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Communication

Biomechanical properties of the costovertebral joint

Sonia Duprey*, Damien Subit, Hervé Guillemot, Richard W. Kent

University of Virginia, Center for Applied Biomechanics, Charlottesville, VA, USA

Abstract

Proper modeling of the human trunk requires a quantitative assessment of the stiffness of the costovertebral joints.

Twelve samples (adjacent thoracic vertebrae and one rib segment) were harvested from three subjects. The ribs were loaded in the cranial–caudal direction, the ventral–dorsal direction and in torsion around the cervical rib axis. The force applied to and the displacement of the loading point on the rib were measured and used to determine the moment–angle responses. Characteristic average curves and boundary curves containing the dataset were developed.

The torsion response presented a range of motion—defined as the change in the angle for an applied moment varying from $-0.1$ to $0.1 \text{ Nm}$—of $16.9 \pm 6.8^\circ$ which is more than three times the range in cranial–caudal flexion and five times the range in ventral–dorsal flexion. Statistical tests showed a significant difference between these ranges of motion. Significant inter-subject variability was observed for the cranial–caudal flexion ($p < 0.05$) while no intra-subject variability appeared. The characteristic moment–angle responses of the joints were well represented by third order polynomials ($R^2 > 0.9$).

This study expands and supplements the limited data available in the literature. Furthermore, it provides biomechanical data (closed-form moment–angle functions) that can be directly integrated into spine-ribcage models.
Table 1
Anatomical samples.

<table>
<thead>
<tr>
<th>Subject</th>
<th>420</th>
<th>427</th>
<th>430</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td>M</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Age (years)</td>
<td>59</td>
<td>79</td>
<td>74</td>
</tr>
<tr>
<td>Size (m)</td>
<td>180</td>
<td>181</td>
<td>173</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>93</td>
<td>79</td>
<td>47</td>
</tr>
<tr>
<td>Test samples (testing order)</td>
<td>R2a, R2b, R4b, R6b, R8b, R10b</td>
<td>R2a, R2b, R4b, R6b, R8b, R10b</td>
<td></td>
</tr>
</tbody>
</table>

Testing order:
- +Fy, −Fz, −Fy, +Fz, torsion.
- Torsion, +Fy, −Fz, −Fy, +Fz.

Review Panel of the National Highway Traffic Safety Administration, and all procedures were reviewed and approved by an independent Oversight Committee at the University of Virginia. Each sample included one rib segment (R) from the right side and two thoracic vertebrae (T): the vertebra corresponding to the harvested rib segment and the immediately superior vertebrae. The samples are referenced by their rib number: for instance the unit made of the second rib R2 and the thoracic vertebrae T1 and T2 is called sample 2.

All the samples from rib 2 to rib 10 were harvested from all three subjects. A careful dissection was performed to remove all the surrounding muscles and leave the ligaments intact. However, due to the choice made to retain only 1 rib and 2 vertebrae, the anterior costotransverse ligament was removed. Three samples could not be tested: in two of them, the costotransverse ligaments were damaged during the harvesting process (R10 for subject 420 and R8 for subject 427) and one sample presented a bone fusion between the rib and the vertebra (R4 for subject 427).

For each sample, the right rib was sectioned about 100 mm away from the costovertebral joint. A hole was drilled in the right rib cross-section to accommodate an aluminum loading rod aligned with the cervical rib axis (Fig. 1). The loading rod was securely screwed in the rib so as to bear the various types of loading applied to it without loosening. Finally, the left rib was removed so that the sample presented a bone fusion between the rib and the vertebra (R4 for subject 427).

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The testing order slightly varied between different samples in order to limit its influence in the results (see Table 1). The device used to load the rod was designed to be directly actuated by the experimenter. This device was composed of a guiding rail, a 1-axis load cell (44.4 N capacity load cell, Sensotec® Model 31, Honeywell, OH, USA) and a linear potentiometer (Model T25, full-scale 25 mm, Novotechnik US, MA, USA) enabling the acquisition of the force and displacement signals. The acquisition rate was 1612 Hz. The loading device produced loadings in the horizontal plane, while the sample could rotate on its support to enable the generation of the forces in the Y and Z directions. The experimenter had for instructions to stop loading when he felt the sample might be damaged if he kept loading it. The set-up used to generate the forces is illustrated in Fig. 3a. The torsion was applied to the rod via a rack and pinion assembly (Fig. 3b) that was added to the loading device to convert its translation into torsion around the X-axis.

2.2. Test set-up

The samples were loaded using the rod inserted in the rib (Fig. 2): a force was applied on the rod and the generated displacement of the rod was measured.

- The rotation around the X-axis, i.e. torsion, was created by applying torsion on the rod.
- The rotation around the Y-axis, i.e. cranial–caudal flexion, was generated by applying $F_Z$ and $-F_Z$ forces on the rod.
- The rotation around the Z-axis, i.e. ventral–dorsal flexion, was generated by applying $F_Y$ and $-F_Y$ forces on the rod.

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2.3. Data processing

2.3.1. Torsion loading—calculation of the moment–angle response around the X-axis

The applied angle $\theta$ was calculated by dividing the measured displacement $D$ by the radius of the pinion $R$ (Eq. (1)). The moment $M$ was calculated by multiplying the measured force $F$ and the radius of the pinion $R$ (Eq. (2)).

$$\theta = \frac{D}{R} \quad (1)$$
$$M = F \times R \quad (2)$$

The torsion tests were performed along one loading direction only (the direction corresponding to a positive moment (Fig. 2)).

2.3.2. Cranial–caudal and ventral–dorsal flexion loading—calculation of the moment–angle responses around the Y and Z-axes

The applied angle $\theta$ was calculated by considering the right-angled triangle formed by the rod and the actuator of the loading device (Fig. 4). In Eq. (3), $D_0$ is the distance on the rod between the force application point and the joint origin; $D$ is the measured displacement.

$$\theta = \arctan \left( \frac{D}{D_0} \right) \quad (3)$$

The moment $M$ was calculated by multiplying the measured force $F$ and the distance on the rod $D_0$ between the force application point and the joint origin (Eq. (4)).

$$M = F \times D_0 \quad (4)$$

2.3.3. Loading rate

The loading rate was controlled to some extent by the experimenter who actuated the loading device by hand, while monitoring that the motion was linear and continuous thanks to a real-time feedback loop. The goal was to reach a quasi-static loading rate of about 3 mm/s in order to allow comparison with the previous static studies [5,4]. The experimenter practised prior to testing to reach the desired loading rate. Linear regressions were performed on the measured displacements to check their linearity (a regression coefficient $R^2 > 0.9$ was required) and allowed to estimate the loading rate.

2.3.4. Characteristic curves and corridors

Response envelopes and characteristic average responses were developed for each loading direction using the technique described by Lessley et al. [13], which normalizes each response curve in time, calculates an average curve from the set of normalized curves and de-normalizes this to obtain a characteristic average curve. A corridor is then developed around the characteristic average response using standard deviation calculations for both time and magnitude. The characteristic average responses and corridors were approximated by polynomials. These polynomials were required to fit closely the curves ($R^2 > 0.9$) while being polynomials of the lowest order.

2.3.5. Range of motion

The range of motion (ROM) for each response was defined as the variation of angle between $-0.1$ and $0.1$ N m. This $\pm 0.1$ N m bound was inspired from the study of Lemosse et al. [5] and allowed for the comparison of the results. For the torsion tests, only half of the ROM could be measured (from 0 to $0.1$ N m) and the total ROM was approximated by multiplying the range of motion between 0 and $0.1$ N m by two.

2.3.6. Statistical analysis

Non-parametric Mann–Whitney tests were performed on the ROM using significant values of $\alpha = 0.05$ and $\alpha = 0.01$ in order to assess the variability inherent to the loading direction, the inter-subject variability, and the intra-subject variability, i.e. variability between the samples of the upper thorax (levels 2, 4, 6 corresponding to the true ribs) and the lower thorax (levels 8 and 10 corresponding to the false ribs).

3. Results

The responses of the samples from the three donors and for the three loading directions are plotted in Fig. 5. The averaged speed of the loading rod for all the tests was $3.5 \pm 2.4$ mm/s. The moments generated by rotations around the X-axis are an order of magnitude lower than those for the rotations around the Y and Z-axes (the maximum applied moments were: $0.09 \pm 0.02$ N m for the torsion, $0.49 \pm 0.15$ N m and $0.51 \pm 0.19$ N m for the moments generated by rotations around Y and Z). Thus, corridors with the characteristic average curves were calculated from the sample responses for
Fig. 5. Moment–angle responses around the X, Y and Z-axes for all the samples from the three anatomical subjects.

the three loadings separately (Fig. 6). The characteristic average curves and the corridors can be accurately approximated by third order polynomials ($R^2 > 0.9$). The equations of these polynomials are listed in Table 2.

The averages of the ROM calculated for each subject, for the upper and lower thorax levels and for all the samples were compared to the results from the literature [5] (Fig. 7). The averaged ROM for all the samples was $16.9 \pm 6.8^\circ$ for the rotation around $X$, $4.5 \pm 1.9^\circ$ for the rotation around $Y$, and $2.6 \pm 2.8^\circ$ for the rotation around $Z$. Thus, the torsion presents the largest ROM: more than three times the ROM for cranial–caudal flexion and five times that for ventral–dorsal flexion. The difference in ROM was significantly greater than zero for all pairs of axes (Fig. 7). Subjects 420 and 430 had significantly different ROM in the $Y$-axis ($p < 0.05$), but no other significant inter-subject variability in ROM was found. The upper and the lower thorax did not have significantly different ROM ($p = 0.05$).

4. Discussion

Costovertebral joints were tested using a method that allowed to measure continuous biomechanical data. These results supplement the data available in the literature [4,5] where the joint stiffness was characterized for given load increments. Specifically, Schultz et al. [4] provided low resolution force–displacement curves (1 point each 2.5 N, from $-7.5$ to $+7.5$ N), Lemosse et al. [5] acquired low resolution moment–angle responses (1 point each 0.1 N m, from $-0.6$ to $+0.6$ N m) and provided only the general curve features.

<table>
<thead>
<tr>
<th>Rotation around X</th>
<th>Rotation around Y</th>
<th>Rotation around Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristic average</td>
<td>$M_x = 0.00059d_x^3 - 0.00386d_x^2 + 0.0205d_x$</td>
<td>$M_y = 0.00210d_y^2 + 7E - 060d_x^2 + 0.0459d_y$</td>
</tr>
<tr>
<td>Corridors</td>
<td>$M_x = 0.0012d_x^3 - 0.00856d_x^2 + 0.0388d_x$</td>
<td>$M_y = 0.0018d_y^2 + 0.0116d_x^2 + 0.0578d_y$</td>
</tr>
<tr>
<td></td>
<td>$M_x = 0.0002d_x^3 + 0.001d_x^2 + 0.0022d_x$</td>
<td>$M_y = 0.0024d_y^2 - 0.0115d_x^2 + 0.0333d_y$</td>
</tr>
</tbody>
</table>
Fig. 6. Moment–angle responses around the X, Y and Z-axes (black thin line), characteristic average curves (black solid line) and corridors (black dashed line).

The study by Minotti and Lexcellent [9] suggested a representation of the costovertebral compound articulation as a revolute joint: one free rotation around the cervical axis of the rib (the X-axis here). The results presented here confirmed that the X-axis is a preferred degree of freedom since the response around this axis presented a larger ROM than the other responses and a much lower effective stiffness.

The present study has the advantage of providing high acquisition rate measurements while the previous studies used incremental loadings and provided scarce data. Furthermore, this study provides curve equations that characterize the mechanical response of the joint and can therefore be directly integrated into spine-ribcage models.

The main limitation of the current study is the number of samples. The samples were harvested from only three donors, and even when supplementing our data with the data available in the literature [5,4] it was not possible to assess whether the costovertebral joint mechanical response is age-dependent, gender-dependent or level-dependent. The non-parametric statistical tests performed here did not show any difference between the upper and the lower thorax levels, so we present a single response envelope and a single characteristic average for all the samples. More data are needed to refine the level sensitivity of the responses: the costovertebral samples that were not tested here (1, 3, 5, 7, and 9) should be investigated to determine whether response envelopes and characteristic averages should be developed specifically for each thoracic levels.

A second key limitation of this study is the definition of the coordinate system attached to the costovertebral joint and the method used to load along these axes. The actual rotational mechanics of the compound joint system between the ribs and the spinal vertebrae are complex with possibly non-orthogonal and non-fixed axes of rotation. Thus, our coordinate system is necessarily simplistic and not able to capture interactions among actual physiological instantaneous centers of rotation. Previous studies have attempted to quantify these co-rotations [5] but without success.

The test set-up also generated some limitations:

- The potting technique, by immobilizing the vertebral bodies and the intervertebral disk, may have altered the natural anatomical boundary conditions of the joint.
- The rack and pinion system was assumed here as a perfect mechanism. Since this system was located between the load cell and the sample, any friction in this mechanism could have introduced some errors (not quantified here) in the results.

Furthermore, the experimental protocol implied several tests on the same sample. Care was taken not to damage the samples: 1/the loading was stopped before any visible damage happened, 2/the testing order of the sample was slightly changed, 3/the average maximum moments reached in the present study were below the maximum moments reported in the previous non-injurious study of Lemosse et al. [5]. However micro-damages could still have hap-
pened and a limitation of the study is the potential artifacts due to repeated testing.

Finally, the loading rate varied slightly over the different tests: 3.5 ± 2.4 mm/s. The range of variation of the loading rate is not substantial, however considering the rate sensitivity of the soft tissues, an improvement of the testing method would be to control perfectly the rate. The data are limited to the quasi-static regime in the present study. There are applications for thoracic models that involve dynamic loading scenarios (e.g., restraint loading during an automotive crash) and future research should consider if and how the moment–angle relationships reported here depend upon rate.

5. Conclusions

The responses of the costovertebral joint have been studied in three main anatomical directions. The rotation around the cervical axis exhibited a larger ROM than the other loading directions studied. This study expands and supplements the limited data available in the literature describing the interaction between the vertebrae and the corresponding rib. Third order polynomials equations representing the characteristic average curves and the response corridors were identified; they can be directly integrated in the numerical joints of thoracic models.

Conflict of interest statement

This study was sponsored by Toyota Motor Company. The opinions expressed in this paper are the opinions of the authors alone and do not necessarily represent the views of the sponsoring organization.

References