

FORCE-DEFORMATION PROPERTIES OF HUMAN RIBS*

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Abstract—Experiments were conducted to measure geometrical and force-deformation properties of individual human ribs. These data are needed to enable studies to be made of the mechanical rôle of the rib cage in different situations.

Right ribs 2, 4, 6, 8, 9 and 10 were obtained at autopsy from each of 5 male cadavers. The head of each rib was fixed, and the antero-medial free end dead-wt loaded in three increments, in six directions. When subject to 0.75 kp loads, deflections of the order of 3 cm in the upper ribs and 6 cm in the lower ribs often occurred in the direction of the load. Deflections occurred in directions other than that of load application as well, and significant nonlinearities in load-deflection response were found.

INTRODUCTION

Very little quantitative information concerning mechanical and geometrical properties of the human rib cage is available at present. Measurements of rib cage dimensions are given by Clauser *et al.* (1969) and Roberts and Chen (1970), for example, and of individual rib cross-sectional geometry by Roberts and Chen (1970a, b, 1972) and Santoro and Frost (1968). Rib cage motions in respiration have been described by Wade (1954) and Jordanoglou (1969), among others. Stein and Granik (1972) measured the modulus of elasticity and of rupture in four inch long segments of rib bone. Some measurements have been reported concerning force-deformation properties of the whole thorax. Agostoni *et al.* (1966) measured the change in both thoracic diameters *in vivo* resulting from lateral squeezing forces up to 15 kp. Patrick *et al.* (1965) measured changes in the antero-posterior dia. in four embalmed cadavers when posteriorly directed static loads were applied to the sternum. Similar measurements were reported from two cadavers subject to sternal impact. Volunteers tolerated statically applied loads of 300–400 lb. but their chest deformations were not reported. Nahum *et al.* (1970) extended this work to include static and dynamic measurements made with fresh cadavers, as well as measurements made

during more localized impacts. Beckman and Palmer (1970) and Beckman *et al.* (1970) measured thoracic force-deflection characteristics in Rhesus monkeys.

The human rib cage plays an important mechanical role in many situations. For example, the rib cage is intimately involved in respiration, protects the thoracic viscera, and contributes to maintenance of the stability of the spine. Studies of normal and pathological respiration mechanics, of protection of thoracic viscera during vehicle collisions, of progression and correction of scoliotic deformities of the spine and of many similar problems all would be aided by better knowledge of the mechanical behavior of the rib cage. Often studies of these types are conducted with models which simulate mechanical behavior, to overcome the difficulty of conducting experiments *in vivo*. To construct a reasonably representative model of the rib cage, the mechanical properties of each of its elements need to be known. No direct measurements of many of these properties seem to have been made. For these reasons, experimental studies were undertaken to collect needed rib-cage element geometrical and mechanical property data. This paper describes properties of individual ribs, and a companion paper Schultz, Benson and Hirsch, (1974) describes properties of the costosternal and costo-vertebral articulations.

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MATERIALS AND METHODS

Ribs 2, 4, 6, 8, 9 and 10 were obtained at autopsy from the right side of the thorax of five fresh male

cadavers within 24 hr of death, so that in all, 30 ribs were tested. The cadavers were selected from a moderately young population of suicide and accident victims. Table 1 lists the age and cause of death of each cadaver. There were no obvious abnormalities in any of the material.

Table 1. Specimen age (yr + months) and cause of death

| Cadaver | Age | Cause of death |
|---------|--------|--------------------|
| 1101 | 29 + 3 | Suicide, pills |
| 1105 | 43 + 5 | Suicide, pills |
| 1110 | 38 + 1 | Suicide, hanging |
| 1117 | 40 + 5 | Cardiac infarction |
| 1374 | 30 + 7 | Suicide, pills |

Each rib was disarticulated at its head and separated from the remainder of the rib cage. The ribs were severed from the sternum just lateral of the costo-sternal joint, so that almost all of the costal cartilage was included. Except for Cadaver 1117, the sternum of each cadaver was also obtained and tested, so that any cartilage not included as part of a rib was included as part of the sternum. Sternum test results are reported in the companion paper cited in the Introduction.

The material was sealed in plastic bags and frozen for storage. For specimen preparation and testing, the material was defrosted and later refrozen if preparation and testing could not be completed in a single session. All testing was completed with 20 days of death or sooner. During the course of defrosting, preparation, and testing, a stream of air from a cold-mist humidifier was directed onto each rib, and all work was conducted in a high humidity environment. Galante (1967) surveyed reports concerning the effect of freezing on the mechanical properties of human tissues, and cited nine in which freezing was said not to alter mechanical characteristics. The one counter-example concerned rabbit ligament properties. Tkaczuk (1968) found that freezing had no significant effect on the mechanical properties of human spine longitudinal ligaments.

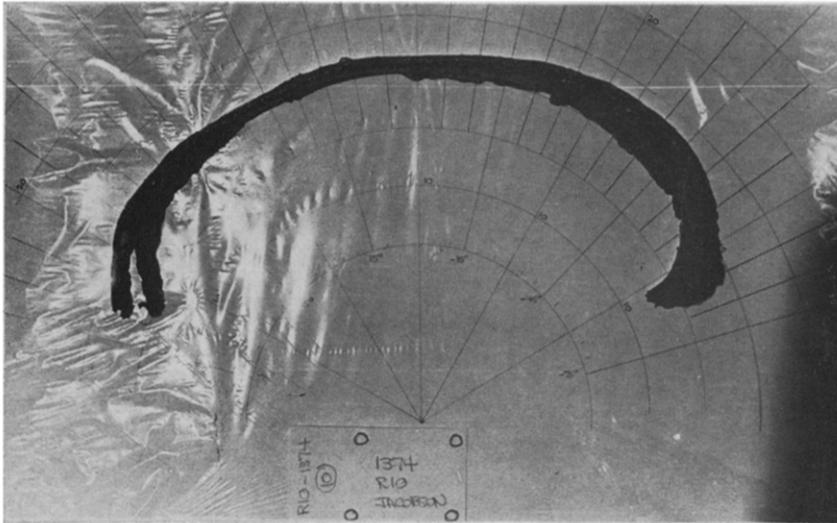
Excess soft tissue was removed from each rib and four of the five rib sets were weighed. The lateral perimeter of each rib was determined with a tape measure, and a photograph was taken to define rib geometry. The rib was placed upon a table with either its superior or inferior edge upwards, depending upon which produced the better overall conformity of the central portion of the rib edge with the table surface. The table top established an imaginary 'horizontal plane' of the rib. The directions 'superior' and 'inferior' as used in this

report refer to the directions of lines perpendicular to this horizontal plane.

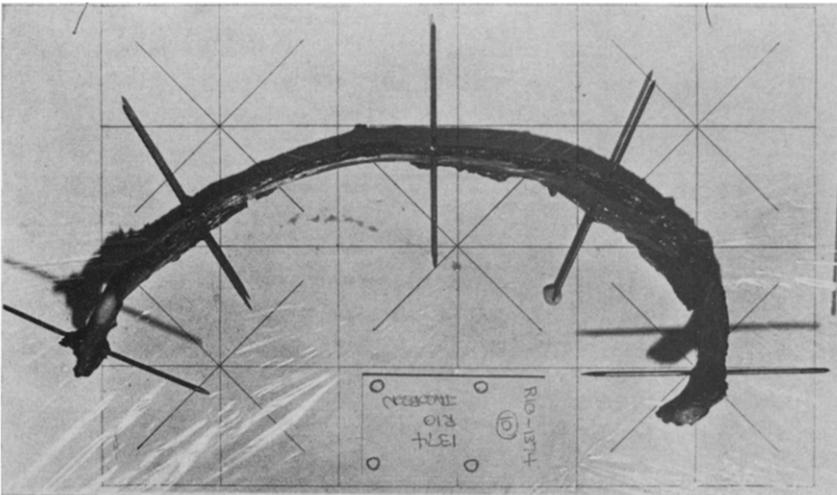
A stiff wire pin was inserted through the head of the rib just medial to the costotransverse facet. The pin was placed parallel to the horizontal plane, and pointed to the sternal end of the specimen. The axis of this pin established the 'anterior' and 'posterior' directions. The 'medial' and 'lateral' directions were then considered to be along axes mutually perpendicular to the superior-inferior and anterior-posterior directions. If the imaginary horizontal plane established for each rib were parallel to the true horizontal planes of the body, the directional terms used here would nearly agree with standard anatomic nomenclature. However, due to the different inclinations of each rib in the body and the way in which the antero-posterior direction was defined, the terms agree only approximately with this nomenclature.

A second pin, the loading pin, was inserted through each rib approximately 0.5 cm lateral of its sternal end, approximately parallel to its horizontal plane. Three more pins were similarly inserted near the 1/4, 1/2 and 3/4 points along the outer perimeter of the rib. For rib 2, the 1/4 and 3/4 point pins were omitted. Two more photographs were taken to define further the geometry of the rib and the locations of the pins. A typical set of the three geometry-defining photographs is shown in Fig. 1. The head of the rib medial to the head pin was then imbedded within a heavy cardboard cylinder with acrylic bone cement, so that the axis of the cylinder lay in the medial-lateral direction and the head pin constituted a dia. of the cylinder. When the cement had set, the cylinder was secured in the testing fixture, so that the mounted rib constituted a fixed-free, multiply-curved beam.

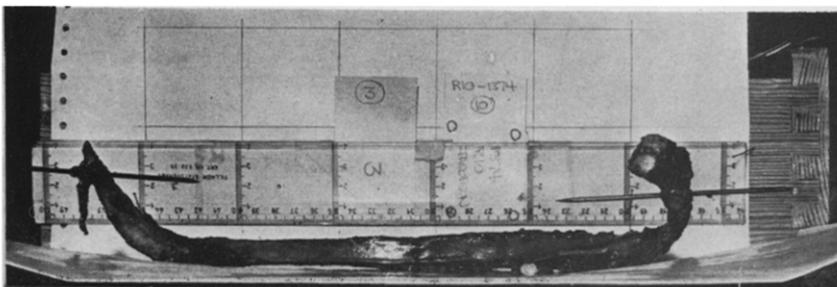
The testing fixture was a rotating turntable which lay in a vertical plane. The rib was mounted in the fixture so that in the 0° position of the turntable, the antero-posterior axis of the rib was horizontal. By hanging weights on a flexible cord from the loading pin, the rib was loaded in the inferior direction. This same procedure produced loading in the superior and anterior directions when the turntable was rotated counterclockwise to the 180° and 270° positions respectively. Figure 2 shows a rib being loaded in the 180° position. Posterior loading would result if the turntable were in the 90° position. However, to permit the hanging weights to clear the testing fixture, the 60° position of the turntable was used, so that these loads had components in both the posterior and inferior directions, and this loading direction is referred to as the *p*-direction. Medial and lateral loading were produced in the 0° position of the turntable by running the cord horizontally from the rib over a single pulley, from



A



B



C

Fig. 1. A typical set of photographs used to define the approx geometry of a rib (Rib 10, Cadaver 1374)

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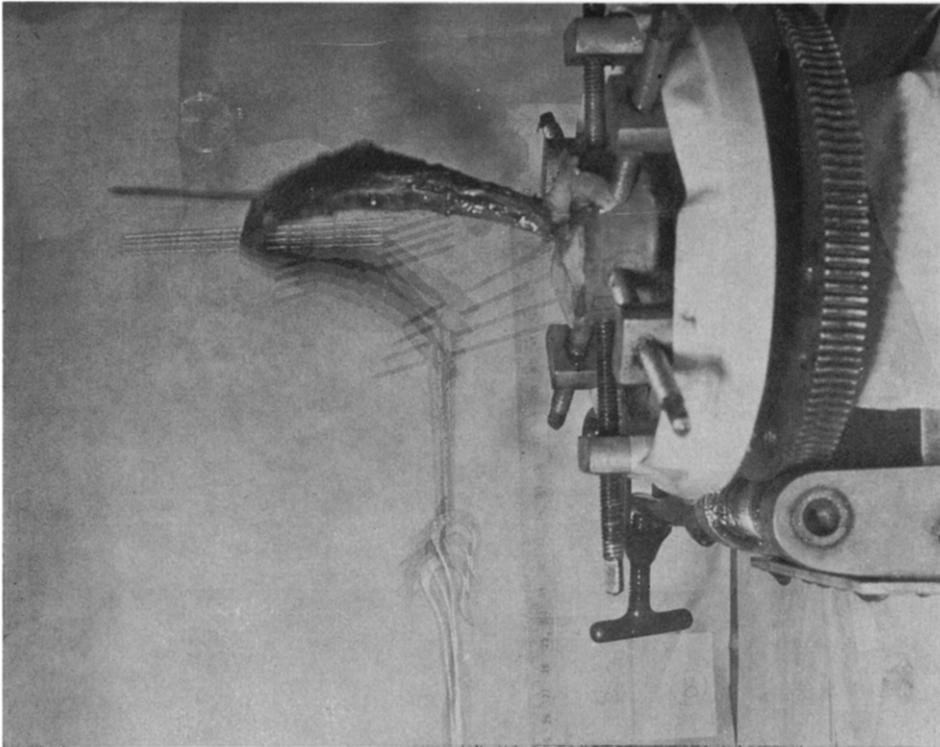


Fig. 2. Superimposed images of Rib 10, Cadaver 1117, under loads of 0, 0.25, 0.50, and 0.75 kp. Turntable position 180°, superior loading direction, viewed from a posterior position.

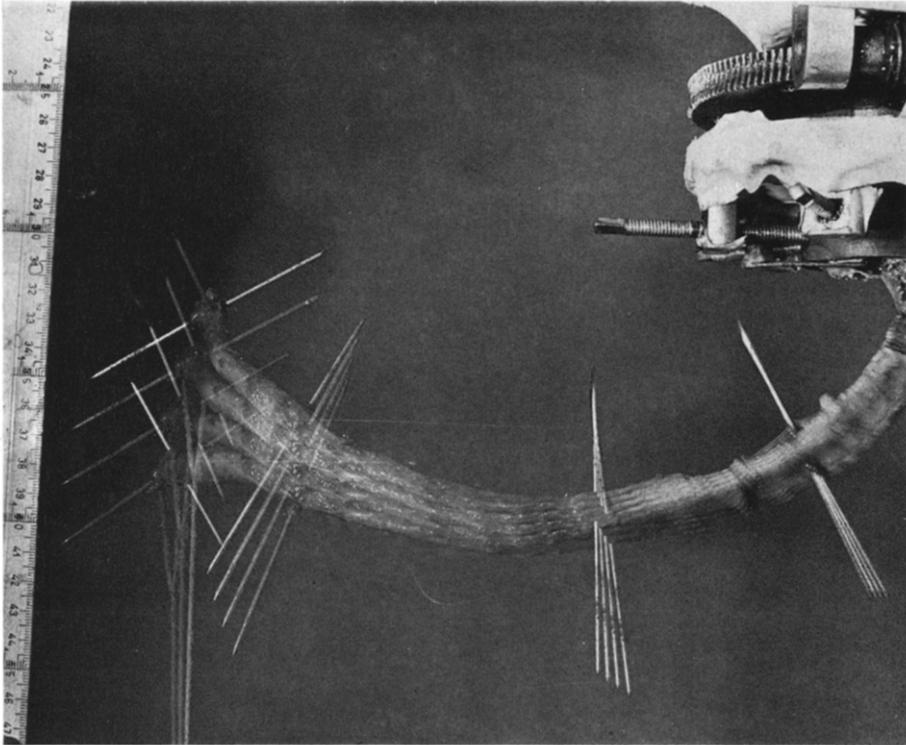


Fig. 3. Superimposed images of Rib 10, Cadaver 1374, under loads of 0, 0.25, 0.50, and 0.75 kp. Turntable position 0°, lateral loading direction, viewed from an inferior position.

which the weights were hung. Figure 3 shows a rib loaded in this way. Weights were applied in three increments of 0.25 kp each.

For each loading, deformations were recorded photographically. The unloaded rib was photographed along with a length scale, and images of the rib after application of each of the three 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 rib along an axis perpendicular to the original, and that loading sequence was repeated. In this manner motions of the rib were recorded in three dimensions, and the displacement in the direction of the load was available from both views, providing a check on reproducibility. Additional tests were made to insure that the response of the rib 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. Measured displacements are believed accurate to 1 or 2 mm, in almost every case. More precise measurements could have been made using electronic transducers. However, in view of the scatter found in the mechanical properties of biological tissues, and the probability that the data would be used in only semi-quantitative studies, it was felt that collection of a large amount of less-precise data obtained photographically would be preferable to the collection of a small amount of more-precise data via transducer techniques.

RESULTS AND DISCUSSION

Rib geometry. Table 2 serves to define approximately the geometry of each rib. Column 9 lists the length of the lateral perimeter, and column 10 the mass of each specimen if that was determined. The quantities listed in the other columns can be defined with the help of Figs. 1A, 1C, 4 and 5.

Figure 1a is an example of the first photograph taken of each rib. The rib was placed on top of a polar coordinate grid so that its central portion nearly lined up with a circular coordinate arc of the grid. Figure 4 is a schematic diagram of Fig. 1A. The center of the portion of the head pin embedded in the rib is denoted as point H , and the corresponding point on the loading pin, point L . The projection of point H onto the coordinate grid (which lies in the horizontal plane) is considered the origin of a rectangular, right-handed coordinate system. In this system, the x -, y - and z -directions correspond to the medial, posterior, and superior directions defined earlier.

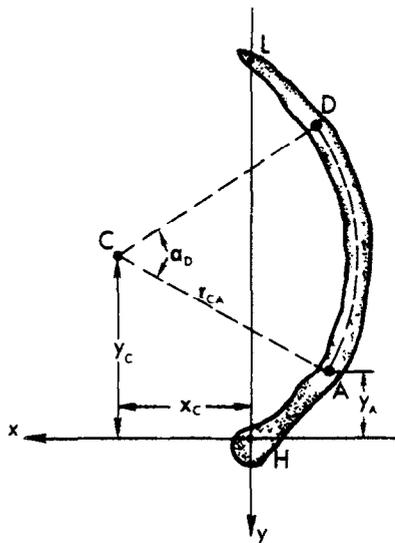


Fig. 4. Schematic diagram showing how the approx rib geometry is determined using the polar-grid photograph. Symbols correspond to those used in Table 2.

Columns 1, 7 and 8 of Table 2 locate points L and H in this coordinate system. If the z coordinates of these points are positive, the horizontal plane lay along the inferior surface of the rib when the lateral geometry photograph was taken. Columns 3 and 4 locate point C , the center of curvature of the circular arc nearly coinciding with the projected central portion of the rib. Points A and D are estimates of the end points of the circular arc; beyond these points a circular arc does not reasonably describe the approx geometry. The information reported in columns 2, 5 and 6 serves to locate points A and D .

The dimensions reported in Table 2 are probably not meaningful except to within 5 mm, and the angles to within 5° . They are intended to provide only a simple description of a complicated geometry.

Displacements in the direction of load application. Figures 6 and 7 show the deflections in the direction of load application that resulted when each of the 30 ribs was subjected to a 0.75 kp load in each of the six loading directions. The displacement scales in the two figures differ by a factor of 2. Some of the photographs showed motion at the head (fixed-end) of the rib. This



Fig. 5. Schematic diagram showing how z_H and z_L are determined using the lateral geometry photograph.

Table 2. Approximate rib geometry and mass.

| Cadaver, Rib | A | 1 | 2 | 3 | 4 | 5 | 6 | B | 7 | 8 | 9 | 10 |
|-----------------|---|-------|-------|-------|-------|----------|---------------|---|-------|-------|-----------|----------|
| | | y_L | y_A | x_C | y_C | r_{CA} | α_{AD} | | z_H | z_L | Perimeter | Mass (g) |
| 1101-2 | I | -10.5 | -4.6 | 5.3 | -0.9 | 11 | 42 | S | -0.6 | -1.2 | 22 | 20 |
| 1105-2 | I | -12.5 | -3.8 | 8.1 | 0.4 | 16 | 35 | I | 1.0 | 0.5 | 26.5 | 26.9 |
| 1110-2 | S | -11.8 | -2.6 | 5.4 | -2.6 | 11 | 61 | I | 0.9 | 0.3 | 24.5 | 25 |
| 1117-2 | I | -11.5 | -3.2 | 5.0 | -1.9 | 11 | 55 | S | -0.4 | -1.9 | 25 | 24.6 |
| 1374-2 | S | -12.6 | -1.9 | 2.3 | -4.5 | 8 | 92 | S | -0.5 | -1.9 | 24 | |
| 1101-4 | I | -16.6 | -0.9 | 2.4 | -5.7 | 11 | 88 | I | 1.7 | 0.8 | 32 | 40 |
| 1105-4 | I | -18.5 | -1.6 | 5.2 | -7.3 | 12.5 | 94 | I | 3.3 | 0.7 | 34 | 37.6 |
| 1110-4 | S | -18.2 | -0.5 | 2.6 | -6.9 | 11 | 75 | S | -0.4 | -3.2 | 33.5 | 47 |
| 1117-4 | S | -17.2 | -4.4 | 1.9 | -5.9 | 11 | 65 | S | -0.5 | -1.8 | 33 | 41.9 |
| 1374-4 | S | -18.4 | 0.3 | 1.5 | -6.6 | 10.5 | 105 | S | -0.5 | -2.1 | 35 | |
| 1101-6 | I | -21.5 | -2.9 | 7.3 | -7.6 | 15.5 | 82 | I | 2.5 | 1.0 | 35.5 | 50 |
| 1105-6 | I | -23.6 | -3.0 | 14.0 | -9.5 | 20.5 | 60 | I | 2.6 | 1.0 | 36 | 40.0 |
| 1110-6 | I | -22.4 | -2.8 | 10.5 | -9.8 | 18 | 57 | S | -0.4 | -1.9 | 36.5 | 55 |
| 1117-6 | I | -20.9 | -0.7 | 4.3 | -8.8 | 13 | 111 | I | 3.1 | 1.8 | 35 | 52.8 |
| 1374-6 | I | -21.2 | -0.8 | 6.6 | -9.1 | 16 | 80 | I | 2.4 | 1.0 | 37 | |
| 1101-8 | I | -24.5 | -3.5 | 7.6 | -8.9 | 16 | 70 | I | 3.8 | 3.9 | 38.5 | 55 |
| 1105-8 | I | -23.9 | -1.8 | 10.6 | -10.7 | 18 | 70 | I | 4.4 | 4.9 | 38.5 | 44.8 |
| 1110-8 | I | -25.6 | -1.7 | 12.0 | -12.4 | 21 | 50 | I | 3.2 | 3.7 | 39 | 60 |
| 1117-8 | I | -22.8 | -0.6 | 4.2 | -10.3 | 13 | 114 | I | 4.4 | 0.8 | 38 | 56.8 |
| 1374-8 | I | -23.6 | -1.0 | 9.7 | -10.9 | 18 | 65 | I | 3.8 | 1.2 | 39 | |
| 1101-9 | I | -21.4 | -1.3 | 5.6 | -9.3 | 13 | 90 | I | 1.9 | 3.3 | 36 | 50 |
| 1105-9 | I | -23.0 | -0.8 | 6.3 | -10.7 | 13 | 97 | I | 2.8 | 4.4 | 36 | 36.1 |
| 1110-9 | I | -24.7 | -0.4 | 6.4 | -11.5 | 15.5 | 100 | I | 3.2 | 3.9 | 40.5 | 52 |
| 1117-9 | I | -21.6 | -0.1 | 4.1 | -10.3 | 12.5 | 125 | I | 2.9 | 1.7 | 36 | 51.3 |
| 1374-9 | I | -24.8 | -0.8 | 11.4 | -11.5 | 20 | 60 | I | 3.7 | 4.4 | 39.5 | |
| 1101-10 | I | -23.6 | -0.9 | 5.6 | -9.7 | 13 | 95 | I | 4.3 | 4.3 | 33 | 45 |
| 1105-10 | I | -19.8 | -0.3 | 4.9 | -9.1 | 11 | 105 | I | 3.2 | 1.8 | 30 | 27.7 |
| 1110-10 | I | -22.4 | -2.3 | 7.7 | -10.8 | 15.5 | 70 | I | 0.9 | 1.6 | 35.5 | 40 |
| 1117-10 | I | -21.1 | -0.7 | 1.9 | -10.0 | 10.5 | 130 | I | 2.8 | 2.0 | 36 | 42.2 |
| 1374-10 | I | -24.4 | 0 | 6.3 | -11.9 | 15.5 | 105 | I | 3.8 | 4.9 | 41 | |

Symbols used are defined in Fig. 4. Column A indicates whether the superior or inferior edge was lying on the table-top in the polar-grid geometry photograph, and column B the same for the lateral view geometry photograph. Lengths in cm, angles in degrees, masses in g. (Note: Prior to testing a length of cartilage broke off from the end of Rib 1105-9. The coordinates of the load point used in testing were approx -1.3, -22.3, 1.8.)

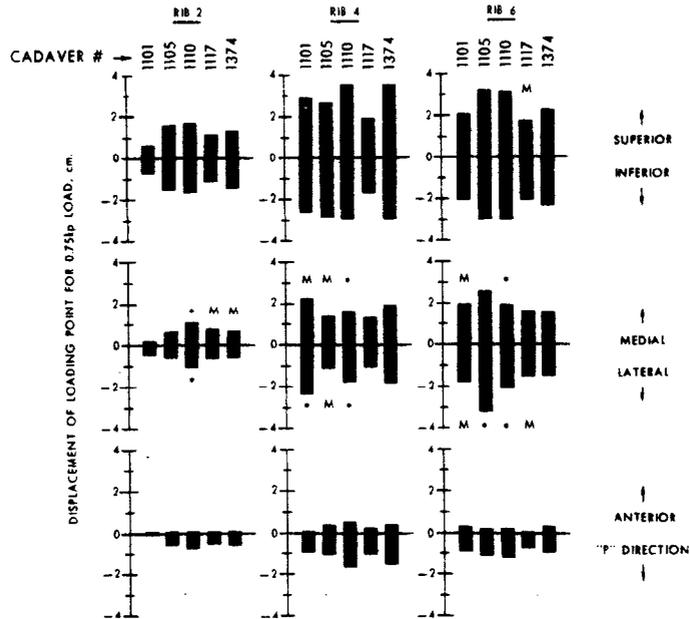


Fig. 6. The displacement of point *L* in the loading direction, under a 0.75 kp load, for ribs 2, 4 and 6.

sometimes resulted from inadequate fixation of the rib head in the acrylic cement, but most often from a small amount of free play in the turntable mechanism. An *M* adjacent to a graph bar in these figures denotes that a small amount of fixed-end motion was suspected, and

an asterisk denotes that fixed-end motion definitely was observed. In these cases, which occurred most often for medial-lateral direction loadings, the displacements reported overestimate the rib deformation caused by the loads.

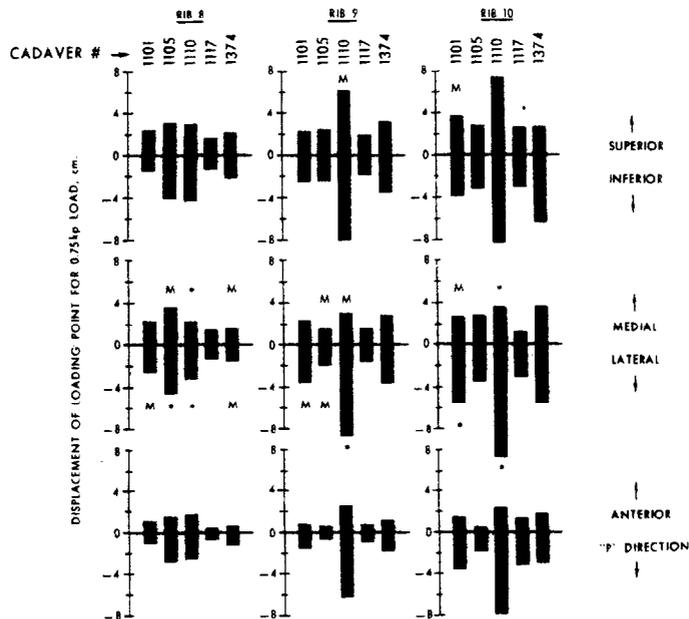


Fig. 7. The displacement of point *L* in the loading direction, under a 0.75 kp load, for ribs 8, 9 and 10.

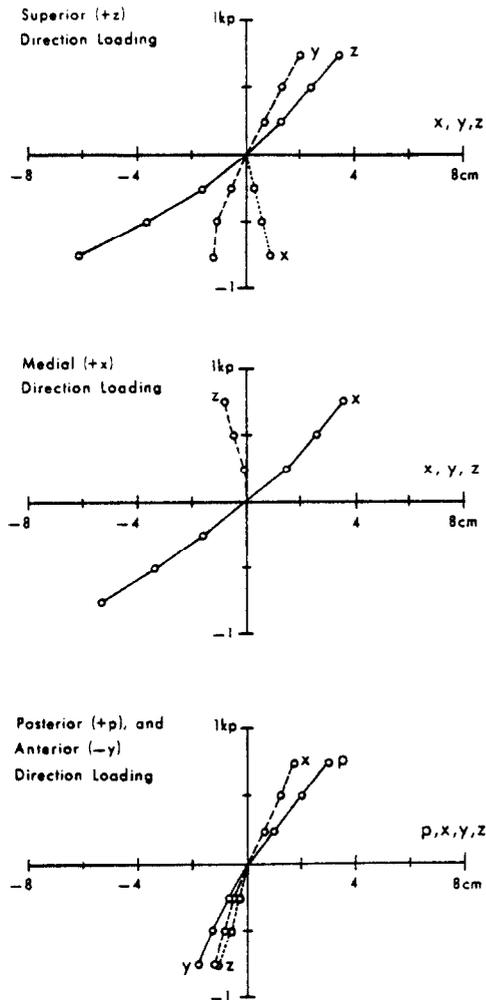


Fig. 8. Details of behavior of Cadaver 1374, Rib 10. Omitted data indicate non-significant motions.

Other displacements, and nonlinear behavior. Figures 6 and 7 report only the displacement of the loading pin center in the direction of the load, under the maximum load applied. For each rib, displacements also occurred in the two directions mutually perpendicular to the loading direction. Moreover, all the displacements tended to increase non-linearly with increases in load. Most often, hardening behavior (stiffness increasing with load) was exhibited. Both phenomena were more pronounced in the lower ribs. The upper ribs are calcified along most of their length, while the lower rib antero-medial sections are composed of relatively flexible cartilage. These cartilage sections experienced deflections large enough for geometrical nonlinearities to play a significant rôle in the response.

Space does not permit all these data to be reported, but Fig. 8 shows the complete load-three-dimensional displacement response of a representative lower rib.

SUMMARY

Geometrical and mechanical properties of individual human ribs, obtained from fresh cadavers, have been reported. The ribs are flexible. When mounted as fixed-free beams and subjected to 0.75 kp loads, deflections of the order of 3 cm in the upper ribs and of 6 cm in the lower ribs often occur. Deflections occur in directions other than that of load application as well, and there are significant non-linearities in the load-deflection response.

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