Journal of Biomechanical Science and Engineering
Vol. 3, No. 4, 2008

Dynamic Mechanical Characteristics of Thorax Structure*

Hisashi OHKAWA**, Yushi SUZUKI**, Yutaka KANETA**,
Masafumi ODA*** and Toshiaki HARA****
**Graduate School of Science & Technology, Niigata University
***Center for Cooperative Research, Niigata University
****Faculty of Engineering, Niigata University
8050 IKARASHI 2-nochou, Nishi-ku, Niigata City, Niigata 950-2181,Japan
E-mail: f07b125a@mail.cc.niigata-u.ac.jp

Abstract
Thorax plays a crucial role in shielding internal organs from external loads. To establish a rational safety criterion for traffic accidents, it is important that we understand the mechanical behaviors of the thorax. We studied the response of thorax to impact experimentally. The purpose of this study is to understand the characterization of thoracic structure from measurement parameters by impact test. The specimen used was porcine thorax, the size of which was approximately equal to human thorax, after removing the internal organs. Using original test apparatus, the specimen was subjected to low energy impact and a sensitivity study was conducted to explore various parameters, including the response to the impact load, strain on each rib, and the acceleration and displacement in the thorax. Comparison of impact locations (front, back, and lateral) showed characteristic variations among the results. A frontal impact produced large acceleration and displacement. Therefore, it could be expected to stress the internal organs directly. In the case of an impact from behind, the impact response load was higher and the deformation of thorax was remarkably small. It appeared that the thoracic resists backward impact, and provides protection of internal organs. In lateral impact, the concentrated load tends to occur in the ribs, and the rib strain was high. Hence, the rib parts were prone to fracture, and the internal organs were subject to increased risk of secondary damages of the bone fracture due to bone sticking organs. In conjunction with the impact tests, static compressive tests were conducted. The deformation behavior of the thorax is grossly affected by the constraints of the binding of ligaments connecting bones. Therefore, this structure provides smooth elasticity by transforming the whole structure when a load is applied to the thoracic parts. This provided confirmation of the structural characteristics that were obvious in impact testing. This is the first time that attention has been paid to the thoracic structure and its deformation behavior has been investigated. The response of thoracic structures to external loads requires further research.

Key words: Crash Test, Thorax Structure, Mechanical Characteristic, Deformation Behavior , Transformation, Traffic Accident

1. Introduction

Functions of bone structure include support to body trunk and protection of soft tissues such as the internal organs represented by the thorax breast. The bone structure covers only particularly fragile organs that are vital to maintaining life, such as the brain, heart and lungs. Paradoxically, organs covered by a bone structure are especially important, and damage to them can lead to death. Therefore it is very important to obtain the dynamic

*Received 9 June, 2008 (No. 08-0405)
[DOI: 10.1299/jbse.3.468]

information of the structure protecting them. Hence, many studies employing various methods have been performed to acquire the dynamic characteristics of these anatomies, such as the thorax bone. These methods mostly consider traffic accidents; for example, crash experiments are performed using cadavers[(1)(2)(3)], or dummy dolls[(4)(5)]. Recently, numerical analysis using finite element methods[(6)(7)(8)] were also performed. Other researches use a technique to reproduce the dynamics of the formation by performing an examination in a compositional unit such as the muscle fiber, ligaments and bones, and by combining mechanical characteristics of these elements[(9)]. But it considers this approach as a part of numerical analysis, because it pieces the elements together.

However, due to ethical issues and other factors, few experiments have been performed with cadavers. In addition, for crash experiments with dummies or crash numerical analysis by FEM, there is still room for more examination into whether theses models reproduce the dynamic behavior of the biological object at a level that is useful for practical application. There is extremely little experimental information available based on a real biological object. Many researchers have focused on determining a general-purpose injury criterion in the living body, but it is necessary to perform fundamental experiments with a biological object to determine if the injury criterion is reliable enough. Today, although the technology of the computer simulation has progressed drastically and has attracted attention, it seems that experiments on biological objects are essential to establish boundary conditions that will allow the usage of simulation technology effectively.

So, in this study, the dynamic and structural characteristics of a detailed thorax were obtained. We examined its ability to protect internal organs in crash and compression tests and anatomy, using a fresh pig thorax. In particular, this report describes the basic dynamic behavior in detail rather than the applied discussion, including searching for injury criterion.

2. Methods

2.1 Crash test device

Figure 1 shows a schematic diagram of the crash testing device. The device transmits the elastic energy of the torsion spring to the impactor on the rail through a slider crank mechanism, and blasts the impactor into the sample. The mass and the initial speed of the impactor can be changed by the bending angles of the torsion spring, and an experiment is possible with a mass in the range of 3-10 kg at a speed of 8-20 km/h. The crash speed is found by measuring the speed just before the collision with a speedometer. In order to take into account the material of car bumper, an MC nylon which is made of plastic is attached to the front of impactor. The crash plane is 24mm long by 100mm wide.

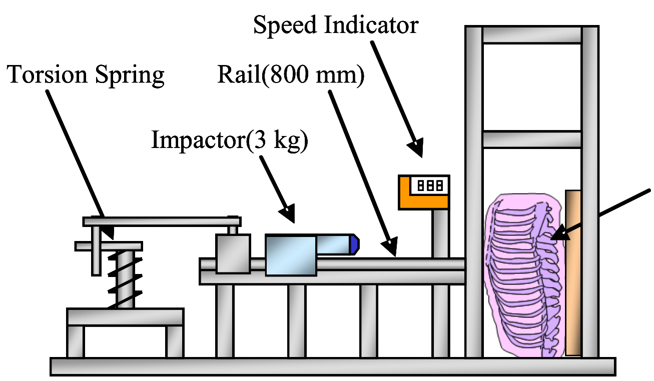

Fig. 1 Schematic diagram of the impact experimental setup. The thorax specimen was fixed in the rear of the crash plane with a board. The impactor, including the load cell, was launched toward the specimen using the energy of the torsion spring and slider-crank mechanism.

2.2 Specimen

The experiment used fresh body of an 18-week-old pig, which has a thorax comparable in size to that of a human. Although the porcine thorax has two more ribs than a human thorax and is flatter, they are applicable to estimate the adequate index to reproduce the dynamic behavior of a human thorax. Because of the size, cartilage compages and articular structures of porcine thorax resemble those of humans. Surely, human thorax structure differs from porcine thorax structure in terms of degree of costal curvature and the collective thoracic shape. Additionally, they differ in the point that whereas spinal concatenation of human is vertical, pig is transverse in basic body position. Hence, to apply the properties of porcine thoracic structure that are obtained in this study for human, evincing the difference of structural properties is needed. However, even human property is remaining poorly understood, and from an ethical viewpoint, test using human cadaver becomes increasingly difficult. Therefore, we thought that the best efficient approach to obtain the characteristics of human thorax was to evince impact resistance properties by applying combination amassing many data by experiment use of accessible porcine thorax with considering anatomical difference of these thoraxes and case examples of human injury in traffic accidents.

The specimen thorax is removed by separating the intervertebral joint between the cervical vertebrae-thoracic vertebra and the thoracic vertebra-lumbar vertebrae. In this study, the costal outside muscle and subcutaneous fat were preserved intact, and all the intracostal internal organs were removed to evaluate the characteristics of only the thorax structure. In addition to the specimen, the shoulder blade along the rib was removed.

Fig. 2 Thoracic structure of the pig. The bone structure is similar to a human's.

2.3 Experimental condition

Because the frame of the thorax is not symmetric in the vicinity of the coronal plane, mechanical characteristics, such as transformation behavior, vary according to the direction of the applied load. In this study, the impact testing is performed in each direction. The specimen was placed so that the front, backward, and lateral of the thorax as seen from the coronal plane faced the impactor respectively. The differences in characteristics depending on the crash direction were noted. Additionally, the posterior facies of the specimen, in the crash plane, was supported with an aluminum board. One specimen remained the position that was set up initially until changing the impact direction. When only impact direction was changed, the specimen was reset. The mass of the impactor was fixed at 3kg and the speed was regulated to three phases of about 7.4, 11.6, and 15.2 km/h. Thus, nine conditions were examined. The impact location was fixed such that the center of the impactor struck the center of the breastbone, when observed from the front. Though 27 times impact was applied for one specimen in this study, we have performed a preliminary test to apply 50 times impact for one specimen, and confirmed no damage to the specimen by unchanged response during the test. Moreover, we confirmed no damage to the specimen by anatomical observation after the test. We judged that it was no problem to repeat impacts for one specimen based on the above result.

2.4 Evaluation of impact response

The measurement parameters are the impact force at the time of the crash, the acceleration of the internal thorax parts, and the strain of each costal central part. Considering them in a comprehensive manner evaluated the dynamic response characteristics the thorax structure offered from the viewpoint of its ability to provide protection.

Crash force was measured using a dynamic force sensor (ICP® Dynamic Force Sensor Model M200C20, PCB PIEZOTRONICS) that was set up in the impactor, and the input load applied to the specimen was measured.

The transformation behavior of the thorax structure was measured with acceleration sensors (ICP® Accelerometer Model M350B23, PCB PIEZOTRONICS) installed at four points inside the thorax structure—the breastbone, thoracic vertebra, the right rib, and the left rib. These points are in a transverse plane of the central breastbone. In addition, four strain gauges (1 mm long, from Kyowa) were glued to positions, which were at 100 degrees in the transverse axis circumference from the median sagittal plane anterior, and also inside four ribs (3^{rd}–6^{th}), to measure rib strain during analysis of transformation behavior.

The output voltage from these sensors were amplified with a motion distortion amplifier and bussed to a PC, sampling at 1 [ms], where it was evaluated.

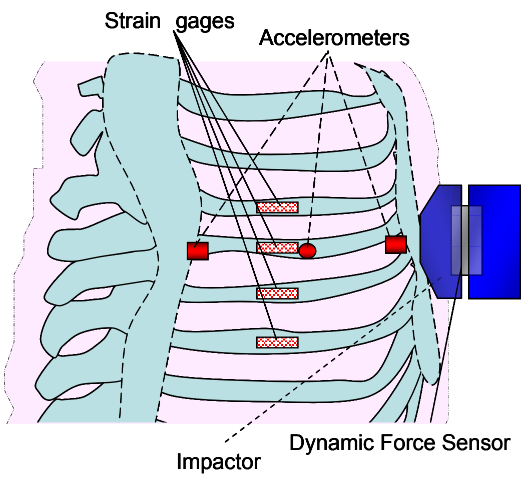

Fig. 3 Geometry of the specimen. The impact height was fixed at the center of the breastbone. Four acceleration sensors were set on the breastbone, thoracic vertebra, the right rib, and left rib, inside the thorax structure. Dynamic force and acceleration sensors were in one plane, which was parallel to the transverse plane. Four strain gauges were bonded to the middle of the 3rd, 4th, 5th, and 6th ribs.

3. Results of impact testing

Figures 4, 5, and 6 show representative wave patterns of the impact response, transformation acceleration, and 5th rib strain during a crash at 15.2 km/h. Comparing these graphs shows the dynamic characteristic of the thorax. The acceleration showing figures is the value measured by one accelerometer that was set in the internal surface of impact location.

The frontal crash indicates that the structure is flexible, and transforms easily—the shock response obtained is slow and small. This allows smooth changes in the angles of joints, such as the articulations sternocostales or the costochondral junction, when a load is

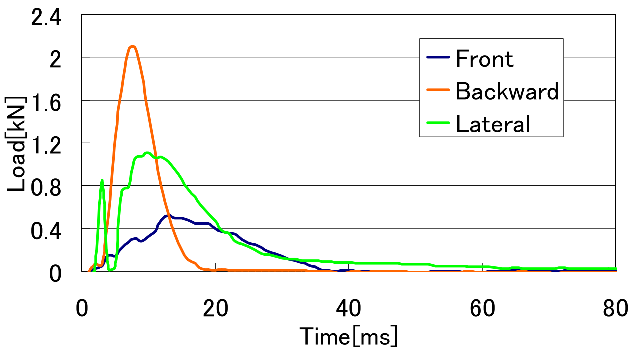

Fig. 4 Force–time responses for impacts at 15.2 [km/h] for each impact direction.

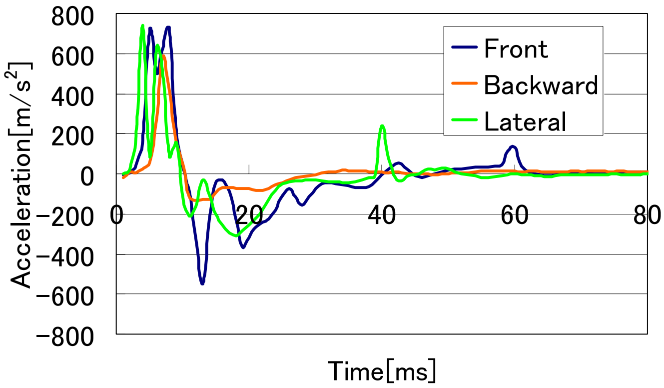

Fig. 5 Acceleration–time responses for impacts at 15.2 [km/h] for each impact direction.

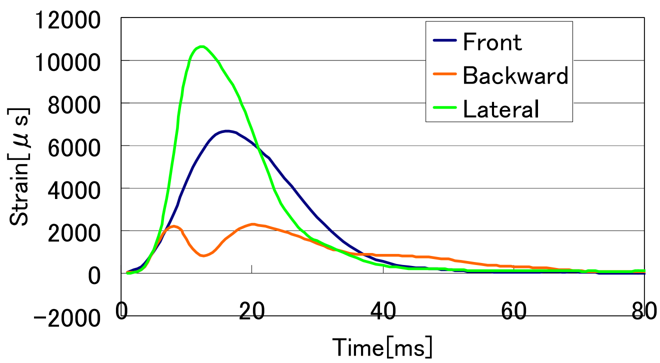

Fig. 6 Strain–time of 5th rib responses for impacts at 15.2 [km/h] for each impact direction.

applied from the front. Therefore, although the thorax transforms most of the load, but the rib strain is not big for the joints, and the thoracic structure absorbs the external force using the joints, balancing among the bone and the soft tissue.

In the crash from the rear, the thoracic structure is very firm and strong, because the thoracic vertebra is strongly connected. The transformation acceleration of the structure and ribs strain are small. It is thought that the mass at the part that is transforming becomes so large that the whole thoracic vertebra bends the rib, and the distortion occurs for a long time.

In a crash impacting lateral side, there is a lot of rib strain and it is thought that the thorax structure absorbs the crash energy mainly in the transformation of the bone, because for a joint to transform a large amount it must move away from the shock. The crash load is small in comparison with the frontal crash.

4. Discussion

4.1 Discussion of impact testing

Figure 7 shows the results of examination of Figs. 4, 5, and 6 with a load-displacement curve. At this point, the displacement is calculated by integrating acceleration twice. The load-displacement curve output during the crash test with biological objects generally measures the displacement of the biological object's surface, but this graph calculates the displacement of the structural parts. Although the dynamic behavior of the thoracic structure equals the input energy, the behavior clearly differs according to the crash direction. The form of the load-displacement curve differs considerably, depending on the crash direction, indicating a different mode of load transmission, and different characteristics for providing protection. The mechanical load conditions on the tissues of the internal organs are changed when the crash direction changes. Presently, the conditions under which internal organ tissues are easily damaged, or the mechanism and cause of the damage are still unknown. But, to understand the behavior of internal organs, this difference should be determined.

Figure 8 shows the acceleration detected in the crash test, and Figs. 9 and 10 show the results of calculated velocity and displacement by integrating the acceleration. These results became average values at N = 5. Acceleration and speed in the opposite direction, caused by restorative force after transformation, were evaluated as negative values in conjunction with positive values, in other words, compressive and tensile directions are described positive and negative values respectively. This is because the fragile organization of the brain is too weak to load the negative pressure than positive pressure as reported previously(10), and the expansion behavior of the thorax structure, which generates the tension inside the thorax and produces negative stress distribution, is thought to be an index of the damage mechanism of internal organs. The figures showing negative velocity and displacement at low speeds in a lateral crash are not given here, because our measurements could not acquire enough reliable data. The unevenness of the integral calculus value was large and several calculated results could not converge on a value. In this study, we used shock accelerometer to evaluate high frequency response accurately, because it was closely related with injury of internal organs. Then, relatively-low acceleration was not acquired amply, besides, in the case of lateral impact, change of acceleration was rapid and convexoconcaves in acceleration wave pattern were most in the three impact directions. However, further testing and regulating sensitivity of sensor hereafter would adjust this problem.

The maximum transformation acceleration of the thoracic structure increases with an increase in crash speed, and the rate of increase vary with the crash direction. The maximum acceleration value does not correspond one-to-one with the maximum velocity and displacement. This is due to the rate of change of the acceleration in the time axis.

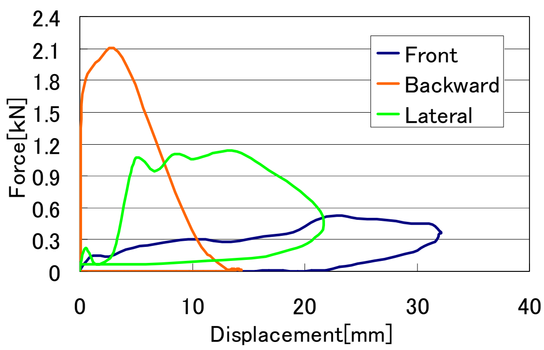

Fig. 7 Force–displacement curve of the thoracic structure for impacts at 15.2 [km/h] for each impact direction.

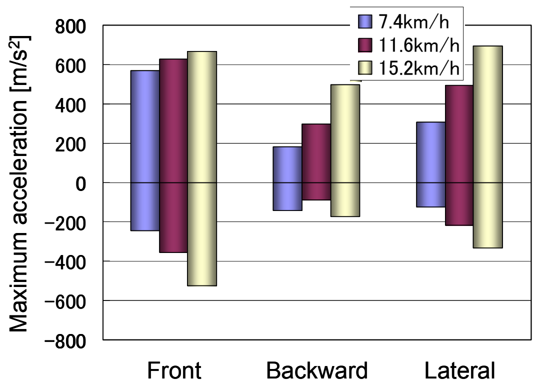

Fig. 8 Comparison of positive or negative maximum acceleration for impacts at 7.4, 11.6, and 15.2 [km/h] for each impact direction.

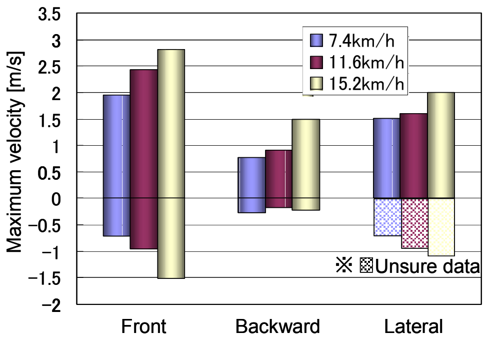

Fig. 9 Comparison of positive or negative maximum velocity for impacts at 7.4, 11.6, and 15.2 [km/h] for each impact direction.

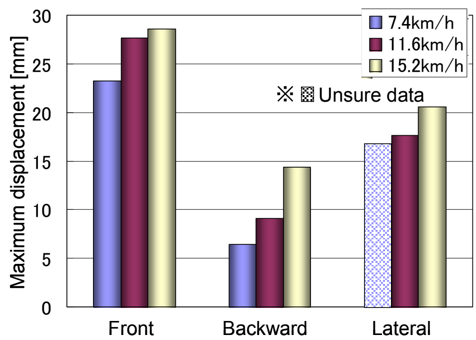

Fig. 10 Comparison of positive maximum displacement for impacts at 7.4, 11.6, and 15.2 [km/h] for each impact direction.

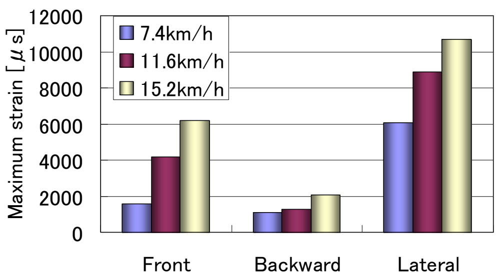

Fig. 11 Comparison of the maximum strain of the 5th rib for impacts at 7.4, 11.6, and 15.2 [km/h] from each impact direction.

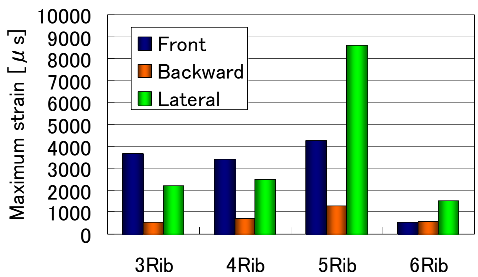

Fig. 12 Comparison of the maximum strain of the 3rd, 4th, 5th, and 6th rib at 11.6 [km/h] from each impact direction.

When there is a crash from any direction, the time that the acceleration occurs does not differ, but for a frontal crash, the acceleration wave pattern is almost a trapezoid; for a rearward crash, the wave pattern exhibits sharp peaks. In particular, the transformation of the thorax is very small in a rear crash. At this point, the time of acceleration does not change because the impactor mass is fixed. Thus a crash test that assumes the mass is a variable is necessary for a more detailed examination of transformation behavior.

Figure 11 shows the strain at the 5th rib, according to the speed and crash direction. Figure 12 shows the strain at each rib when the crash speed is 11.6 [km/h]. The maximum strain increases with an increase in crash speed, but when the crash direction changes, the maximum distortion changes greatly. The correlation of the strain and displacement change is shown in Fig. 10~12. When crashing from the front and rear, the strain occurs over several ribs and the shock can be absorbed over a large domain of the thorax. For a side crash, however, the high strain occurs locally in ribs, and the strain also occurs in the bone except for the 5th rib, which is not pushed directly. This is due to strong cohesion of the muscle and fat between the ribs, as well as the strength of the ligament.

A strain of 10000 [μs] occurs at the maximum. This is a large amount of bone strain, and illustrates that the rib is comparatively flexible. However from the results of FEM analyses(6)(7)(8) reported by literatures, deformation on the rib bone is found to be extremely larger than the aforementioned results, because there are few studies that have measured the quantity of rib strain at the time of crash using an actual survey. Certainly, at the time of the crash, though the thorax structure transforms greatly, moving a couple of centimeters, this result indicates that the displacement is not caused by distortion of the ribs, but by angle variation of the joints in the thoracic structure.

However, it is very difficult to evaluate the amount of rib strain quantitatively. Figure 11 and 12 show the results when the crash test was performed several times with a single specimen. They do not consider test results for different specimens. Thus, the graphs of Figs. 11 and 12 do not take individual differences into account, although they provide a representative result. Hence, we decided to show the example to put forth a more conservative argument in this report. The maximum strain changes around 2 times for specimens, and the strain amount and the behavior of each rib part changes greatly depending on how the specimen is set, for instance, the transformation of a rib becomes first-order mode or second-order mode, although the test results is obtained considerably quantitative toward one specimen which states is fixed once. It is difficult to establish a routine set up for multiple specimens due to differences among samples, such as in the bone structure, the form of the bone structure and the amount of muscle in the body of the thorax—it is difficult to experiment on specimens having limitlessly uniform state.

While this means that the stress states of the thorax structure and internal organ tissues change from a gentle contact, the restraint conditions, and body type in the crash test, and due to the complexity of the biological structure. Thus, it is necessary to conduct experiments on real biological objects.

This experiment evaluated dynamic behavior in low energy crash tests and compared the protection ability in the range of the thorax structure was not damaged. It is necessary, however, to evaluate a larger domain, such as performing the crash test with higher energy and under different test conditions. In particular, examining destruction behavior closely identifies injury criterion directly; we will investigate this later. In addition, the specimen was used in a form without internal organs. It is necessary to examine any change of dynamic behavior between this and the presence of internal organs. It is also necessary to consider the style of the specimen. At the scene of an accident, there is not a simple correlation between the damage to the thorax structure and the internal organs tissues. For example, although no damage may be seen in the thorax structure, the internal organs might be injured, or reverse. Therefore it is necessary to examine the differences in load transmission characteristics of the thoracic structure and the inside it for various external force conditions, to be able to evaluate injury criterion for internal organs.

4.2 Discussion of anatomical observation

In this experiment, to improve our understanding of the thoracic structure, static compression tests and detailed autopsies of thoracic parts were conducted in parallel with impact tests.

The ability to accommodate large deformation is a prominent feature of the thoracic structure. It features a very wide elastic range, possesses high load-bearing power, and the joints transform lithely. When compressing the entire area, the bearing load was not decreased after yielding, and the compressive surface transformed so that the opposite interior surface contact, becoming so large that the structure could not be destroyed completely. After the load was removed, the structure partially resumed its original shape. During deformation, the ribs collapsed onto the lumber spine side, although there were differences among their compression velocities, yield strength occurred in lesions of ligaments and ribs.

The thorax is characterized by increasing strength as you approach the neck. The ribs in the neck side are thicker, in addition, the binding of ligaments around the costovertebral and sternocostal joints is stronger. Consequently, there is less range of motion in the costovertebral joints on the neck side. If there was only a binding of ligaments covering joints, the costovertebral joints, costochondral junction, and sternocostal joints would have a wide range of motion which could not resist external force. However, because of the muscles and membranes existing around joints and he binding of ligaments connecting ribs expressly, this range of motion is lost. Thus, such structures provide smooth elasticity through the transformation of the whole structure, when a load is applied to thoracic parts and structures that provide large deformation.

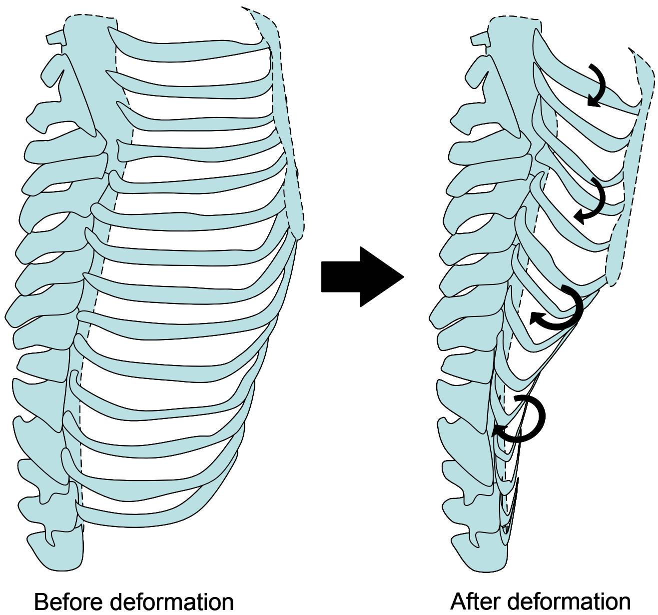

Fig. 13 Transformation behavior of the thorax during compression from the front. The thorax is transformed primarily by costovertebral joints changing their angle.

5. Conclusions

In this study, we conducted thoracic impact tests, using fresh porcine carcasses. Most research has not paid attention to the thoracic structure and investigated its deformation behavior. Therefore, this study, which describes the mechanical behavior of the thoracic structure under external load in detail, could be extremely useful. As mentioned in the apparent limitations of this study, experiments with real living subjects are essential.

References

(1) Lizee, E., et al. "Finite Element of the Human Thorax Validated in Frontal, Oblique, and Lateral Impacts: A Tool to evaluate New Restraint Systems," IRCOBI Conf., (1998), 527

(2) Cavanaugh, J.M., Zhu, Y., Huang, Y., King, A.I. "Injury and response of the thorax in side impact cadaveric tests," In: Proceedings of the 37th STAPP Car Crash Conference, no. 933127, 1993

(3) Cavanaugh, J.M., Walilko, T.J., Malhotra, A., Zhu, Y., King, A.I. "Biomechanical response and injury tolerance of the thorax in twelve sled side impacts," SAE 902307, 1990

(4) Allan, F.T., et al. "Factors Affecting Pelvic and Thoracic Forces in Near-side Impact Crashes: A Study of US-NCAP, NASS, and CIREN Data," Accident Analysis and Prevention 37 (2005) 287–293

(5) Kristine, J.S., et al. "Two-Car Impact Test Of Crash-Energy Management Passenger Rail Cars: Analysis Of Occupant Protection Measurements," Proceedings of IMECE'04 ASME 2004 International Mechanical Engineering Congress & Exposition Anaheim, CA, November 13-19, 2004

(6) Lee J.B. and Yang K.H. "Development of a Finite Element Model of the Human Abdomen," Stapp Cor Crash Journal,Vol.45

(7) Haug, E. "Biomechanical Models in Vehicle Accident Simulation," In: J.A.C Ambrosio. M.F.O. Seabra Pereira, P.F. Silva (Eds), Crash-worthiness of Transportation Systems: Structural Impact and Occupant Protection, Kluwer Academic Publishers, Dordrecht, 1997, pp, 237–259

(8) Furusu, K., Kato, C.. "Fundamental Study of Side Impact Analysis Using the Finite Element Model of the Human Thorax," R&D, Vol.36, No.2, 2001.6

(9) Abe, H, Hayashi, K, Sato, M. "Data Book on Mechanical Properties of Living Cell, Tissues, and Organs," 1996

(10) Ward, C.C., Chan, M, and Nahum, A.M. "Intracranial Pressure-A Brain Injury Criterion," Proceedings of the 24th Stapp Car Crash Conference, SAE Paper No. 801304, 1980, pp. 347–360