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# Experimental biomechanical assessment of plate stabilizers for treatment of pectus excavatum

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The paper discusses results of experimental research involving new generation of plate stabilizers used for the treatment of deformation of the front chest wall. Previous clinical monitoring revealed instances of minimal rotation, which caused destabilization of the anastomosis and pain in patients. In order to prevent this, transverse stabilizing plates were introduced to the structure of the stabilizer. The new structure of stabilizers was tested using two specially prepared research posts: 1 – which enables fastening of the plate stabilizers to a platform simulating human ribs, 2 – using a pig chest, to which plates were fastened according to the stabilization conditions in the stabilizer–chest structure. The tests recorded displacement values in selected areas of the plates in response to applied loading forces.

*Key words*: *biomechanical characteristics, metallic biomaterials, plate stabilizers, pectus excavatum*

## 1. Introduction

The chest protects main respiratory and cardiovascular organs. It consists of thoracic vertebrae, ribs and sternum. Deformation of the front chest wall has been an important therapeutic problem for years. This practically concerns two pathologies, which is pectus excavatum and pectus carinatum [1]. Pectus excavatum deformation is present in 0.4% of children, five times more often in boys than in girls [2], [3]. Children affected by this defect present weaker physical development and abnormal posture. They are usually apathetic, inactive, and prone to cardiovascular and respiratory system diseases [4]. Pectus carinatum occurs less often than pectus excavatum. It is an innate or developmental malformation, usually resulting from rickets. What is characteristic of this deformation is malformation of the sternum, which significantly protrudes forward [4], [5].

Methods of treatment for those deformations are chosen individually in each case. The treatment process varies. With small deformations conservative treatment is used (corrective exercises). Unfortunately, this method is inefficient with larger deformations of the sternum, therefore in those cases the only method of reconstruction is surgical treatment, applied especially when the deformity progresses quickly, or in cardiovascular-respiratory system disturbances [2]. For many years, operation with classical Ravitch's method has been a basic procedure in therapy of patients with pectus excavatum [6]. It appeared, however, that the most important problem following operations based on this technique was the recurrence of deformations and significant disfigurement in the form of flat chest [7].

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In 1997, Donald Nuss presented to the American Paediatric Surgical Association a new surgical method, which consisted in introducing into a previously created tunnel between the pericardium and the anterior surface of sternum a properly shaped plate, and rotating it in order to elevate the sternum, Fig. 1. The method does not require cutting or resection of osteocartilaginous parts [8]. This technique proves that it is possible to perform a surgical procedure correcting this defect in a way less traumatic for patients, and to accelerate the healing and rehabilitation processes [9], [10].

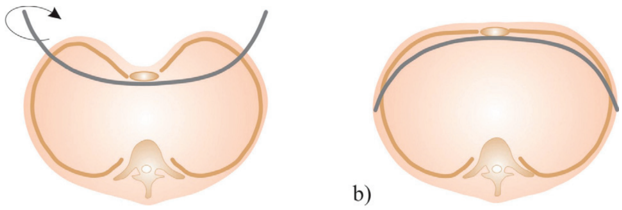


Fig. 1. Treatment of pectus excavatum with Nuss' method: (a) placing a properly shaped metal plate under the sternum, (b) rotating the plate by 180º and suturing it to the ribs

Considering the opportunity to apply low-invasive surgical methods and to minimize costs, the Centre for Biomedical Engineering of Silesian University of Technology developed a range of plate stabilizers and surgical instruments, which were implemented for manufacturing in BHH Mikromed [11], [12].

The results of clinical trials have been very positive so far. Single cases of plate rotation, leading to destabilization and pains, have been observed during loading of the sternum. This effect was rare when the plates were fastened with wires only, directly to the ribs. The results of previous experimental research conducted by the authors [13]–[19], concerning analysis of the bone tissue–implant system, support the need for biomechanical studies in order to assess stabilization after introducing changes in the plate structure and using additional bars preventing the plate rotation. As a consequence, new methods for correcting abnormalities of the front chest wall have been created.

The research results also provided basis for optimization of geometric features of some elements in the plate stabilizer, and for the choice of mechanical properties of the metal biomaterial with relation to anthropometric characteristics of patients in age groups from 5 to 15.

# 2. Materials and methods

## 2.1. Research material

The research was conducted using plates with modified structure, made of Cr-Ni-Mo steel, whose chemical composition and mechanical properties complied with the ISO 5832-1 standard [20]. The structure involved (Fig. 2):

- a modified (compared to the initial structure) plate with prepared sockets for blocking screws, which enable regulation of its position and allow for a more dynamic treatment after the surgery by increasing or decreasing pressure to the ribs,
- two transverse plates with wholes to fasten them with surgical wire to the ribs, which disable rota-

Fig. 2. Structure of an implant for treatment of chest deformations

tion of the plate, simultaneously blocking its position,
- four blocking screws.

Plates selected for testing were the most commonly used ones with the following dimensions: width 16 mm, thickness 2.5 mm and length 340 mm with transverse plates and blocking screws. The plates were bent using special surgical instruments to fit typical anatomical curvature of the chest. In practice it is known that bending of the plate depends on patient's individual anthropometric characteristics. Plates are bent individually, so that after placing them the chest can have correct form. Accounting also for the fact that each deformed chest under the treatment is characterized by different geometry, the curvatures of plates after the final modelling differ. This can influence the relations between the various values of forces and displacements.

## 2.2. Experimental research post

The biomechanical research was conducted using a universal testing machine manufactured by MTS Insight company. A special post in the form of a platform was used for attaching the plates. Geometrical features of the designed "platform" corresponded to the shape of the chest. In the second research cycle, a pig chest was used to reflect real conditions of stabilization. To determine displacement values at the characteristic points on the model (along the "*x*" axis) Mitutoyo sensors were used (sensor 1 – point A, sensor 2 – point B), as shown in Figs. 3–5. Displacement values in the direction of "*z*" axis were recorded with the use of special software of the universal testing machine.

### 2.2.1. Experimental research – stage I

In the first test a specially designed handle was used, which enabled attachment of plates, assuming that the limitations of physiological displacement are max. 10 mm on one side, simulating natural mobility of the chest (Figs. 3 and 4), ensuring at the same time stability of the whole measurement system. The plate was fastened with blocking screws to a stabilizing bar, which was then attached, following the surgical technique, to the handle of the universal testing machine with surgical wire of 1.2 mm in diameter. The test was conducted for plates with comparable geometry.

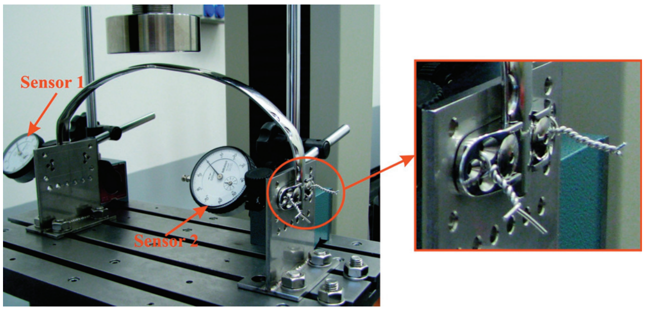


Fig. 3. Experimental research post

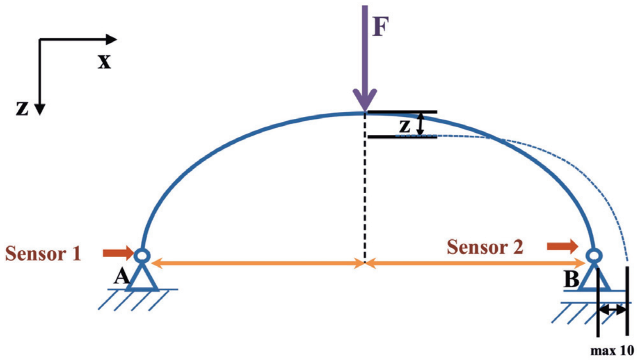


Fig. 4. Schematic presentation of boundary conditions used in experimental research

The experimental research measured values of loading forces *F* and displacements in the direction of "*x*" axis for applied axial displacement in the direction of "*z*" axis from 0 mm to 10 mm, every 1 mm.

### 2.2.2. Experimental research – stage II

The experimental biomechanical characterisation of the plate stabilizer was recorded also for the implant–pig chest system. Geometrical features of the system used were adequate for the age range of 8–15 years. Values of loading forces *F* and displacements in the direction of "*x*" axis recorded for axial displacement in the direction of "*z*" axis from 0 mm to 20 mm, every 5 mm, were assessed. The sternum displacement values were adapted according to felt pain, and they remained within the range of 10 mm to 20 mm. The maximum value adapted in the research was 20 mm, or loading force of 130 N, which causes pains at the sternum displacement by 10 mm [20].

The final stage of the research consisted in loading the stabilization system until one of the elements of the anastomosis is damaged – measurement IV.

The experimental research posts in stage II are presented in Fig. 5, while Fig. 6 illustrates particular stages of the implantation of the stabilizing plate into the pig chest, which was conducted by the team of doctors from the research group. The contact points between the plate and chest were in the sternum area and in the chest deformation area.

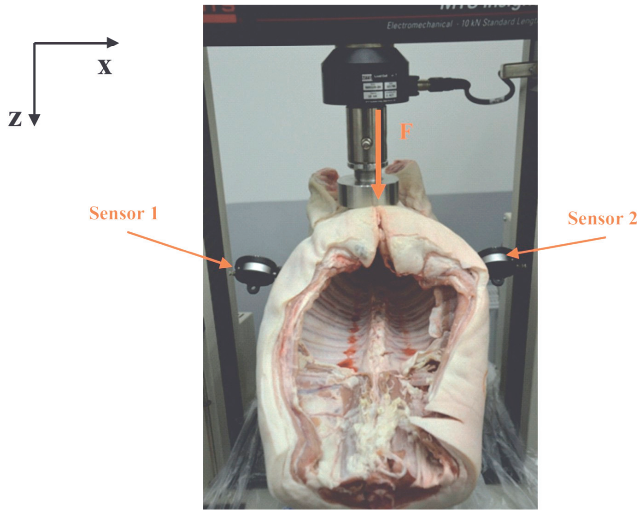


Fig. 5. Experimental research post for the plate stabilizer–pig chest system

and for displacements in selected places on the plate in the directions of "$x$" and "$z$" axes.

### 3.1. Experimental research results – stage I

For the tests conducted the values of forces $F$ were between 295 N to 303 N in displacement by 10 mm in the direction of "$z$" axis. Recorded displacements on "$x$" axis, located near the permanent support of the system, were between 0.36 mm to 0.50 mm. Displacements along "$x$" axis at the place of contact with the movable support were between 7.95 mm to 9.45 mm, and they were similar to the displacement value along the "$z$" axis, Table 1. The tests results are presented in Table 1 and in Figs. 7 and 8.

Displacement characteristics for specific analysed points of the system are presented in Figs. 6 and 7. Detailed analysis of the characteristics shows that similarity occurs between relationship of displacements and loadings applied with force $F$. Displacements at point A (Fig. 4) are related to pliable deformation of the plates resulting from the applied load. At point B (Fig. 4), a displacement in the direction of "$x$" axis occurred, propor-

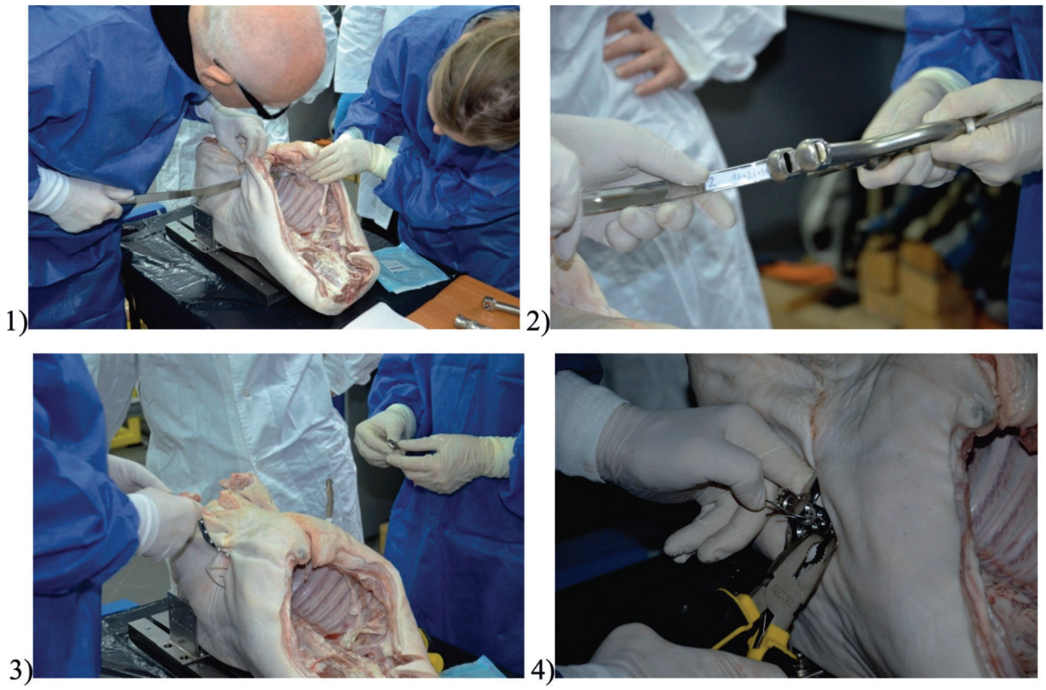


Fig. 6. Stages of the plate stabilizer implantation: (1) introducing the leading tape under the ribs, (2) final bending of the plate to fit the curvature of the chest, (3) introducing the plate under the ribs and rotating it, (4) fastening the plate with transverse plates and surgical wire

## 3. Results

In two-stage experimental tests values were determined for forces affecting the stabilizing system

Table 1. Values of forces and displacements in the direction of "*x*" axis obtained with axial displacement values "*z*": from 1 to 10 mm, every 1 mm

| No. | D – axis "*z*", mm | Force *F*, N | | Sensor 1 – direction and displacement value – axis "*x*", mm | | Sensor 2 – direction and displacement value – axis "*x*", mm | |
|---|---|---|---|---|---|---|---|
| | | M I | M II | M I | M II | M I | M II |
| 1 | 1 | 21 | 12 | 0.02 | –0.02 | 1.25 | 0.49 |
| 2 | 2 | 42 | 17 | 0.00 | –0.05 | 2.40 | 0.24 |
| 3 | 3 | 61 | 27 | –0.02 | –0.09 | 3.30 | 0.43 |
| 4 | 4 | 95 | 55 | –0.10 | –0.13 | 4.15 | 0.92 |
| 5 | 5 | 133 | 99 | –0.17 | –0.18 | 5.00 | 2.18 |
| 6 | 6 | 161 | 143 | –0.21 | –0.23 | 5.80 | 3.30 |
| 7 | 7 | 194 | 188 | –0.26 | –0.26 | 6.85 | 4.45 |
| 8 | 8 | 221 | 226 | –0.33 | –0.29 | 7.80 | 5.60 |
| 9 | 9 | 250 | 266 | –0.38 | –0.32 | 8.70 | 6.80 |
| 10 | 10 | 295 | 303 | –0.50 | –0.36 | 9.45 | 7.95 |
| D – Displacement, M – Measurement | | | | | | | |

tionate to the displacements in the direction of "*z*" axis.

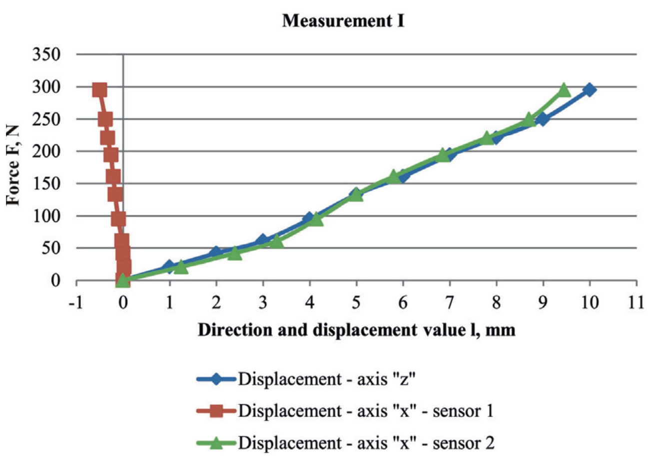


Fig. 7. Diagram of relations between displacements along "*x*" and "*z*" axes, and force *F* – a movable support was used

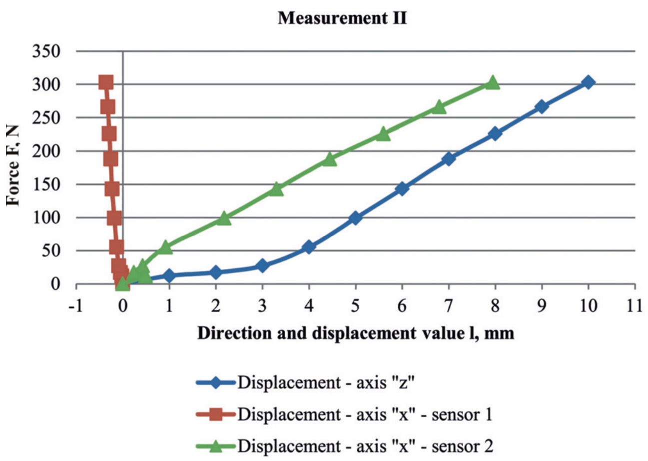


Fig. 8. Diagram of relations between displacements along "*x*" and "*z*" axes, and force *F* – a movable support was used

The differences between displacements and applied loadings, which occurred in the initial phase of loading, were related to the way the transverse plate was fastened to the measuring platform with surgical wire, and to a different curvature of the plate, adapted to individual geometrical characteristics of the patient's chest.

As a result of the research conducted no damage was reported to the elements of the implant, the whole system remained stable, and the plate did not rotate.

## 3.2. Experimental research results – stage II

In the second stage, 4 tests were conducted using pig chests with geometrical features resembling those of human chest at the age of 8–15 years. Adapted testing models were used to verify the results received in the first stage of the research. First three measurements were conducted with maximum displacement of the working part in the direction of "*z*" axis to 20 mm, measurement IV was conducted until one of the elements of the system was damaged (ribs, surgical wire, stabilizing bar or blocking screws). Results of the analysis of the three trials are presented in Table 2 and in Figs. 9–12. The results of measurement IV are shown in Fig. 13. Maximum registered values of forces with the displacement of 20 mm along "*z*" axis for the 3 measurements were comparable, and they were respectively *F* = 250 N (measurement I), *F* = 262 N (measurement II), *F* = 256 (measurement III). The corresponding displacements on the "*x*" axis read from sensor 1 were between 2.3 mm to 2.5 mm, and for sensor 2 from 0.57 mm to 3.15 mm. On the three models here there

Table 2. Values of forces and displacements in the direction of "*x*" axis obtained with axial displacement values "*z*": from 5 to 20 mm, every 5 mm

| No. | D – axis "*z*", mm | Force *F*, N | | | Sensor 1 – direction and displacement value – axis "*x*", mm | | | Sensor 2 – direction and displacement value – axis "*x*", mm | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | M I | M II | M III | M I | M II | M III | M I | M II | MIII |
| 1 | 5 | 60 | 58 | 51 | –0.25 | –0.35 | –0.4 | 0.52 | 0.43 | 0.45 |
| 2 | 10 | 136 | 122 | 110 | –0.60 | –0.90 | –1.00 | 1.12 | 0.66 | 1.17 |
| 3 | 15 | 202 | 203 | 186 | –1.35 | –1.35 | –1.50 | 1.12 | 0.65 | 2.10 |
| 4 | 20 | 250 | 262 | 256 | –2.50 | –2.40 | –2.30 | 1.12 | 0.57 | 3.15 |

D – Displacement, M – Measurement

were even displacements at the measuring points in sensors 1 and 2.

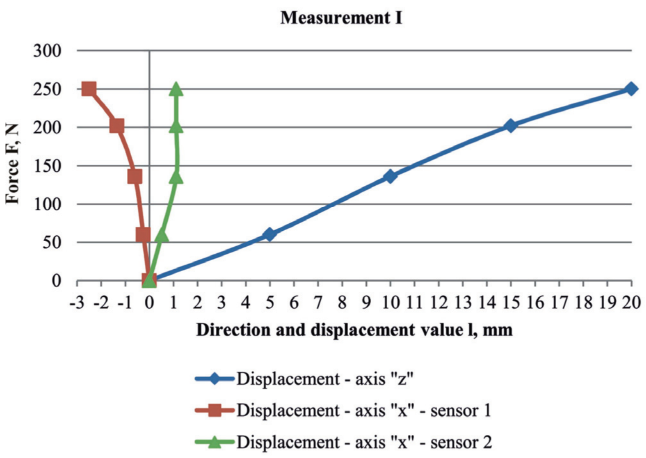


Fig. 9. Diagram of relations between the displacement values "*z*" and "*x*" and the applied force *F* – measurement I

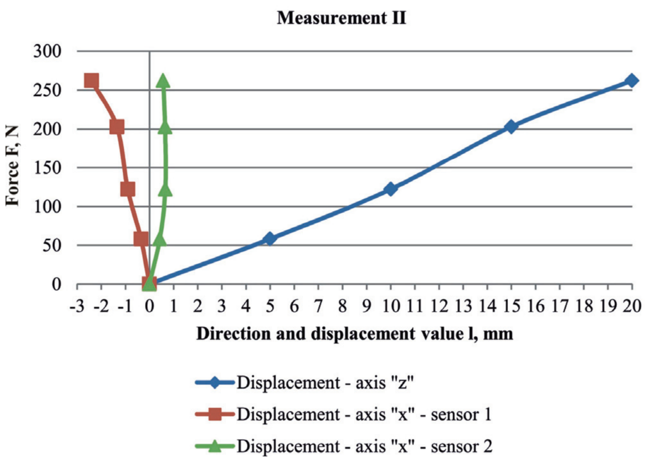


Fig. 10. Diagram of relations between the displacement values "*z*" and "*x*" and the applied force *F* – measurement II

In measurement IV the stabilizer–pig chest system was loaded until one of its elements was damaged. With displacements in the direction of "*z*" axis by the value of ca. 70 mm, one of the ribs, to which a transverse plate was attached, broke. The loading value for maximum displacement was *F* = 643 N, Fig. 12. No damage to the elements of the plate stabilizer was detected. It is a benefit that with the maximum permissible displacement on the "*z*" axis, which is 20 mm [20], there is no stabilizer rotation, so the transverse plate used is efficient in stabilizing the skid plate of the stabilizer.

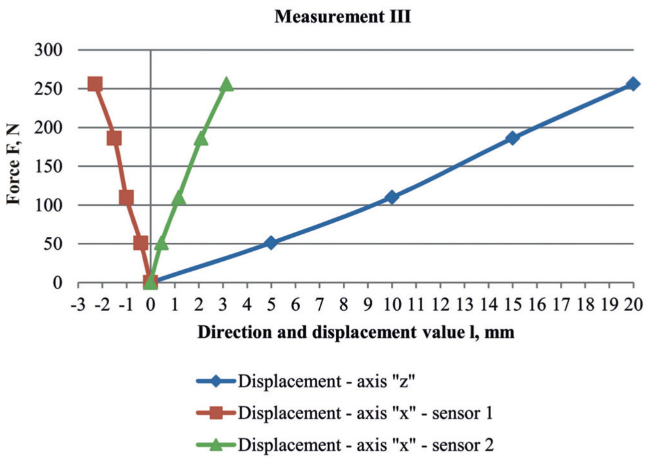


Fig. 11. Diagram of relations between the displacement values "*z*" and "*x*" and the applied force *F* – measurement III

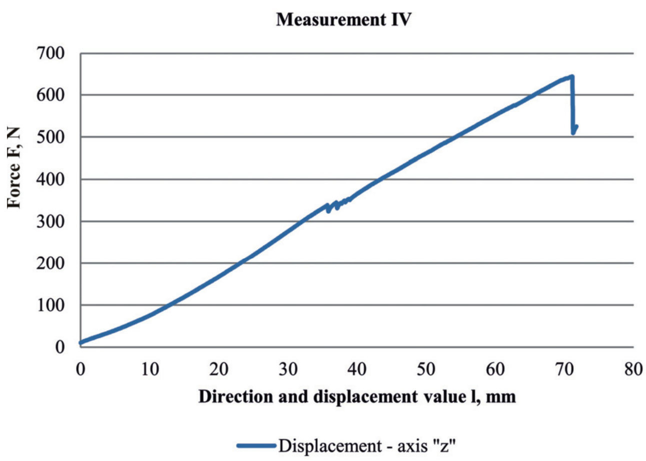


Fig. 12. Diagram of relations between the displacement values in the direction of "*z*" and "*x*" axes, and the applied force *F* – measurement IV (using maximal force causing a rib to break)

# 4. Discussion

Published data regarding the use of Nuss' minimally invasive method in the treatment of anterior surface deformity of the chest indicate its significant effectiveness which is connected with the minimal traumatization of the tissue during the implantation of the stabilizer, very positive final effect of the treatment without relapse of the defect and, compared to other methods, shorter time of hospitalization [8], [9], [22]–[26]. Nevertheless, the method is not deprived of disadvantages causing post-surgical complications. Problems connected with the use of Nuss' method can be divided into two groups. The first one is connected with the incorrect implantation technique and related to it risk of damaging organs including heart during the introduction of the implant into the body. The other group concerns the implant itself, its displacement, rotation and the organism reaction to the metallic biomaterial the implant is made of [22]–[24], [26]. The authors [25] indicate also the possibility of more frequent complications related to the displacements of the plate in elderly patients, which is connected with higher stiffness of the chest in comparison with the chest of a child at the age of 8 to 15. Research conducted by the authors [24] showed that one of the main complications connected with the implant is its displacement and rotation. In the group of patients with the deformation of the front chest treated with Nuss' method this problem occurred in 9% of the cases. In order to minimize the amount of complications transverse stabilizing plates were introduced. As a result, the complications decreased to about 2%.

However, analysis of literature regarding plate implants in surgical treatment of front chest wall deformations revealed that so far authors did not present any results of experimental research showing biomechanical characteristics of such anastomoses, and particularly biomechanical characteristics of stabilizers, as well as the possibility of side effects related to durability of stabilization, that is the risk of post-surgical complications.

The experimental research undertaken by the authors was intended to determine the biomechanical characteristics of plate stabilizers with modified structure (Figs. 13–15) useful in surgical technique for the treatment of the front chest wall deformations proposed by Nuss [8]. The modification consisted in introducing transverse plates and screws to fasten them, which prevent adverse rotation, and enable adjustment of the pressure the plate exerts on rib configuration.

The analyses revealed that maximum sternum displacement values in patients aged 8–15 years reach 10 mm without an implanted plate. Larger displacements cause pains. Such displacement value occurs with a maximum force of ca. 130 N, while in most cases the values changed from $F = 30$ to $F = 70$ N [20]. The values of axial forces, obtained in experimental research of the stabilizer–pig chest, which cause bending of the sternum by 10 mm were two times higher, and they changed within the range of $F = 110$ N to $F = 136$ N. For the sternum displacement of 20 mm they ranged from $F = 250$ N to $F = 262$ N. A rib was broken when an axial force of $F = 643$ N was applied, with the sternum displacement by 70 mm. Monitoring of the plate fastening areas revealed that the wires used did not get damaged. These findings are important for clinical practice in the special time of patients' rehabilitation.

The results of research conducted by the authors on chest rigidity in children of school age [20] show that the stabilizer–pig chest system is characterised by increased rigidity compared to a person without implant, but decreased rigidity for the research post only simulating a chest, used in the first stage of the research, Figs. 13–15. In the tests for the sternum bending by the value $z = 10$ mm for the system simulating chest movements while breathing, an axial force of $F = 295$ N to $F = 303$ N was obtained.

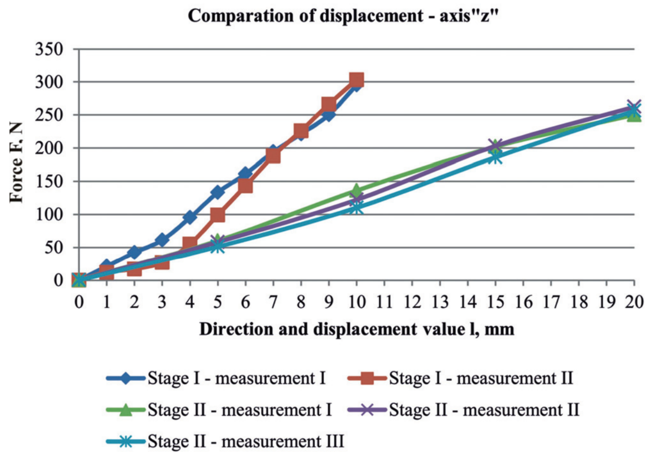


Fig. 13. Comparison of relation between recorded loading force *F* and displacement of the working part of the universal testing machine in the direction of "*z*" axis for two stages of research

The monitoring of plates and fastening elements (bars and surgical wire) after two stages of the research did not reveal any visible damage. No plate rotation was detected, neither its loosening, both during loading of the system with maximum force which does not cause pain, and with the force which causes fracture of one of the ribs to which the plate was fastened. Therefore, it could be concluded that the way of fastening with the use of transverse plates and the surgical wire of 1.2 mm in diameter ensures proper stabilization of the system. It was also found that during the loading slacks were eliminated between the bar fastened with surgical wires and the platform simulating the chest – stage I and ribs – stage II, which contributed to increased stability of the system.

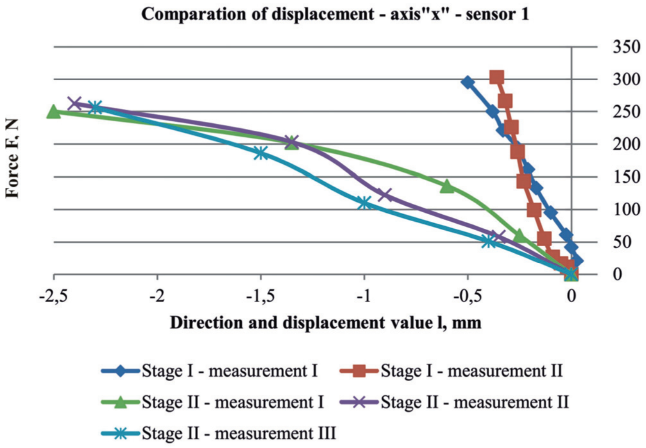


Fig. 14. Comparison of relation between recorded loading force $F$ and displacement on the "$z$" axis read by sensor 1 for two stages of research

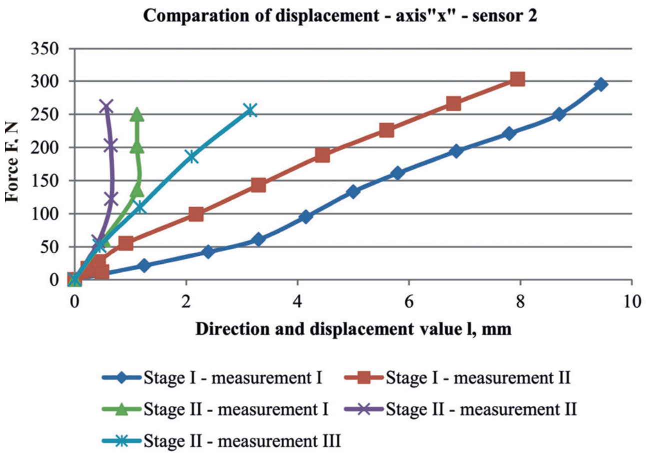


Fig. 15. Comparison of relation between recorded loading force $F$ and displacement on the "$z$" axis read by sensor 2 for two stages of research

Moreover, it is worth noting that the displacement values in the direction of "$x$" axis will change depending on the abnormality and the anthropometric characteristics of the patient, which cause unique bending of the plate in its pre-surgical modeling, adapting to the patient's chest curvature.

# 5. Summary

Summing up the biomechanical analysis of the modified structure of stabilizers for the treatment of the front chest wall, it can be stated that the biomechanical characteristics determined provide important information concerning the biomechanical stability of the anastomosis, which can be used to correct the procedure of implanting stabilizers and biomechanical indications in the rehabilitation process.

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