Evaluation of Mechanical Properties of Ribs Fusion by Three-point Bending Experiment

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Abstract: The aim of the study is to compare the effect of surgical therapy of rib fractures with conservative treatment by means of biomechanical analysis of healed fractures. The surgical therapy is based on a metallic plate fixation of the rib fractures whereas the conservative treatment is based on spontaneous bone healing leading to fibrocartilage callus formation. Adult minipigs with terminated growth were used as the animal model and 6 fixed and 9 unfixed ribs were analyzed by means of the maximum bending moment, bending strength (maximum bending stress), and external bending stiffness of intact and broken (fixed and unfixed) ribs. Other evaluated parameters are maximum force, bending stiffness, maximum deflection, and energy. The experiment showed higher values of maximum bending moment and external bending stiffness (structural parameters) for unfixed ribs compared to fixed ribs. Conversely, the strength (material parameter) of unfixed ribs reached lower values than that of fixed ones.

Keywords: mechanical properties; ribs; three-point bending; experiment.

1 Introduction

Although many experts adhere to conservative treatments, there are several modern fixation devices for the treatment of the rib segment. This work deals with the influence of fixation with a metal plate on the healing of rib fractures. The prerequisite is an improvement in the stability of the chest wall, breathing, and a shorter recovery time [1, 2].

During the three-point bending experiment, many parameters can be measured that reflect the mechanical behavior of various technical and biological materials. In any case, it is important to realize what each parameter represents. Our task was to evaluate the structural and material parameters of the fusion of broken ribs. The structural parameters reflect the force transmitted by this fusion, and the material properties describe the quality of the evaluated material [3, 4].

2 Methods and materials

The study was approved by the Animal Welfare Advisory Committee of the Ministry of Education, Youth and Sports of the Czech Republic (approval ID MSMT_31280_2018_2). An animal model of an adult minipig (>9 months, >50 kg) with terminated skeletal growth was used in the project. Each minipig underwent total right-side osteotomy of 6 ribs under general anesthesia. 3 minipigs received surgical therapy (fractures fixation by metallic plate) and 3 minipigs remained without fixation. The experiment was terminated after 8 weeks and the ribs were extracted for biomechanical, micro-CT, and histological analysis. The time of termination was selected on previous experiments when the ribs were analyzed after 3 weeks and the fragments were connected by the callus composed of fibrous tissue, cartilage with minor of mineralized bone tissue, i.e. the healing process was not in its later stages when the majority of callus is composed of mineralized bone tissue. Furthermore, the physiological process of fracture healing takes several weeks and 8 weeks of healing represents the time period when the most of callus is composed of mineralized bone tissue, but still not healed completely [5]. For biomechanical analysis 6 fixed, 9 unfixed, and 39 intact ribs were applied. The main goal was to compare the mechanical parameters of fixed and unfixed ribs relative to intact ribs.

The samples were loaded on a special fixture for three-point bending at a constant feed of 5 mm/min. All samples were tested without metallic plates. Force, displacement, and time data were recorded during the experiment with a sampling frequency 40 Hz. The data recorded from the test were processed into graphical force-deflection dependences (see Fig. 1). The evaluated parameters were maximum force, strength, external bending stiffness, maximum bending moment, bending stiffness, maximum deflection (corresponding to maximum force), and energy. Using these parameters, we try to evaluate the structural and material properties of healed bone [4, 6].

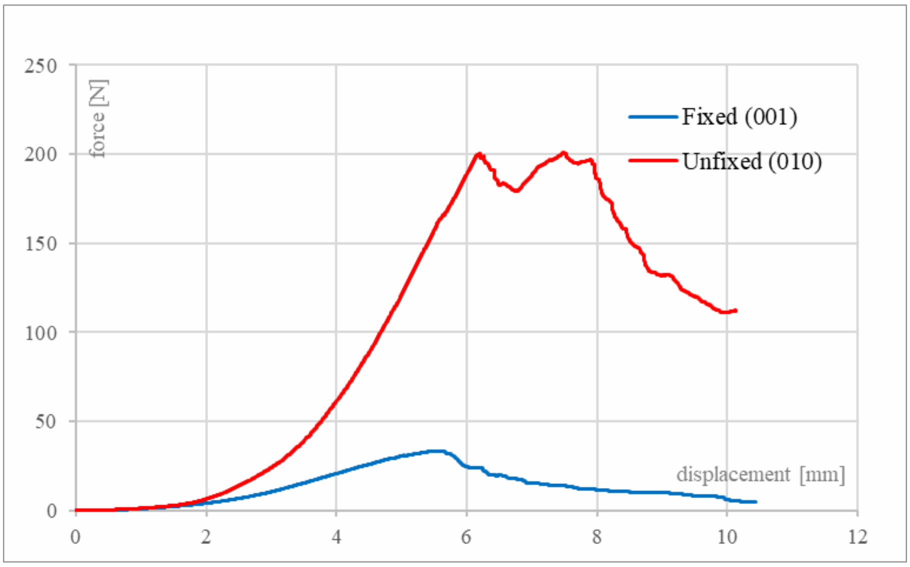
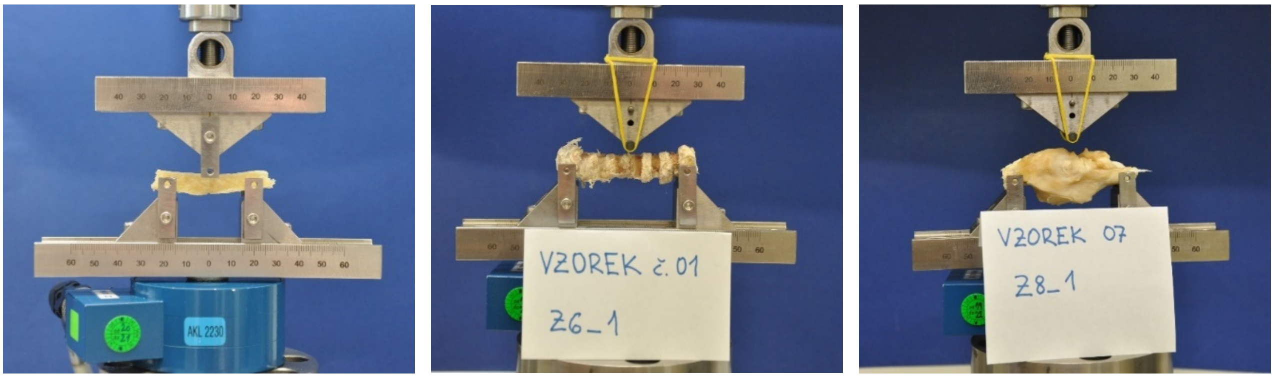


Fig. 1: Graphical force-deflection dependence of fixed and unfixed ribs.

A fibrocartilage callus is formed around the fracture of the unfixed ribs (see Fig. 2), its large size distorts the evaluated parameters, which depend on the cross-section. For these evaluated parameters to be comparable, it is necessary to compare similarly large ribs. The broken ribs (fixed and unfixed) were divided according to the size of the bending cross-section modulus into the intervals of intact ribs [3].

For further evaluation, 3 parameters were selected, 2 structural parameters – maximum bending moment, external bending stiffness, and 1 material parameter – strength. To enable the comparison of fixed and unfixed ribs, these parameters were related to the arithmetic averages of intact ribs of the same size for each parameter.

The division into groups was performed using Scott's rule, verification of normality using Q-Q plots, statistical evaluation using the Mann-Whitney nonparametric test, and effect size using the Cohen's delta.



(a) intact rib (b) rib after fixation (c) rib without fixation

Fig. 2: The loading of the ribs (intact, fixed, and unfixed) on a special fixture for three-point bending and force sensor (MTS Mini Bionix 858.02).

3 Results

It is evident (Tab. 1, Fig. 3) that the structural parameters of unfixed ribs are higher than those of fixed ribs. The fixed ribs reached only less than 10 % of the maximum bending moment of the intact ribs, however, the unfixed ribs reached more than 68% of the original bending moment of the intact ribs. The external bending stiffness of the fixed ribs increased by only over 3 %, while that of the unfixed ribs reached almost 10 %. The trend is opposite for the material parameter, the strength of fixed ribs reached more than 8 % of the strength of intact ribs, which is more than that of unfixed ribs, whose strength reached only about 4 % of the original (of the intact ribs) strength.

Tab. 1: Evaluated parameters of fixed and unfixed ribs related to intact ribs.

	STRUCTURAL PARAMETERS		MATERIAL PARAMETER
	Maximum bending moment $M_{o\_\max}$ [%]	External bending stiffness S [%]	Strength $\sigma_{\max}$ [%]
Fixed ribs	9.95	3.37	8.20
Unfixed ribs	68.33	9.43	4.16

In the statistical comparison of the maximum bending moment and the external bending stiffness for fixed and unfixed ribs, there was a statistically significant increase (according to the Mann-Whitney test) for unfixed ribs compared to fixed ribs. The external bending stiffness increased by 180 % and the maximum bending moment even by 587 %, and the effect size reached (according to Cohen's delta) a very high significance. The opposite trend was observed for the strength when it was 49 % lower for unfixed ribs compared to fixed. However, this fact is not statistically proven due to the high data variance. A summary of the statistical evaluation is given in the table below (Tab. 2).

Tab. 2: Summary of statistical comparison of fixed and unfixed ribs.

	STATISTICALLY SIGNIFICANCE				EFFECT SIZE		
Relative parameters	Test	p-value	Significance	Test force	The ratio of arithmetic means	Cohen's delta	
Maximum bending moment	M-W	0.0018	proven	99.8 %	+ 587 %	2.88	Very high level
External bending stiffness		0.0056	proven	95.4 %	+ 180 %	2.14	Very high level
Strength		0.2629	not proven	19.4 %	– 49 %	0.57	Medium level

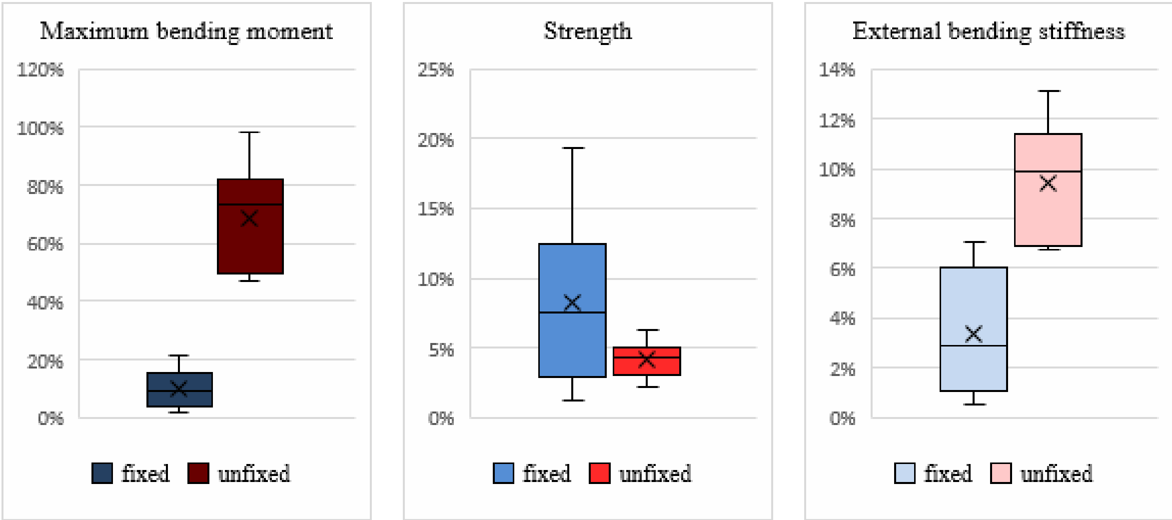


Fig. 3: Boxplots of evaluated relative parameters.

4 Conclusion

A three-point bending experiment was performed on a total of 54 rib samples, of which 6 were fixed and 9 were unfixed. The values of fixed and unfixed ribs were related to the values of intact ribs of the same size for parameters of maximum bending moment, external bending stiffness (structural parameters), and strength (material parameter). The obtained data show that the unfixed ribs reached the values of intact ribs better compared to fixed ribs in the structural parameters supported by statistical significance and high effect size. Conversely, the fixed ribs reached the values of intact ribs better compared to unfixed ribs in the material parameter, however without statistical significance and the effect size of medium level.

The biggest problem is the formation of a fibrocartilage callus around the unfixed rib, causing an uneven fracture and obstructing breathing. Further research will address the evaluation of these mechanical parameters depending on tissue healing using micro-CT and histology.

Acknowledgement

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