**Supplemental Digital Content 2**

**Clinical Studies of Voluntary Cervical Intervertebral Motion**

Material in this supplement is provided to support the statement in the second paragraph of the Results in the primary manuscript stating that “predicted maximum values for intervertebral rotation and translation did not meaningfully exceed physiologically normal maximum values*.”*

**Rotation (Extension and Flexion)**

Table S2-1 shows model predictions for maximum segmental rotation (flexion or extension) achieved among the 48 combinations of laryngoscope scope force application location, magnitude, and direction when starting with the cervical spine in neutral position (data from table 1 of primary manuscript). At each segment, maximum rotation occurred with application of 97.6 N of force; see Results in primary manuscript. Table S2-2 summarizes intervertebral motion in voluntary range of motion studies in healthy volunteers without cervical spine disease when starting from the neutral position.1-5 In tables S2-1 and S2-2, extension is represented with positive values and flexion is represented with negative values.

Comparing values between tables S2-1 and S2-2, from Oc-C1 through C4-C5, modeled maximum extension at each segment is less than or equal to the mean value reported in the clinical studies, with the possible exception of C1-C2. However, because the model value for maximum C1-C2 extension (11.3 degrees) is contained within the mean plus 1 standard deviation (SD) of the value reported in Anderst et al., 20155 (8.0±5.5 degrees), these two values are comparable. At C5-C6 and C6-C7, modeled maximum flexion values are much less than mean flexion values in the clinical range of motion studies.

**Table S2-1**. Finite Element Model Predictions for Maximum Segmental Rotations (data from table 1 of primary manuscript)

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **FE Model Motion Characteristic** | **Intervertebral Segment** | | | | | | |
| **Oc-C1** | **C1-C2** | **C2-C3** | **C3-C4** | **C4-C5** | **C5-C6** | **C6-C7** |
| Maximum Rotation (degrees) | 13.6 | 11.3 | 5.4 | 5.4 | 4.0 | -1.5 | -4.3 |

**Table S2-2**. Segmental Rotation in Clinical Studies of Maximum Voluntary Range of Motion

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Clinical Motion Characteristic** | **Reference** | **Intervertebral Segment** | | | | | | |
| **Oc-C1** | **C1-C2** | **C2-C3** | **C3-C4** | **C4-C5** | **C5-C6** | **C6-C7** |
| Extension | Ordway et al., 19991,\* | 14.2  (19.4) | 5.2  (8.3) | 9.3 | 11.3 | 13.3 | 11.1 | 4.1 |
| Lin et al., 20012,† |  | 7.0 | 4.3 | 6.6 | 8.2 | 6.7 | 4.1 |
| Wu et al., 20073,‡ |  |  | 7.7±3.7 | 10.0±5.6 | 12.6±5.2 | 9.4±6.7 | 7.9±7.7 |
| Anderst et al., 20134,§ |  |  | 4.2±2.2 | 6.3±3.3 | 7.9±3.3 | 7.3±3.8 | 5.4±2.3 |
| Anderst et al., 20155,∥ |  | 8.0±5.5 | 5.2±2.6 | 7.4±3.3 | 10.3±4.5 | 10.6±4.6 | 6.7±4.3 |
|  | | | | | | | | |
| Flexion | Ordway et al., 19991,\* | 0.7  (-6.0) | -3.5  (-4.1) | -3.7 | -5.3 | -5.7 | -7.5 | -12.5 |
| Lin et al., 20012,† |  | -4.3 | -3.3 | -7.1 | -9.0 | -9.7 | -10.9 |
| Wu et al., 20073,‡ |  |  | -5.8±2.8 | -7.3±3.8 | -10.0±6.4 | -9.6±6.1 | -10.0±6.6 |
| Anderst et al., 20134,§ |  |  | -5.9±2.4 | -7.9±3.6 | -8.0±2.6 | -7.4±2.9 | -7.1±3.9 |
| Anderst et al., 20155,∥ |  | -7.7±3.8 | -7.7±2.6 | -9.8±2.6 | -9.3±3.1 | -9.3±3.3 | 9.3±3.5 |

Values are mean or mean ± SD. Gray shaded cells indicate that no data was provided in the original publication.

\* Ordway et al., 1999. Values are means, calculated by the author (B.J.H.) as differences in mean intervertebral angles reported in table 1 of the original publication. Although standard deviations (SD) are reported in table 1 of the original publication, it not possible to calculate SD of the differences because the covariance is not known. Extension values in parentheses at Oc-C1 and C1-C2 are values obtained in protrusion position rather than full extension. Flexion values in parentheses at Oc-C1 and C1-C2 are values obtained in retraction position rather than full flexion.

† Lin et al., 2001. Values are means, calculated by the author (B.J.H.) as differences in mean intervertebral angles reported in table 1 of the original publication. Although standard deviations (SD) are reported in table 1 of the original publication, it not possible to calculate SD of the differences because the covariance is not known.

‡ Wu et al., 2007. Values are mean ± SD. Rotation values are from table 1 of the original publication.

§ Anderst et al., 2013. Values are mean ± SD reported in table II or the original publication.

∥ Anderst et al., 2015. Values are mean ± SD reported in table 2 of the original publication.

**Anterior-Posterior Translation**

Table S2-3 shows model predictions for maximum segmental anterior-posterior translation (subluxation) achieved among the 48 combinations of laryngoscope scope force application location, magnitude, and direction when starting with the cervical spine in neutral position (data from table 1 of primary manuscript). At each segment, maximum subluxation occurred with application of 97.6 N of force; see Results in primary manuscript. Table S2-4 summarizes maximum intervertebral translation in voluntary range of motion studies in healthy volunteers without cervical spine disease when starting from the neutral position.2-4,6,7 In tables S2-3 and S2-4, translation of the superior vertebral body posterior to the inferior vertebral body is defined as posterior translation and is represented with positive values; translation of the superior vertebral body anterior to the inferior vertebral body of the segment is defined as anterior translation and is represented with negative values.

Comparing values between tables S2-3 and S2-4, at C3-C4 and C6-C7 modeled maximum anterior translations are less than or equal to the mean plus 1 SD of anterior translation values reported in Wu et al.3 and/or Anderst et al.4 At all other segments, model values for maximum translation exceed corresponding values by Wu et al.3 and Anderst et al.4 (mean plus 1 SD) by less than 0.9 mm, usually 0.5 mm less. Reitman et al. reported full range of motion intervertebral translation occurring between full flexion and full extension.7  In the studies by Lin et al.,2 Wu et al.,3 and Anderst et al.4 the amount of anterior translation with flexion is approximately equal to the amount of posterior translation with extension. Thus, in Reitman et al.,7 anterior and posterior translation values (from neutral) should each be approximately 50% of the reported value for full range of motion translation. Likewise, 95th percentiles for anterior and posterior translations should be approximately 50% of the upper 95th percent confidence interval values for the full range of motion translation. When compared to 50% of the upper 95th percent confidence values of translation reported in Reitman et al.,7 (1.1-2.1 mm) modeled maximum translations in the corresponding segments have comparable values.

**Table S2-3**. Finite Element Model Predictions for Maximum Segmental Translations (From table 1 in the primary manuscript).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **FE Model Motion Characteristic** | **Intervertebral Segment** | | | | | | |
| **Oc-C1** | **C1-C2** | **C2-C3** | **C3-C4** | **C4-C5** | **C5-C6** | **C6-7** |
| Maximum Translation (mm) | 2.3 | 1.5 | 1.8 | -1.4 | -2.0 | -1.6 | -0.6 |

**Table S2-4**. Segmental Translation in Clinical Studies of Maximum Voluntary Range of Motion.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Clinical Motion Characteristic** | **Reference** | **Intervertebral Segment** | | | | | | |
| Posterior Translation during Extension | **Oc-C1** | **C1-C2** | **C2-C3** | **C3-C4** | **C4-C5** | **C5-C6** | **C6-C7** |
| Parfenchuck et al., 19946,\* | 1.66 |  |  |  |  |  |  |
| Lin et al., 20012,† |  | 0.8 | 0.7 | 0.8 | 1.1 | 0.6 | 0.2 |
| Wu et al., 20073,‡ |  |  | 0.7±0.2 | 1.1±0.3 | 1.3±0.4 | 1.1±0.4 | 0.4±0.7 |
| Anderst et al., 20134,§ |  |  | 0.9±0.6 | 1.1±0.5 | 1.2±0.5 | 0.8±0.5 | 0.5±0.3 |
|  | | | | | | | | |
| Anterior Translation during Flexion | Lin et al., 20012,† |  | -0.5 | -0.8 | -1.2 | -1.2 | -1.3 | -1.0 |
| Wu et al., 20073,‡ |  |  | -0.7±0.2 | -1.0±0.3 | -1.2+0.3 | -1.1±0.3 | -0.9±0.4 |
| Anderst et al., 20134,§ |  |  | -1.1±0.5 | -1.2±0.7 | -1.1±0.5 | -0.9±0.4 | -0.7±0.5 |
|  | | | | | | | | |
| Anterior-Posterior Translation during Full Flexion to Full Extension | Reitman et al., 20047,∥ |  |  | 1.73  [3.34] | 2.26  [3.72] | 2.41  [4.20] | 1.82 [3.37] | 0.99 [2.29] |

Values are mean or mean ± SD. Gray shaded cells indicate that no data was provided in the original publication.

\* Parfenchuck et al., 1994. Only the mean value was reported in healthy controls. Range and standard deviation were not reported.

† Lin et al., 2001. Values are means, calculated by the author (B.J.H.) as differences in mean intervertebral translations reported in table 1 of the original publication. Although standard deviations (SD) are reported in table 1 of the original publication, it not possible to calculate SD of the differences because the covariance is not known.

‡ Wu et al., 2007. Values are mean ± SD. Translation values are from table 2 of the original publication.

§ Anderst et al., 2013**.** Translation data provided by Dr. William Anderst (personal communication, June 3, 2014).

∥ Reitman et al., 2004. Values are mean and [upper 95th confidence interval value] as reported in table 2 of original publication. Values are for translation occurring between full flexion and full extension.

**Other Considerations and Conclusion**

In clinical studies of cervical flexion/extension range of motion, segmental motion values can differ based on whether x-ray images were obtained with static positioning or with dynamic movement. This is because of differences in muscular and/or inertial forces between static and dynamic conditions. In addition, during flexion and extension, individual segments do not reach their maximum range of motion simultaneously and/or may not be at their maximal value at the extreme of the motion cycle. As a result, individual segments may not exhibit their maximum possible motion when the cervical spine is at maximum flexion or extension.1 Furthermore, when compared to voluntary motion, motion at each cervical segment is increased by 2 to 3 degrees when the head and neck are flexed and extended manually, i.e., by applying an external force to the head.8 Thus, cervical segments have the capacity for additional motion beyond that observed during voluntary motion studies. Accordingly, it is to be expected that with the application of an external force—97.6 N of intubation force in this model—modeled segmental motions should be slightly greater than those observed in voluntary range of motion studies.

These findings were the expected behavior of an anatomically normal and intact (stable) cervical spine. There are stabilizing effects of spinal facet joints, ligaments, and bony contacts. Consequently, when motion has reached its maximum anatomic (mechanical) limit, increasing applied force magnitude does not result in greater motion. Only when the applied force magnitude is so great as to distort or disrupt (stretch, tear, dislocate, or fracture) the anatomic structures that constitute the mechanical limit does motion occur beyond the normal anatomic maximum.9 Such injuries require several hundred9 or even thousands10 of Newtons of force. These findings support the validity of this FE model to predict clinical cervical spine motions.

In conclusion, model predictions for maximum achievable intervertebral rotations during intubation do not differ from voluntary maximum rotations. Although quantitatively very small (consistently < 1 mm), in some segments model predictions for maximum achievable translation during intubation exceed translations that occur with voluntary motion. It is unlikely that maximum achievable intervertebral translations with intubation, even if slightly greater than occurs with voluntary motion, are so great as to result in any clinically meaningful cord compression.

**References**

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