lateral bending. There were, however, fewer studies that assessed the C1LM–C2TL constructs (n = 3) than the C1LM–C2PS (n = 10) and C1–C2TA (n = 5) constructs. Intact lateral bending ROM is less than intact axial rotation and flexion/extension ROM, so stabilization reduces lateral bending ROM relatively less. More data may be required to find statistical significance in lateral bending stabilization for the C1LM–C2TL construct. Future studies are warranted to investigate the clinical significance of this biomechanical finding, which may affect future surgical decision making.

Screw constructs are generally selected on the basis of the patient’s vascular and osseous atlantoaxial anatomy, the specific pathological lesion, and the experience and comfort level of the surgeon. The C1–C2TA screw construct involves a complete reduction of C-1 over C-2 and may be unsuitable if the patient presents with a fixed thoracic kyphosis or obesity that precludes the steep angle of approach required for the screw insertion. Additional disadvantages of the construct are the ineligibility of up to 23.5% of patients for the operation because of a “high-riding” vertebral artery and reported fusion rates ranging from 96% to 98%.2,13,16 The C1LM–C2PS construct does not require reduction of C-1 over C-2 before screw placement and is considered by some to be technically less demanding. Only 9% of patients are deemed anatomically unsuitable for this surgical method. Despite these advantages, considerable risk of vertebral artery or neurological injury resulting from the violation of the transverse foramen or the central canal related to excessive lateral or medial angulation exists.25 Reported fusion rates for the C1LM–C2PS procedure range from 88.2% to 100%.22,44 The C1LM–C2 pars and C1–C2TL constructs have generally been resorted to as surgical alternatives to C1–C2TA and C1LM–C2PS constructs because of their suitability for patients with unfavorable anatomical features for in-

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>Injury Model</th>
<th>Spinal Level (no. of specimens)</th>
<th>Screw Construct</th>
<th>Axial Rotation</th>
<th>Flexion/Extension</th>
<th>Lateral Bending</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hott et al., 2005</td>
<td>Odontoidectomy</td>
<td>Oc–C3 (7)</td>
<td>C1LM–C2 pars screw</td>
<td>1.04 ± 0.93</td>
<td>5.78 ± 3.22</td>
<td>−0.27 ± 0.26</td>
</tr>
<tr>
<td>Sen et al., 2005</td>
<td>Ligament transection</td>
<td>C1–2 (10)</td>
<td>Anterior approach C1–C2TA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

C1LM–C3LM = C1 lateral mass–C3 lateral mass; Oc = occiput. ROM is presented as the mean ± SD, as represented in the included articles, and values are expressed in degrees.
instrumentation in the C-2 pedicle or across the C1–2 articu-
lar surface (hypoplastic C-2 pedicle, high-riding vertebral 
artery, bone loss from pathological lesion, etc.). C1–
C2TL constructs are commonly used for cases in which 
contraindications for C1–C2TA and C1LM–C2PS con-
structs exist, primarily to avoid vertebral artery injury; the 
reported fusion rate is 92.9%. Elliott et al. performed 
a meta-analysis and found a slightly higher incidence of 
vertebral artery injury in C1LM–C2PS constructs than in 
C1LM–C2 pars constructs, with reported fusion rates high-
er for C1LM–C2PS constructs (97.8%) than for C1LM–C2 
pars constructs (93.5%). Given our findings of insufficient 
biomechanical stabilization of lateral bending by the C1–
C2TL construct, clinical studies to compare long-term fu-
sion rates and the incidence of hardware failures to the 
other constructs may help provide a clinical correlation.

If relative instability of the C1–C2TL construct in lateral 
bending has an associated effect on the rates of successful 
fusion and hardware failure, the C1–2 pars construct may 
be a more suitable alternative for patients ineligible for the 
C1–C2TA or C1–C2PS construct.

There are cadaver-based reports in the literature with 
conflicting results when fixation achieved by the C1–C2TA 
construct was compared to that of other screw constructs. 
Sim et al. reported that the C1–C2TA construct provided 
better biomechanical stabilization than the C1LM–C2PS 
construct in flexion/extension only, whereas Guo et al. 
reported better stabilization in axial rotation only. Li et al., Hott et al., and Ma et al. did not find significant dif-
fferences in the stabilization achieved with the C1–C2TA 
and C1LM–C2PS constructs in any degree of motion. Our 
results underline the various strengths and weaknesses 
in biomechanical stabilization of the 4 constructs. The 
results of our meta-analytical comparison of these screw 
constructs suggest that the C1–C2TA and C1LM–C2 pars 
constructs provide better lateral bending stabilization

![Forest plot comparing axial rotation stabilization achieved by various screw constructs. Values are presented as degrees. df = degrees of freedom. Figure is available in color online only.](image-url)
than the C1LM–C2PS and C1LM–C2TL constructs. The C1LM–C2 pars construct provides more flexion/extension stabilization but also less axial rotation stabilization than other constructs.

A limitation of this analysis was that several of the included studies did not report primary data regarding ROM, which required us to retrieve ROM data from provided figures, when available. Another limitation to this study was that bias correction using methods such as trim and fill was not performed. There have been reports of bias toward positive reporting in clinical studies. However, we believe that this bias does not affect cadaver-based studies to the same degree. Finally, there are inherent limitations to the use of cadaveric models for clinical disease states. Nonetheless, cadaver studies are valuable, because they offer a degree of control that is difficult to achieve in clinical studies because of confounding factors.

There was a high prevalence of heterogeneity in the results among reports for these screw constructs, which may be a result of inconsistency in the use of injury models and cervical motion segments potted for motional analysis. Standardized methods in cadaveric models of atlantoaxial instability may help reduce statistical confidence intervals and provide further clarity on comparisons in fixation techniques among the various screw constructs. Our study calls to attention the need for consistent methodology regarding the use of cadaver studies to assess fixation techniques.

Conclusions

Our meta-analysis of systematically reviewed literature revealed that all 4 constructs assessed provided significant stabilization of axial rotation and flexion/extension, but the C1LM–C2TL construct did not provide significant stabilization of lateral bending. Of all 4 constructs assessed,
Fig. 7. Forest plot comparing lateral bending stabilization achieved by various screw constructs. Values are presented as degrees. Figure is available in color online only.

Fig. 8. Funnel plots showing publication bias with regard to axial rotation (A), flexion/extension (B), and lateral bending stabilization (C) accomplished by screw constructs. SE(MD) = standard error (mean difference). Figure is available in color online only.
the C1LM–C2 pars construct provided the most flexion/extension stabilization but also the least axial rotation stabilization. The C1LM–C2 pars and C1–C2TA constructs provided better lateral bending stabilization than the other constructs. Significant heterogeneity was found concerning the methods of injury simulation and cervical-level potting in the cadaver models. Standardized methodology for simulating atlantoaxial fixation and standardized cervical-level potting would enable better assessments of fixation methods for atlantoaxial instability. Additional clinical studies to compare the rates of fusion and the incidence of hardware failure of the 4 constructs may be performed to enable a more precise method of determining the surgical treatment most suitable to each patient’s individual anatomy and pathology.

References
35. Resnick DK, Lapsiwala S, Trost GR: Anatomic suitability of

Author Contributions
Conception and design: all authors. Acquisition of data: Du. Analysis and interpretation of data: all authors. Drafting the article: all authors. Critically revising the article: Aichmair, Kueper, Wright, Lebl. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Lebl. Statistical analysis: Du.

Correspondence
Darren R. Lebl, Spine and Scoliosis Surgery, Hospital for Special Surgery, Weill Cornell Medical College, 535 E. 70th St., New York, NY 10021. email: drlebl@gmail.com.