AN EXPERIMENTAL ANALYSIS OF THORACIC DEFLECTION RESPONSE TO BELT LOADING

by

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INTRODUCTION

In a study of accidents involving fully restrained (3-point belted) occupants, where at least one such occupant sustained an injury at the AIS 2 level or greater (1)*, it was found that injuries to the chest accounted for 12.5% of all non-minor injuries to drivers (exceeded only by head injuries) and 18.8% of such injuries to right front passengers (the most frequently injured passenger body region). Chest injuries accounted for 30% of all injuries at the AIS 5-6 level.

Thus, notwithstanding the thoroughly documented effectiveness of the lap/shoulder belt system (e.g., 2, 3), thoracic injury due to the restraining forces applied by the upper torso belt remains a problem worthy of continued consideration.

To examine the inherent protective capacity of a restraint system, one may rely on post-accident field information or prior laboratory evaluation. The latter of course assumes the availability of some surrogate upon which belt loading may be induced and with which injury probability may be assessed.

In North America, the state-of-the-art in anthropometric test device thorax design is that of the General Motors Hybrid III. This device first described by Foster and Colleagues (4) combines most of the physical requirements for a repeatable test device and possesses certain biomechanical fidelity. That is, in the latter respect, the manner by which the chest structure deforms had been selected to replicate or simulate available human data. The data base upon which the deflection characteristics of the Hybrid III chest were chosen was that of Neathery and co-workers' 50th percentile male thorax force deflection corridors (5, 6). These corridors represent upper and lower limits on mid-sternal deflection as a function of imposed force applied through a blunt mid-thoracic impactor. Indeed, much of our understanding of thoracic injury mechanisms have been based upon this type of mechanical input (7, 8). Many other investigators have studied the specific injuries associated with belt use (9, 10, 11, 12) but, with the possible exception of two recent developments by Ford (13) and MIRA (14), no ATD thorax capable of monitoring for belt-induced skeletal injuries has been available. Since an upper torso belt cannot be considered a blunt mid-sternal impactor, it seemed reasonable that a more suitable ATD thorax may be required to assess the loading characteristic of typical belt webbing

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* Numbers in parenthesis denote references at end of paper.

material.

Toward this end, it was established that more precise and detailed force deformation characteristics of human chests would be necessary. This study explores the variations between a Hybrid III thorax and human 50th percentile volunteers in terms of anthropometric measurements and deflection response to strip loading.

GEOMETRIC AND ANTHROPOMETRIC COMPARISONS

Rationale and Methods

Conventional anthropometry provided neither suitable detail nor the necessary information required for the comparison between the Hybrid III and the human subjects. Some basic measurements such as stature, sitting height, chest circumference and biacromial width were used. However, for the most part, non-conventional measures were necessary. The rationale for using unconventional evaluations was that these measures provided a more meaningful and extensive description of the thoracic region than did traditional anthropometrics. At some point in the future these measures will be the principle references for modification and adjustment, if necessary, of the Hybrid III.

The measurements taken on the human subjects are contained in Table 1. Similar evaluations were also taken on the ATD for comparing the structural components between the humans and the dummy.

CHEST LOADING TESTS

Deflection Measurement

All test subjects were asked to lay supine on a test table, where a shoulder belt and an instrumented chest plate were located and secured in space according to a set protocol. Chest deflections were then measured at 11 pre-determined sights on the thorax, under static point loading, static belt loading and dynamic belt loading. The 11 sights for which deflections were recorded are: the centers of the right and left clavicles, the upper sternum (manubrium), the mid-sternum, the lower sternum and the 3rd, 5th and 7th rib bilaterally lined up below the mid-clavicle (Figure 1). All but the mid-clavicle deflectometer supports were permanently fixed in space to provide a constant deflection measurement angle from one test subject to the next. Clavicle deflectometers were not permanently affixed because of slight variances in subject anatomies.

TABLE 1: MEAN VALUES OF ALL SUBJECTS AND THE ATD

		SUBJECTS MEAN	ATD DATA
Age (yrs)		21.0	
Mass (kg)		77.0	85.5
Sitting Height (cm)		90.3	88.4
Sternal Length (cm)		18.9	13.8
Biacromial Width (cm)		33.8	32.5
Chest Length-3rd Rib (cm)	*	7.3	5.7
Chest Length-5th Rib (cm)	*	14.0	11.0
Chest Length-7th Rib (cm)	*	20.6	15.1
Thorax Length (cm)	*	33.3	27.7
Inferior Rib Rise (cm)		12.1	10.6
Inferior Rib Run (cm)		12.8	9.8
Chest Circumference-3rd Rib (cm)		101.1	101.0
Chest Circumference-5th Rib (cm)		97.6	101.6
Chest Circumference-7th Rib (cm)		90.7	98.8
Clavicular Depth (cm)		12.8	16.5
Chest Depth-3rd Rib (cm)	**	17.6	22.5
Chest Depth-5th Rib (cm)	**	20.2	24.1
Chest Depth-7th Rib (cm)	**	20.0	24.6
Chest Depth-Mid-Sternum (cm)		19.8	23.8
Chest Breadth-3rd Rib (cm)		32.0	29.5
Chest Breadth-5th Rib (cm)		31.4	28.2
Chest Breadth-7th Rib (cm)		30.4	29.9
Distal Thorax Breadth (cm)		27.7	27.9

* These measures are taken with respect to a proximal reference (the clavicle).

** These depth measurements are taken with respect to a constant posterior reference point.

Loading

Static point loading was applied through the axis of each deflectometer by a 3 cm diameter steel pad. Loading ranged from 15 to 20 kg. Belt loading was applied with a 4.8 cm wide automotive seatbelt set diagonally in a driver configuration, 36^{o} to the mid-sagital plane, centered on the sternum. Static belt loading ranged from 0 to 75 kg. Dynamic belt loading was provided by a 45 kg pendulum impactor, dropped from heights up to 40 cm. Total maximum belt load was restricted to 3.6 kN (810 lbs) over 60 ms to avoid injury to the test subjects. The Hybrid III chest was subjected to higher maximum belt loads.

Human Test Parameters

Tests were conducted while the subjects were lying in a supine position, with the lower limbs elevated to simulate a seated position; this also provided full support for the thoracic spine. This posture was also chosen to help eliminate subject movement

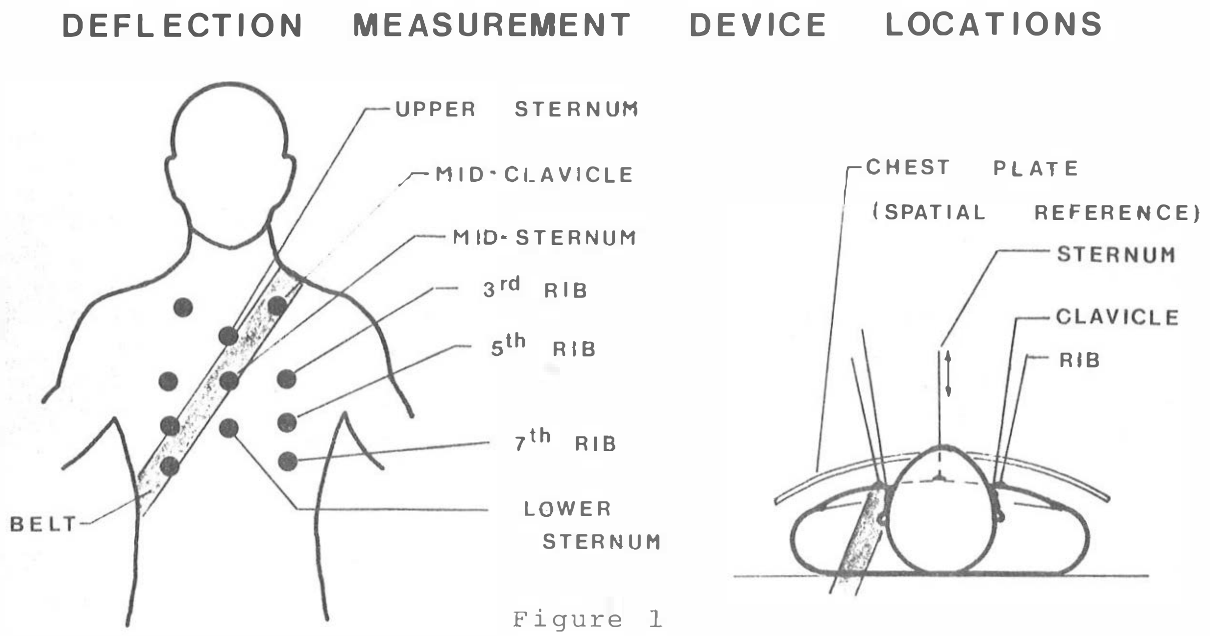


Figure 1

relative to the deflection measurement devices (during the loading and unloading events).

Muscle tensing, it was felt, was an important parameter to document, since preliminary tests confirmed it had a substantial effect on force-deflection response. Hence subjects were tested while relaxed, then re-tested for a tensed state. Lungs were inflated to approximately 50% of their maximum volume.

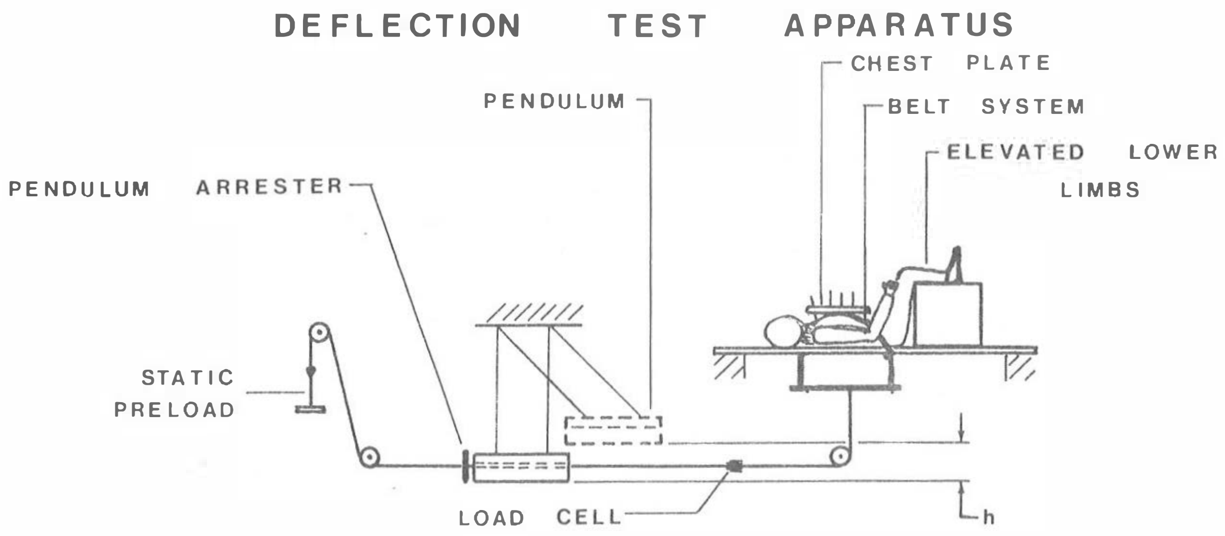


Figure 2

Test Results

Maximum total belt force vs maximum deflection curves were produced for each of the 11 deflection measurement locations. For the Hybrid III chest, two curves were produced: one representing the response of the mechanical structure (ribs only) and the second representing the chest with its soft tissue covering. Human chest response data points were also plotted for each of the seven volunteers tested. Figure 3 illustrates F_{bmax} vs D_{max} responses for subjects relaxed, and Figure 4 for subjects tensed.

OBSERVATIONS

Anthropometrics

In a comparison of the subject means and the ATD anthropometric variables, the results ranged from very similar to quite large differences. These results are compared in Table 1. One set of variables that was not similar were chest circumferences. The ATD exhibited a chest that was cylindrical shaped, as there were not sizeable differences between circumferences at the 3rd, 5th and 7th rib. Although the humans had similar values to the ATD for the 3rd rib circumference, the 5th and 7th rib circumferences were progressively smaller. Thus, the human chest resembled the shape of an inverted, truncated cone as opposed to the cylinder-shape of the ATD.

This same concept can be applied to chest breadths. The ATD had constant breadths at all 4 measurement sites: 3rd, 5th, 7th rib and distal thorax. While the humans have a very similar distal thorax breadth compared to the ATD, the breadths grow progressively larger, superiorly indicating, once again, the general truncated-cone shape of the human thorax. Measurement of chest depths also exhibited other differences between the ATD and humans. The ATD chest was much deeper at all measurement sites when compared to the human values. The ATD chest depths, while uniformly larger, were quite similar to each other in magnitude confirming the barrel chested, cylinder-shaped, analogy.

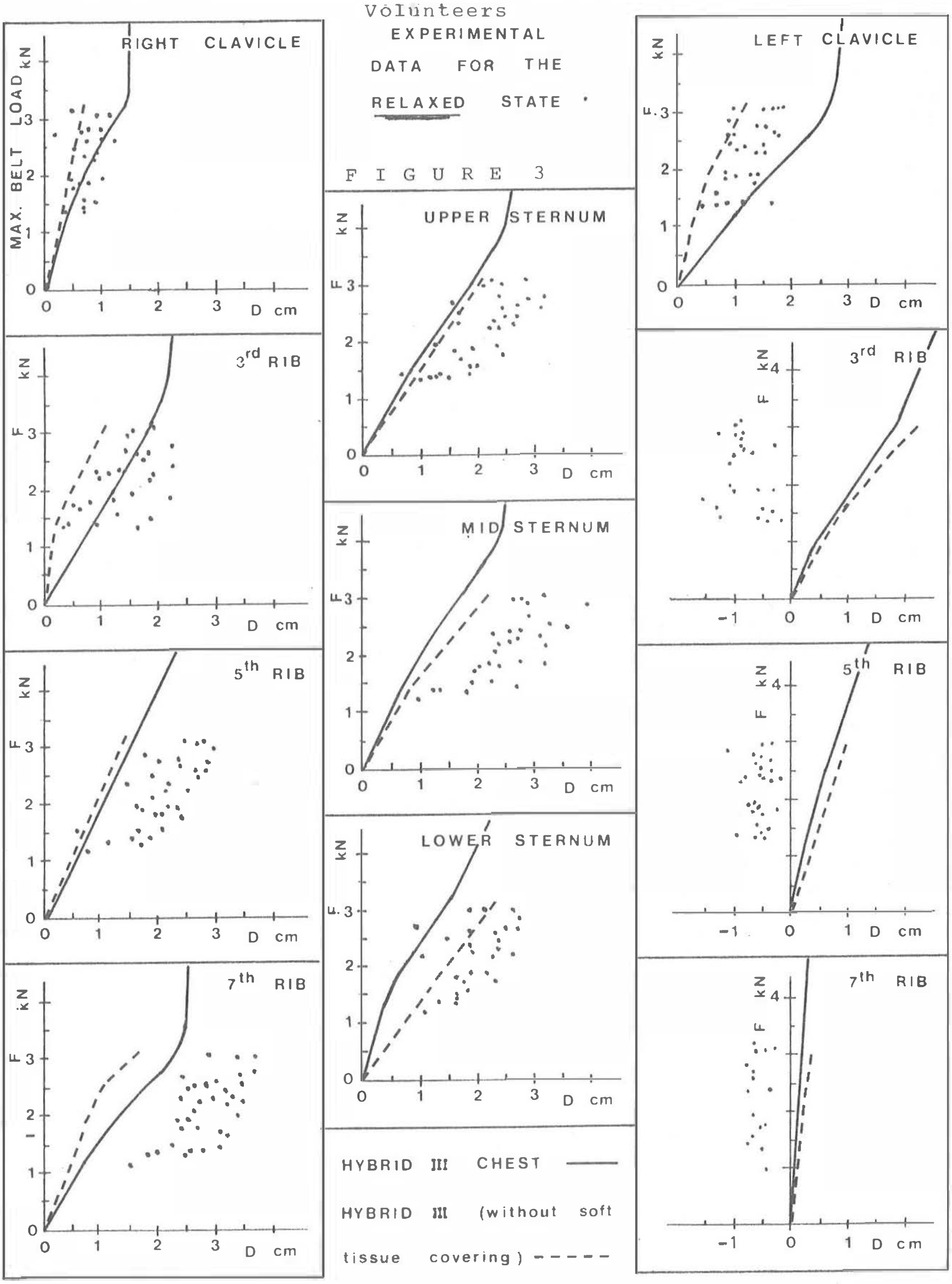
The dimensions of the internal rib cage of the ATD are worthy of scrutiny. When compared to humans, the sternum, and chest lengths from mid-clavicle to the 3rd, 5th, 7th ribs and distal thorax measurements of the ATD were always shorter. In other words, the proportions of chest to abdomen in the ATD were not similar to those in humans. Humans exhibit longer rib cages resulting in the chest comprising a greater proportion of the total trunk length. Again, however, care must be taken in interpreting these results due to low reliability between test trials.

Due to the nature of the soft tissue on the ATD, comparison of human skinfold adipose measurements could not be conducted.

Static Tests

Load levels were kept low during static point load tests because of the pain they caused. Consequently, the data produced

Maximum Force vs Maximum Deflection for Hybrid III and Human Volunteers



EXPERIMENTAL DATA FOR THE RELAXED STATE

FIGURE 3

Maximum Force vs Maximum Deflection for Hybrid III and Human Volunteers

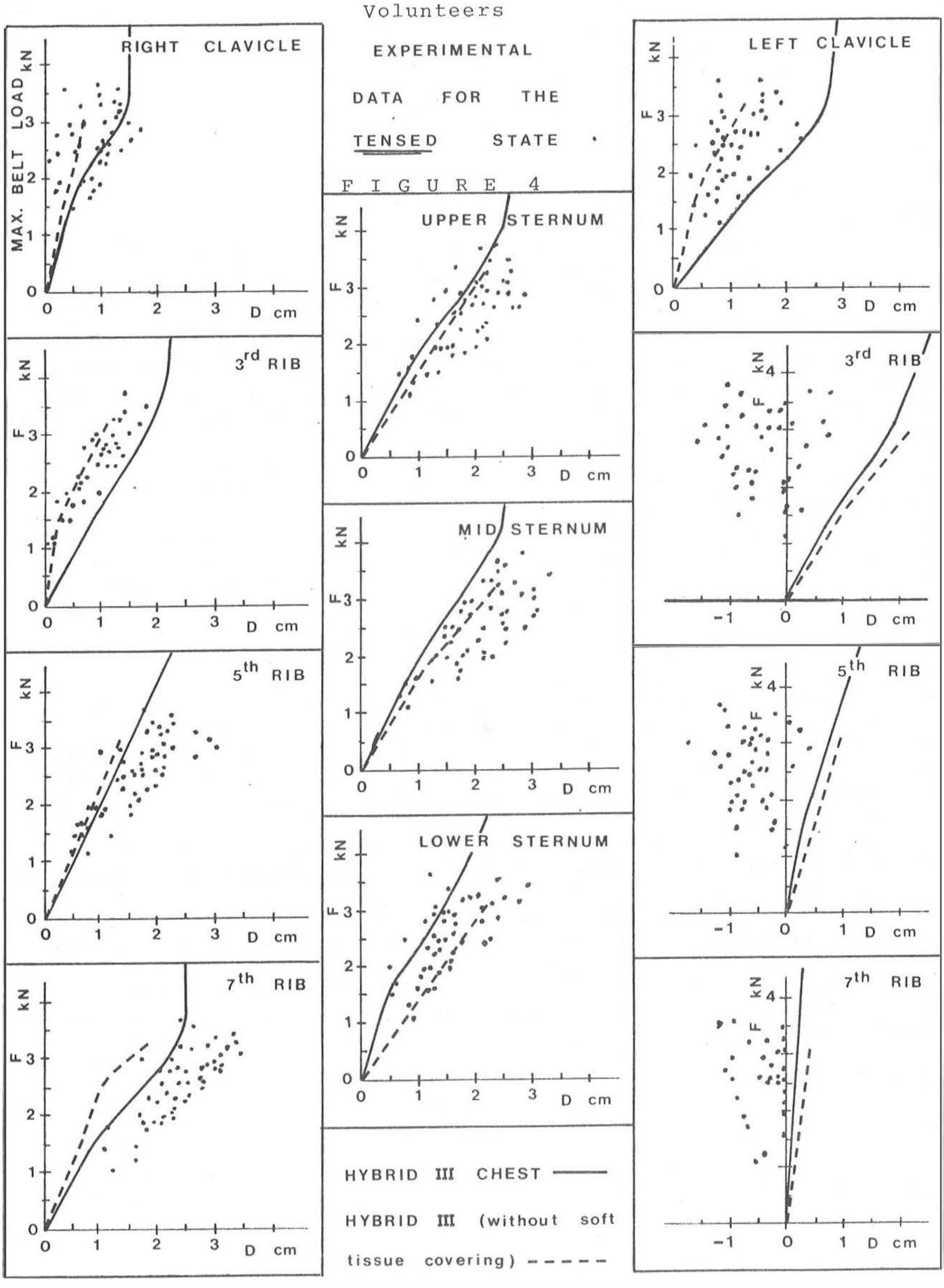


FIGURE 4

was not deemed especially useful at this time. Under static belt loading the Hybrid III chest was much stiffer than the human subjects. Compression of the Hybrid III chest was largely confined to the soft tissue covering.

Dynamic Tests

Total belt load reached 3.6 kN during tests to human subjects. Some volunteers complained of muscle soreness, but no injuries were sustained as a result of testing. Figures 2 and 3 represent the F_{bmax}-D_{max} deflection responses of the Hybrid III and humans.

The Hybrid III chest without a soft tissue covering was stiffer than the chest with the covering for all deflection measurement locations on the right side, as well as the left clavicle. The reverse was true for all other locations. Slight variations between covering and no covering were found for the right 5th rib, the upper and mid-sternum as well as the 3rd, 5th and 7th ribs on the left. Larger variations were detected at the clavicles, right 3rd rib, 7th rib and lower sternum.

The human chest responses were scattered and varied by as much as 1.5 cm from one subject to the next for a relaxed state (under constant belt load). The largest amplitude deflections occurred at the right 7th rib (3.7 cm) and at the upper and mid-sternal locations (3.2 and 4 cm respectively). Loading was limited to 3.2 kN when the humans were tested in a "relaxed" state because subjects invariably tensed at higher loads to counter the discomfort. Outward deflections were noted on all rib measurement locations on the left side (up to 1.5 cm at the 3rd rib). The Hybrid III chest was stiffer in all locations except the left clavicle and Hybrid III did not produce outward deflections on the left rib location.

In the tensed state, the human chest responses were also scattered. Local deformation varied by as much as 2 cm from one subject to another. The largest amplitude deflections were again recorded at right 7th rib (3.5 cm), and upper and mid-sternal locations. Outward deflections were also noted on all left rib locations, however, a few inward deflections were also noted. The Hybrid III chest was stiffer at all locations except the clavicles and the right 3rd rib.

No curves or corridors were traced to represent typical chest responses because of the small size of our sample, however, comparisons between tensed and relaxed state data points (for a given load level) confirm that a "tensed" chest is stiffer. Similar responses were obtained (tensed vs relaxed) in the clavicle regions, as well as the left rib locations.

DISCUSSION

To draw conclusions from the comparative results between the human subjects and the ATD based only on anthropometric measurements, the ATD trunk can be modelled as a cylinder while that of human's as a truncated cone. The ATD appears to be based on the Hanavan model (11) of segmental links. However, Miller and Morrison (16) pointed out the inaccuracies of the model. Based on this anthropometric comparison, a re-evaluation of the ATD thorax is required to closer simulate the human body when one considers that the ATD is to be fitted with human restraint harness systems.

In a general sense, the ATD chest appears not to be a very good model of the human. However, the broad range of human responses re-emphasizes the high degree of variability between different subjects. Even the same subjects may produce markedly different responses as evidenced by the differences in the relaxed and tensed states. Such a large degree of scatter begs the question: Which human thorax under what conditions does one wish to emulate with an ATD? Notwithstanding, the general characteristics of the chest are those in which fluid characteristics appear to predominate over elastic features. This is certainly not true for the ATD as it indeed contains no fluids per se. Its force deformation characteristics reflect this fact.

With respect to the apparent stiffness of the thorax, it is of special interest to note the rather remarkable, and perhaps somewhat fortuitous, similarity between the tensed human volunteers and the Hybrid III at the sternal region. This is to be not entirely unexpected since mid-sternal deflections, induced admittedly by a blunt impactor, were the basis for the Hybrid III design.

The marked differences between the ATD and the subjects on the left (essentially unloaded) side of the chest appear to be manifestations of the basically elastic structure of the ATD and the basically fluid-elastic structure of the human. A better ATD chest surrogate would be one which better emulates this behaviour. Whether or not this would necessarily assist in the monitoring of prospective rib fractures due to belt loading, is not clear at this time.

The different responses at the loaded clavicle are entirely expected of course, because of the two inherently different "designs". An ability to assess possible clavicle fracture, accurate simulation of whole-body kinematics and reliable prediction of upper belt loads can only be achieved if improvements to the dummy are made in this area.

Finally, the excessive apparent stiffness of the mid-lower ribs of the ATD must be addressed if the test device is ever to be employed to assess rib fracture in that area.

ACKNOWLEDGEMENTS

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