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FORCE-DEFORMATION PROPERTIES OF HUMAN COSTO-STERNAL AND COSTO-VERTEBRAL ARTICULATIONS*

ALBERT B. SCHULTZ

Department of Materials Engineering, University of Illinois, Chicago, Illinois 60680, U.S.A.

DANIEL R. BENSON†

Department of Orthopaedic Surgery, University of California, Davis, California 95825, U.S.A.

and

CARL HIRSCH✠

Department of Orthopaedic Surgery, Karolinska Institute, Stockholm, Sweden 10401

Abstract—Experiments were conducted to measure the force-deformation properties of human costo-sternal and costo-vertebral articulations. These data are needed to enable studies to be made of the mechanical role of the rib cage in different situations. Five sterna and five specimens each incorporating the intact right-side costo-vertebral articulations of ribs 2, 4, 6, 8, 10 and 12 were obtained at autopsy from male cadavers. The specimens were dead-weight loaded in a number of ways, and the displacements that resulted are reported.

INTRODUCTION

This is a second report concerned with experimental measurement of some of the mechanical properties of human cadaver rib cage elements. The first report (Schultz *et al.*, 1974) pointed out that little of this information is available, and presented data concerning the geometrical and force-deformation properties of 30 human cadaver ribs. The present report provides similar data for 15 rib-sternum and 28 rib head-vertebra articulations.

These data have been collected to enable reasonably representative models of the human rib cage to be constructed. The rib cage plays an important mechanical rôle in a number of situations: in respiration, in protection of the viscera, and in stabilization of the spine, for example. It is difficult to study the mechanics of the normal and pathological rib cage through *in vivo* experiments, but experiments of this nature can easily be simulated in a representative model. However, the mechanical property data available were insufficient for the construction of such a model, and that is why the mechanical property measurements reported here and in the first paper were made.

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† Present address: Rush-Presbyterian-St. Lukes Medical Center, Chicago, Illinois 60612, U.S.A.

✠Deceased.

MATERIALS AND METHODS

The material tested was obtained at autopsy from the thorax of nine fresh male cadavers within 24 hr of death. The cadavers were selected from a moderately young population of suicide and accident victims, and there were no obvious abnormalities in any of the test specimens. Table 1 reports the age and cause of death of each cadaver.

Five 'sterna' were obtained by cutting through the ribs lateral of the costo-sternal articulations, so that these specimens incorporated the antero-medial portions of the costal cartilages. Figure 1 shows a representative specimen. With the exception of Cadaver 1292, right ribs 2, 4, 6, 8, 9 and 10 were also taken at the same time as the sterna. The testing of the ribs was described in the first paper.

Five complete thoracic spines were obtained by cutting through the spines near vertebrae C7 and L1 and through all of the ribs lateral of the rib heads. After the spines were removed from the cadavers, each spine was sectioned through the T2/T3, T4/T5, T6/T7, T8/T9, and T10/T11 intervertebral discs. The six 'rib-head' specimens so obtained from each spine consisted of the postero-medial portions of ribs 2, 4, 6, 8, 10 and 12, and almost the entire portion of the two vertebrae with which each of these rib heads articulates. All of the costo-vertebral articulations were left intact in these specimens.

Table 1. Cadaver ages (yr + months) and causes of death: *CS* and *CV* denote the costo-sternal and costo-vertebral articulations

Cadaver	Age	Cause of death	Articulations tested
1101	29 + 3	Suicide, pills	*CS*
1105	43 + 5	Suicide, pills	*CS*
1110	38 + 1	Hanging	*CS*
1273	30 + 7	Suicide, pills	*CV*
1292	20 + 1	Drowning	*CS,CV*
1355	16 + 0	Cranial fracture	*CV*
1370	29 + 8	Electrocution	*CV*
1374	30 + 7	Suicide, pills	*CS*
1387	25 + 5	Cranial fracture	*CV*

Sternum 1292 was taken, prepared, and tested in a single session. For all other sternum and all rib-head specimens, preparation and testing could not be completed in a single session. They were sealed in a plastic bag and frozen for storage between sessions. Some specimens experienced several cycles of defrosting and refreezing. References were cited in the first report which show that freezing probably does not significantly affect the mechanical properties of the material tested. Whenever any specimen was not sealed in plastic, it was kept moist with a cold-mist humidifier.

Sterna. Excess muscle tissue was removed from the right side of each sternum, but all ligaments and joint capsules were left intact. A small hole was drilled in the antero–posterior direction through the mid-line of the sternum near the level of the R5 cartilage. To determine specimen geometry, the sternum was photographed along with coordinate grids from anterior, posterior, and right lateral viewing positions. Figure 1 shows a representative set of these photographs.

Two stiff wire loading pins were then inserted in an antero–posterior direction through the right side cartilage of R2 and R4, and a third, I-pin, through one of the inferior-most group of cartilages, those of R6-R10. The three pins were inserted approximately 1 cm medial of the lateral edge of each cartilage, and in the inferior–superior direction, approximately midway in the cartilage.

Using a bolt through the drilled hole and a washer, the sternum was secured against the face of a cylinder in a rotating turntable testing fixture. Three small sharp pins projecting from the cylinder face into the sternum insured that rotation about the bolt would not occur. Figures 2 and 3 show a sternum mounted in the text fixture. The turntable lay in a vertical plane. With the superior direction of the sternum pointed downwards, weights hung by a flexible cord from one of the wire pins would load that cartilage in a superior direction. Figure 2 shows the R4 pin of a sternum being loaded in this manner. By rotating the turntable 180°, the hanging weights produced loading in the inferior direction. Anterior and posterior direction loads were produced by running the cord horizontally from the loading pin over a single pulley, from which the weights were hung. Figure 3 shows a sternum loaded in this way. The sterna were mounted anterior– or posterior–face out as necessary to do this.

The loads were applied in the four directions mentioned to each of the three loading pins. Each load was applied in three increments of 0·25 kp each.

The displacements that resulted from each load were recorded photographically. The unloaded sternum was photographed along with a length scale, and images of the sternum after application of each of the load increments were superimposed on the same film. Figures 2 and 3 show typical photographs produced. When a loading sequence was completed, the camera was moved to photograph the sternum along an axis perpendicular to the original, and the loading sequence repeated. In this manner, motions were recorded in three dimensions and the displacement in the direction of the load could be observed in both views, providing a check on reproducibility. Additional tests were made to insure the response was reproducible, and not affected by the sequence of the loading program. Care was taken to minimize the linear and angular distortion present in the photographs.

Rib heads. A stiff wire loading pin was inserted approximately 1 cm medial of the lateral end of the rib head to be tested. Soft tissues were removed from the right side of each rib head specimen, but the ligaments and joint capsules were left intact. All soft tissues were stripped from the left side, and from the interior of the spinal canal. Two medio–lateral direction holes were cleared with a small drill between facet joints on the left side. The left transverse processes were then imbedded inside a stiff cardboard cylinder, using acrylic bone cement. The spinal canal was also filled with the

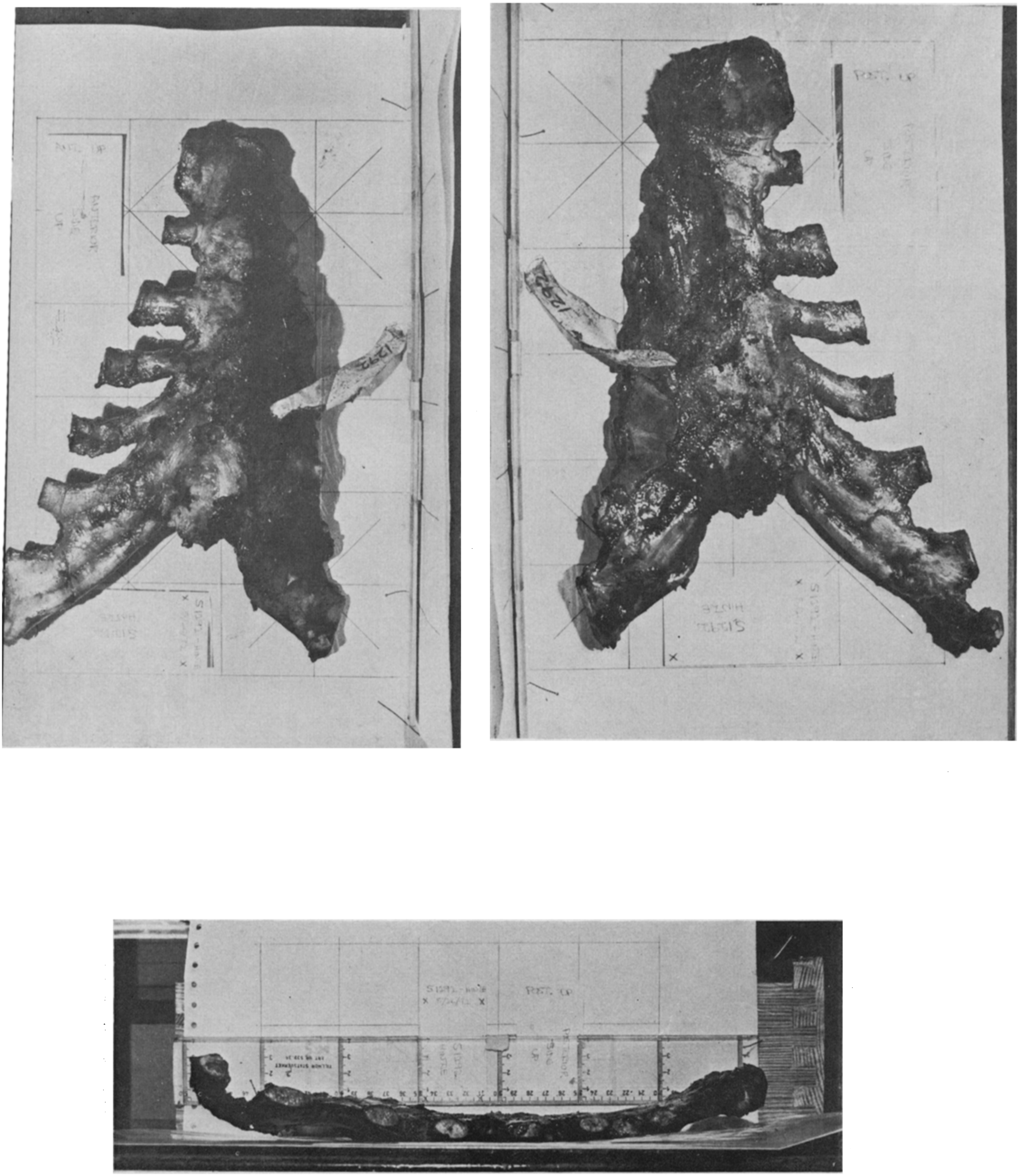

Fig. 1. A typical set of photographs used to define the geometry of a sternum specimen (cadaver 1292).

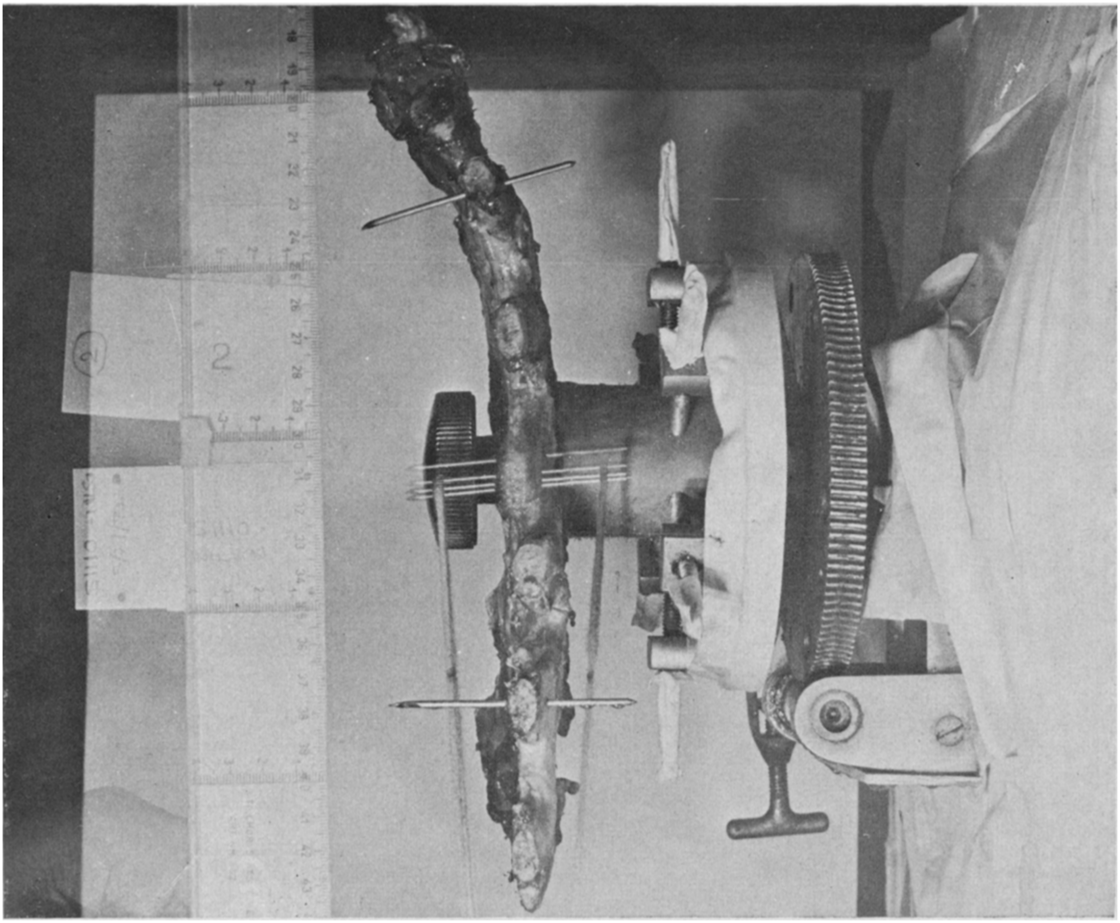

Fig. 2. The R4 pin of a sternum loaded in the superior direction, viewed from a right lateral position (cadaver 1110).

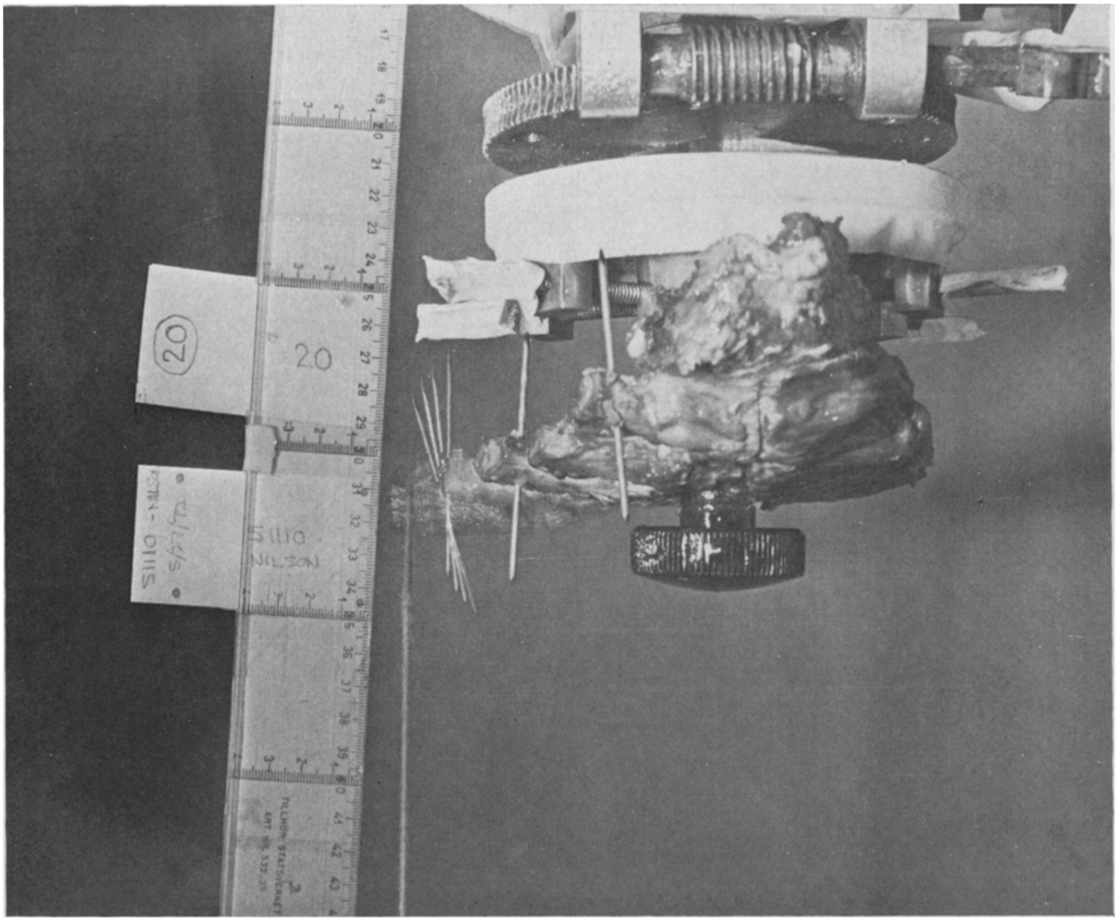

Fig. 3. The I pin of a sternum loaded in the anterior direction, viewed from a superior position (cadaver 1110).

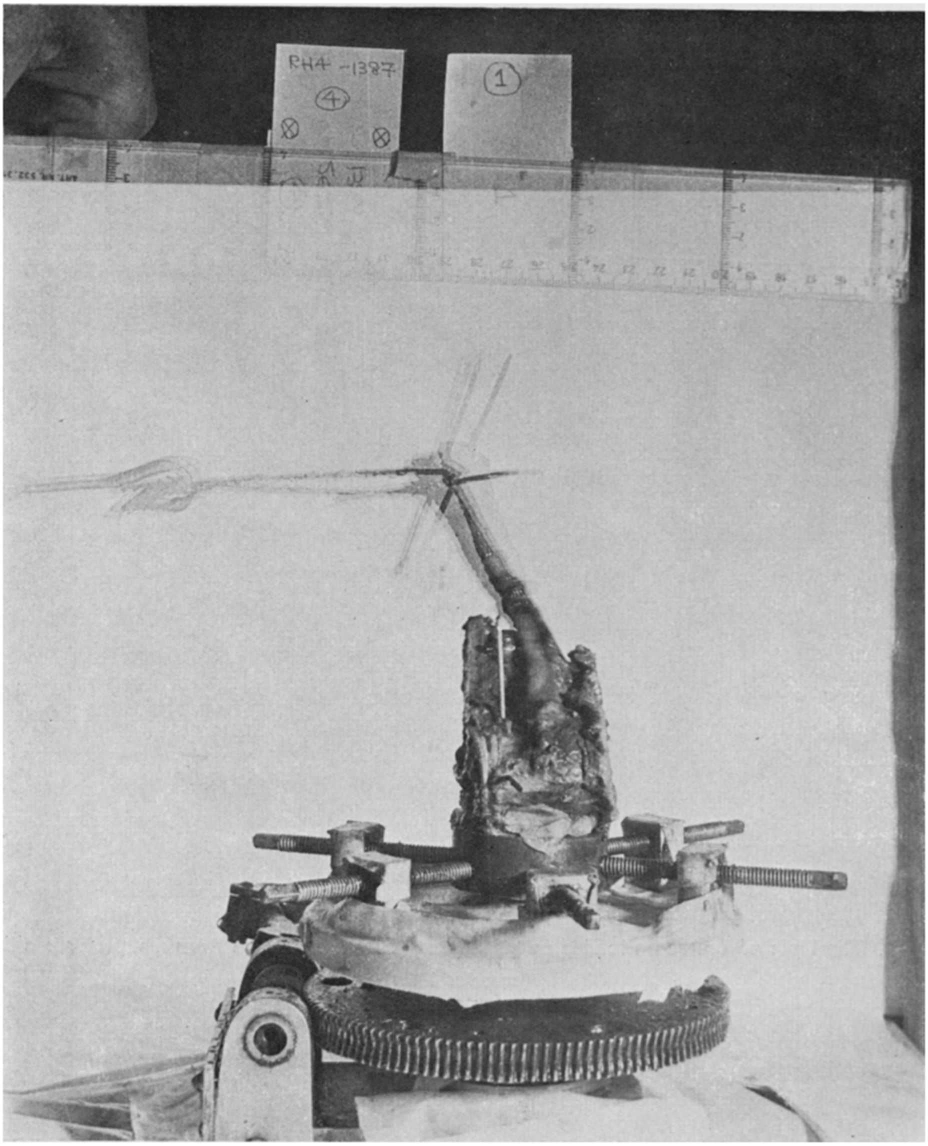

Fig. 4. A rib-head specimen loaded in the inferior direction, viewed from an anterior position (cadaver 1387, rib 4).

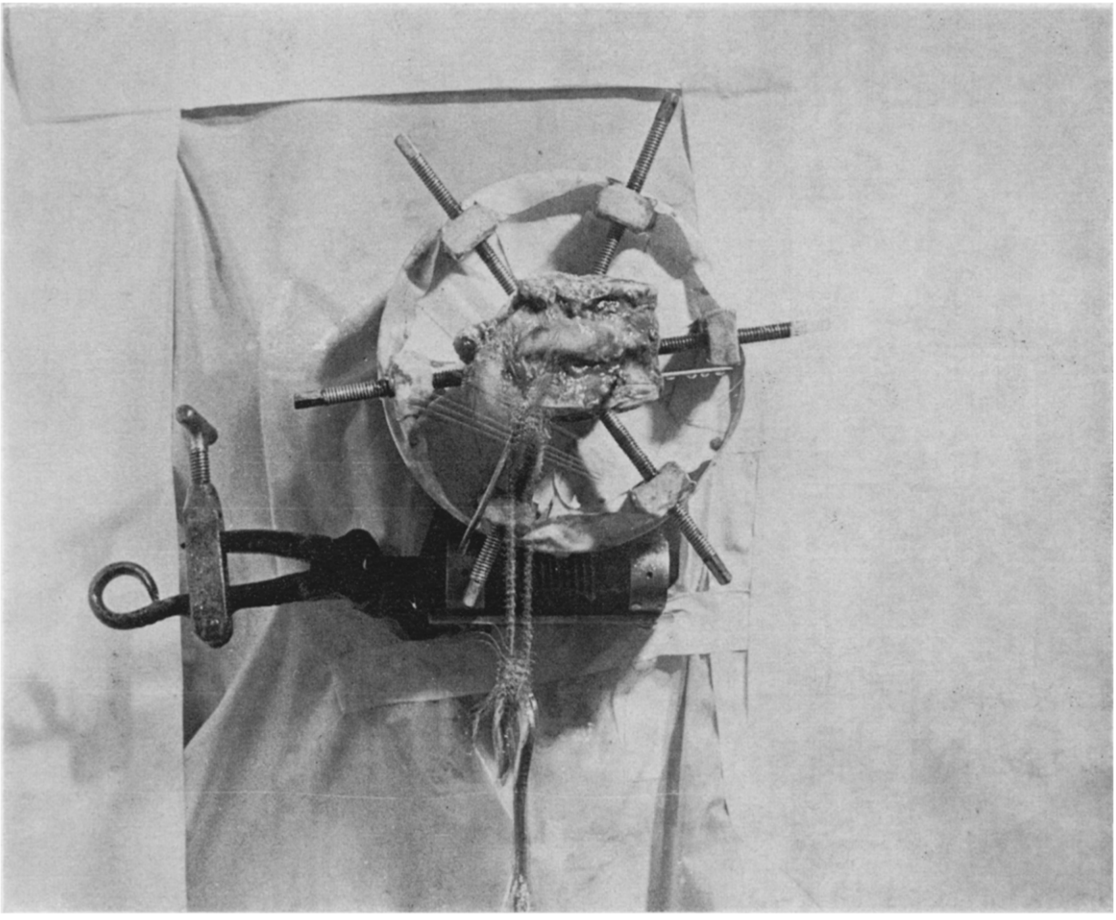

Fig. 5. A rib-head specimen loaded in the inferior direction, viewed from a right-lateral position (cadaver 1387, rib 4).

cement so that it extruded through the two holes, and communicated with the cement in the cylinder. This bonded the two vertebrae to the cylinder such that the sagittal plane of the specimen was perpendicular to the cylinder axis. The cylinder was then secured in the rotating turntable testing fixture. Figures 4 and 5 show a specimen mounted in this way.

In the 0° position of the turntable, the mid-horizontal plane of the intervertebral disc was horizontal and the superior direction vertical, so that weights hung by a cord from the loading pin produced inferior direction loading. By rotating the turntable successively to the 90°, 180° and 270° positions, the hanging weights produced loading in the posterior, superior and anterior directions, respectively. Lateral direction loading was produced in the 0° position by using a pulley, as described for the sterna. Three increments of load were applied in each of these five directions. Load–displacement data were collected in the same manner as for the sterna, and the same loads were used.

Rib head 8 of cadaver 1292, and rib head 12 of cadaver 1370 were damaged in preparation and not tested. Rib head 12 of cadaver 1273 was damaged on the right side, so the intact left side articulation was tested instead.

After all the costo–vertebral articulation loading tests had been completed, the rib heads were disarticulated from the vertebrae, and a set of measurements was made to define the detailed geometry of the articulations.

RESULTS AND DISCUSSION

Sterna. Table 2 reports the geometry of the test specimens. These data can be interpreted with the aid of the schematic diagram shown in Fig. 6. Each sternum was placed anterior face down on a table top, and this surface was considered to define a frontal plane. The projection of the center of the mounting hole onto this plane defined the origin of a rectangular coordinate system in which the y-axis is perpendicular to the plane and directed posteriorly, and the x- and z-axes lie in the frontal plane, and are directed to the left side and superiorly, respectively. Table 2 gives the location of each of the three loading points in this coordinate system, as well as the mid-sagittal height of each sternum. These measurements were scaled from the geometry-defining photographs, and are probably accurate only to within a few mm.

Figure 7 shows the deflections in the direction of load application that resulted when each of the 15 loading pins was subjected to a 0·75 kp load in each of the four loading directions. Table 5 shows, for sternum 1101, how these deflections increased with increasing load. Nonlinear behavior was often evident, and typically, approximately half of the maximum deflection occurred in response to one-third the maximum load.

In addition to the deflections reported in Fig. 7, inferior direction loading tended to produce medial deflections as well, and superior loading, lateral deflections. Anterior and posterior direction loading sometimes produced deflections in other directions also. These tendencies were most pronounced when the I pin was loaded because of deformations in the relatively large section of soft cartilage between the sternum proper and the loading pin. Figure 8 illustrates these phenomena in the response of sternum 1292.

Rib heads. Table 3 reports the geometry of the costo–vertebral articulations and Table 4 the location

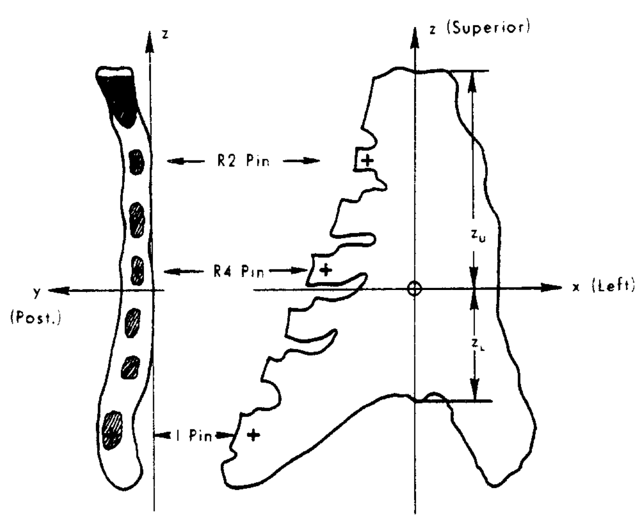

Fig. 6. Schematic diagram showing the coordinate system used to define sternum geometry. This is the coordinate system used for the Table 2 entries.

Table 2. Geometry of the sterna. Dimensions in cm. Quantities are defined in Fig. 6. The cartilage in which the I pin was located is noted

Cadaver No.	1101	1105	1110	1292	1374
Z_U	13·5	14·5	14·8	14·4	14·1
Z_L	−8·4	−8·0	−7·4	−7·7	−6·7
X_2	−5·9	−3·1	−3·9	−2·6	−3·8
Y_2	0·9	1·1	2·2	2·4	2·6
Z_2	9·2	9·1	9·0	9·0	8·6
X_4	−6·6	−5·9	−6·0	−5·6	−5·1
Y_4	0·4	1·1	1·5	0·7	0·5
Z_4	2·4	0·3	0·3	1·5	0·4
X_I	−8·5	−8·8	−8·1	−10·9	−8·8
Y_I	3·4	2·3	1·5	2·8	2·6
Z_I	−8·5	−8·7	−6·5	−9·6	−10·1
I pin location	R7	R6	R6	R7	R7

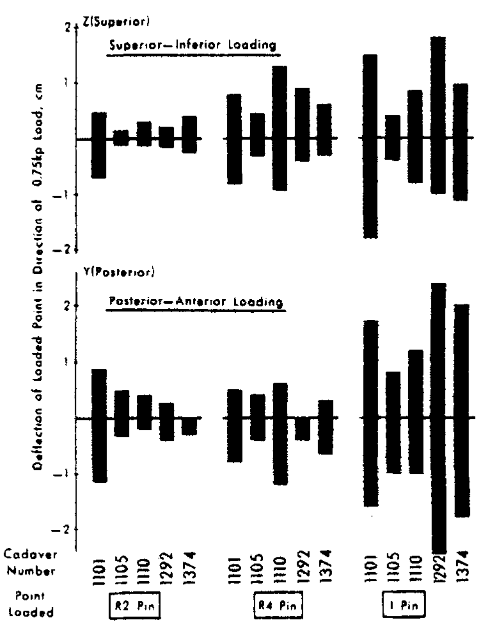

Fig. 7. Deflections of the R2, R4 and I sternum loading pins in the direction of loading. 0·75 kp load.

of each of the loading pins. The dimensions given are accurate only to within a few mm. Figure 10 shows the deflections in the direction of load application that resulted when each of the 28 specimens was subjected to a 0·75 kp load in each of the five loading directions. Table 6 shows, for cadaver 1387, how these deflections increased with increasing load. The variability in the responses resulted in part from the variable length of the rib portions included in the specimens (Table 4).

The deflections caused by the 0·75 kp loads were smaller than those that occurred in either the whole rib or the sternum tests, and therefore more difficult to measure accurately via the photographic technique used. In a few cases, reproducibility of the measurements was not good. Two factors seemed to play a role: inability to obtain completely rigid fixation of the specimens, and inherent hysteresis in the articulations. There was sometimes not one definite equilibrium position to which the rib head would return when all load was removed. Rib head 2 of cadaver 1355 underwent a 2·9 cm deflection under its own weight when the turntable was rotated from the 0° to the 180° position; a deflection almost twice as large as that caused by the

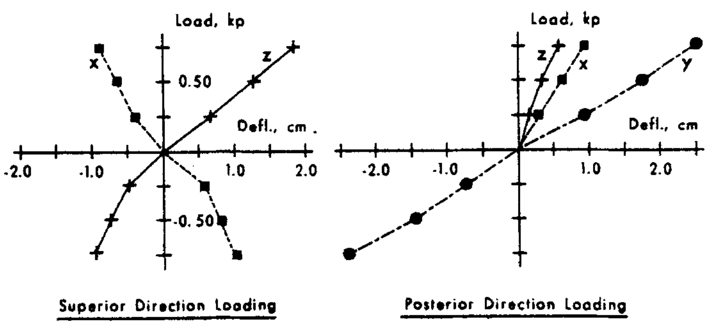

Fig. 8. Load–deflection response of the I pin of cadaver 1292 sternum. Omitted data indicate insignificant deflections in that direction. Terms are used as defined in the text.

Table 3. Geometry of the costo–vertebral articulations

		Rib No. 2	4	6	8	10	12
Body dimensions							
M-L dia.	1273	3·7	3·1	3·1	3·6	3·95	4·75
	1292	3·0	3·4	3·2		4·3	4·8
	1355	3·35	2·6	3·1	3·5	3·8	4·1
	1370	2·9	3·4	3·6	4·0	4·6	
	1387	3·2	2·95	3·1	3·3	3·95	4·65
	Mean	3·23	3·09	3·22	3·60	4·12	4·57
	Lanier	3·22	3·04	3·19	3·52	4·09	4·73
A-P dia.	1273	2·0	2·45	2·6	3·1	3·25	3·4
	1292	2·3	2·7	2·9		3·1	3·7
	1355	2·0	2·2	2·8	2·4	3·0	3·2
	1370	2·1	2·7	3·3	3·6	3·5	
	1387	1·85	2·3	2·8	2·8	3·25	
	Mean	2·05	2·47	2·88	2·97	3·22	3·43
	Lanier	1·95	2·37	2·73	3·03	3·14	3·22
AE height	1273	1·85	1·9	2·05	3·2	2·4	3·0
	1292	2·3	2·4	2·7		2·7	3·1
	1355	1·7	1·8	1·7	1·75	2·3	2·6
	1370	1·9	2·0	2·1	2·1	2·6	
	1387	2·0	2·25	2·6	2·75	2·75	2·5
	Mean	1·95	2·07	2·23	2·45	2·55	2·80
	Lanier	1·77	1·88	1·90	1·97	2·23	2·43
Rotation axis	1273	40°	40°	40°			
	1292	50°	40°	40°			
	1355	40°	40°	50°			
	1370	40°	35°	60°			
	1387	45°	50°	55°			
	Mean	43°	41°	49°			
IC Facet Post. from *AE*:	1273	1·05	2·1	2·55	2·5	3·1	4·0
	1292	1·5	1·7	2·2		2·6	3·4
	1355	1·2	1·9	2·0	2·75	3·1	3·6
	1370	0·9	1·9	2·6	2·8	3·1	
	1387	1·45	2·0	2·9	2·85	3·4	3·6
	Mean	1·22	1·92	2·45	2·72	3·06	3·65
TC Facet Post. from *AE*	1273	3·1	4·6	4·4	4·9	5·3	5·3
	1292	4·2	4·8	5·6		5·7	5·2
	1355	3·0	4·3	4·1	4·8	3·9	4·0
	1370	3·3	4·6	5·1	5·7	5·3	
	1387	3·2	5·2	5·6	6·05	5·5	5·15
	Mean	3·36	4·70	4·96	5·36	5·14	4·91
TC Facet Latl. of ℄	1273	3·4	2·9	3·05	3·1	2·9	2·25
	1292	4·0	3·1	3·9		3·6	3·3
	1355	3·75	3·2	3·0	3·1	2·1	2·0
	1370	4·1	2·9	3·3	3·4	3·2	
	1387	3·8	3·1	3·4	3·0	3·3	2·6
	Mean	3·81	3·04	3·33	3·15	3·02	2·54
IC–TC distance:	1273	3·0	2·95	2·8	3·0	2·45	1·1
	1292	3·3	3·2	3·3		2·8	1·2
	1355	2·7	2·8	2·6	2·6		0·9
	1370	2·8	2·5	3·1	2·4	2·1	
	1387	2·9	3·0	3·0	3·05	2·6	1·3
	Mean	2·94	2·89	2·96	2·76	2·48	1·12

Explanation to Table 3 overleaf

Table 4. The locations of the rib-head points at which loads were applied: dimensions have been scaled from the photographs: the coordinate system used is shown in Fig. 9

Rib	x	y	z	Rib	x	y	z
1273–2	−6·7	3·3	−1·0	1370–2	−9·1	2·7	−1·4
4	−7·4	5·4	−0·8	4	−5·8	5·1	0·0
6	−6·6	5·7	0·3	6	−5·2	5·0	0·3
8	−5·8	5·2	−0·1	8	−6·1	5·6	0·0
10	−5·6	5·4	−0·5	10	−6·3	5·9	−1·4
12*	5·7	5·7	−3·2	12			
1292–2	−7·8	4·8	0·0	1387–2	−7·9	2·3	−0·6
4	−5·9	4·6	0·2	4	−9·7	4·4	−1·9
6	−6·4	6·0	−0·2	6	−10·3	4·5	−1·8
8				8	−9·9	5·5	−1·2
10	−5·6	4·8	−0·5	10	−8·3	6·7	−3·6
12	−7·1	7·0	−3·4	12	−6·9	5·6	−5·4
1355–2	−8·1	1·1	−3·0				
4	−5·1	4·3	−0·7				
6	−5·6	3·7	−0·5				
8	−4·9	4·9	0·0				
10	−5·5	4·8	−1·5				
12	−4·9	5·0	−2·7				

* Left side tested.

Coordinate system used. The mid-horizontal plane of the intervertebral disc was considered to contain the x- and y-axes. z is measured normal to this plane in the superior direction. The x- and y-axes originate from the mid-sagittal, anterior-most point of the disc, x pointing to the left and y posteriorly. Figure 9 shows this coordinate system. Dimensions are in cm.

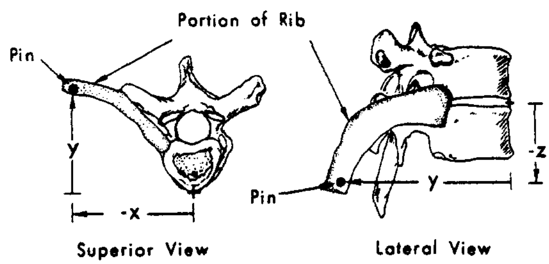

Fig. 9. Coordinate system used to locate the points at which loads were applied to the rib-heads. Data reported in Table 4.

maximum load. This phenomenon was not observed in other specimens, but may have been present to a small degree. The 0·75 kp maximum load seemed to take the articulation through its full range of normal motion; larger loads caused noticeable deformations of the bony structures. The 0·25 kp initial load usually produced a substantial fraction of the total deflection (see Figs. 4 and 5 or Table 6 for example). In other words, the costo-vertebral articulations are kinematically adapted to produce little resistance to small motions of some types. Large motions of these types and any motions of other types are resisted much more.

SUMMARY AND COMMENTS

Geometrical and mechanical properties of human sterna, and of the articulations between the head of a rib and its corresponding vertebrae, have been reported. Under a 0·75 kp load, the largest deflections that occurred in the direction of the load in either type

Explanation of Table 3: All linear measurements in cm.

For ribs 10 and 12, the presence or absence of facets was not always consistent with textbook descriptions. Sometimes when there was not an actual facet, the kinematic equivalent of one could be located from the configuration of the surrounding ligamentous tissues. The dimensions concerning the facets are accurate only to within a few mm.

Body dimensions. These refer to the inferior surface of the vertebral body with the same number as the rib. The medial–lateral dia. is the maximum; the *AP* dia. is at the midline; the height is at the anterior edge (*AE*). The dimensions reported are compared with Lanier's (1939) means for 96 white male American column vertebrae.

Rotation axis. Rib heads 2, 4 and 6 rotated most freely about a single axis, which was estimated to lie in the plane of the intervertebral disc, subtending with the mid-sagittal plane the angle tabulated. At best this angle could be estimated to within 5°.

IC facet. The distance given is posterior from the *AE* to the approximate center of the body inferior costal facet.

TC facet. The distances given are posterior from the *AE* and lateral from the mid-sagittal plane to the approximate center of the body transverse costal facet.

IC–TC distance. The straight line distance between the centers of the *IC* and *TC* facets on the rib head.

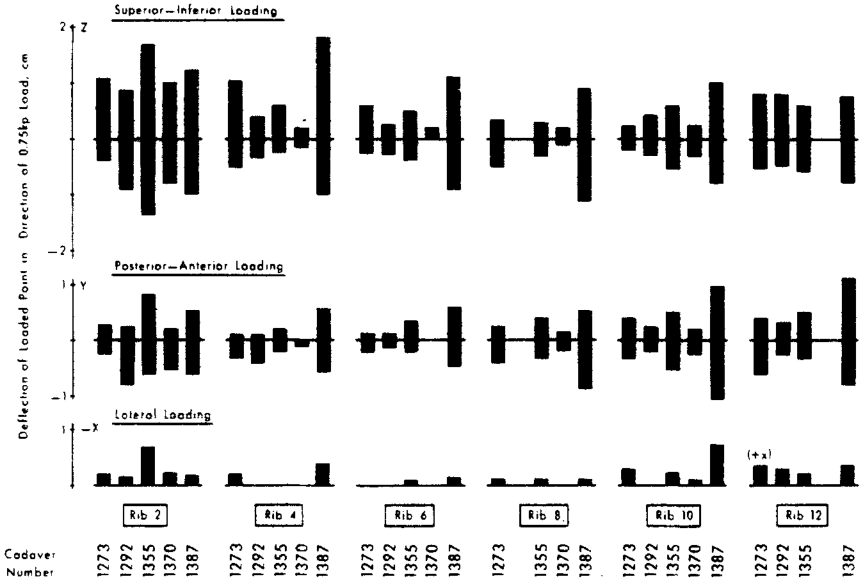

Fig. 10. Deflections of the rib-head loading pins in the direction of loading, 0·75 kp load.

of specimen were of the order of 2 cm. Deflections also occurred in directions other than that of load application, and the load–deflection relation was often non-linear.

Although biological tissues often exhibit viscous behavior, this type of behavior was found not to be significant in these tests. The deflections reported are those that occurred within a minute or so of application of dead weight loads.

In view of the scatter found in the mechanical properties of biological tissues, emphasis was placed on the collection of a large amount of data rather than on a high degree of precision in the measurements. More than 800 photographs were taken to measure the properties reported in this paper and the companion paper concerned with the properties of the ribs themselves.

Andriacchi *et al.* (1974) have used the data reported in this paper, along with those reported in Schultz *et al.* (1974) and elsewhere, to construct a model of the human rib cage. They showed that the behavior of their model reflects the behavior of real rib cages. They

Table 5. Deflections in the direction of the load of the R2, R4, and I loading pins: sternum of cadaver 1101: terms are used as defined in the text

Loading direction (kp)	R2 pin	Deflections (cm) R4 pin	I pin
Superior			
0·25	0·23	0·39	0·65
0·50	0·32	0·61	1·05
0·75	0·48	0·83	1·52
Inferior			
0·25	0·35	0·45	1·02
0·50	0·49	0·65	1·44
0·75	0·70	0·81	1·80
Anterior			
0·25	0·45		0·59
0·50	0·82		1·08
0·75	1·15	0·78	1·60
Posterior			
0·25			0·71
0·50			1·23
0·75	0·91	0·49	1·74

(Data are omitted if intermediate positions were obscured in the photograph.)

Table 6. Deflections in the direction of the load of the rib-head loading pins: rib-heads of cadaver 1387: terms used as defined in the text

Loading direction (kp)	Deflections (cm) Rib 2	Rib 4	Rib 6	Rib 8	Rib 10	Rib 12
Superior						
0·25	0·81	1·22	0·65	0·48	0·64	
0·50	1·06	1·51	0·86	0·74	0·84	
0·75	1·25	1·80	1·10	0·90	1·03	0·76
Inferior						
0·25	0·59	0·61	0·50	0·70	0·44	0·44
0·50	0·81	0·85	0·69	0·92	0·61	0·64
0·75	1·00	1·04	0·90	1·16	0·77	0·79
Anterior						
0·25	0·32	0·24	0·18	0·34	0·73	
0·50	0·49				0·95	
0·75	0·61	0·60	0·45	0·85	1·14	0·81
Posterior						
0·25	0·25	0·23	0·24	0·20	0·66	0·66
0·50	0·44				0·85	0·91
0·75	0·54	0·57	0·59	0·51	0·98	1·13
Lateral						
0·25	0·12	0·27	0·07		0·50	
0·50						
0·75	0·15	0·38	0·15	0·10	0·74	0·35

(Data are omitted if intermediate positions were obscured in the photograph.)

used the model to conduct preliminary analyses of rib cage mechanics. Many questions can be explored with models of this type. For example, it might be possible to resolve controversies over the precise kinematics of respiration. The mechanics of the rib cage in health, disease and trauma can now be studied largely through simulation rather than through experimentation *in vivo*.

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REFERENCES

Andriacchi, T. P., Schultz, A. B., Belytschko, T. B. and Galante, J. O. (1974) A model for studies of mechanical interactions between the human spine and rib cage. *J. Biomechanics* **7**, in press.

Lanier, R. (1939) The presacral vertebrae of American white and negro males. *Amer. J. Phys. Anthropol.* **25**, 341–420.

Schultz, A. B., Benson, D. R. and Hirsch, C. (1974) Force–deformation properties of human ribs. *J. Biomechanics* **7**, 303–309.