Biomechanical Properties of the Bone During Implant Placement

Adam Laszlo Nagy (d.nagyadam@gmail.com)
Szegedi Tudomanyegyetem https://orcid.org/0000-0002-8468-1717

Nándor Tamás Práger
Szegedi Tudomanyegyetem

Zsolt Tóth
Szegedi Tudomanyegyetem

Tamás Tarjányi
Szegedi Tudomanyegyetem

Zoltán Lajos Baráth
Szegedi Tudomanyegyetem

Research article

Keywords: Biomechanics, Dental Implant(s), Fixed and removable prosthodontics, Implant Dentistry/Implantology, Jaw Biomechanics, Oral and Maxillofacial Surgery

Posted Date: September 30th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-72153/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Version of Record: A version of this preprint was published on February 25th, 2021. See the published version at https://doi.org/10.1186/s12903-021-01442-1.
Abstract

Introduction: In our research we examined the biomechanical properties of a bone model. Porcine ribs are used as experimental model. Our objective is to investigate and compare the biomechanical properties of the bone model before and after implant placement.

Methods: The bone samples were divided in three groups, Group 1 where ALL-ON-FOUR protocol was used during pre-drilling and placing the implants, Group 2 where ALL-ON-FOUR protocol was used during pre-drilling, and implants were not placed, and Group 3 consisting of intact bones served as a control group. Static and dynamic loading was applied for examining the model samples. Kruskal-Wallis statistical test and as post-hoc test Mann-Whitney U test was performed to analyze experimental results.

Results: According to the results of the static loading, there was no significant difference between the implanted and original ribs, however, the toughness values of the bones decreased largely on account of predrilling the bones. The analysis of dynamic fatigue measurements by Kruskal-Wallis test showed significant differences between the intact and predrilled bones.

Conclusions: The pre-drilled bone was much weaker in both static and dynamic tests than the natural or implanted specimens. According to the results of the dynamic tests and after a certain loading cycle the implanted samples behaved the same way as the control samples, which suggests that implantation have stabilized the skeletal bone structure, and if even one implant is lost at the implant site during All-On-Four protocol the stabilizing effect of the implants cannot be expected.

Introductions

With the development of dentistry, the aesthetic and functional expectations of patients are also increasing. They anticipate fixed dentures even in total edentulous state. These expectations are challenging for the dentist, especially in cases with severe atrophy of the alveolar ridge, which is particularly complicated, when the teeth have been extracted long time ago. The possible treatment options which allow us to deliver fixed implant-supported dental prosthesis and to achieve a high degree of patient satisfaction, requires to utilize the remaining bone in the most efficient way possible in view of the severity of the involution. The implant placement is usually impossible without guided regeneration surgery (1) in case of elderly people, who typically have D1 quality bone with high degree of cortical bone volume (2). The guided bone regeneration procedure (3) carries high risk of patient morbidity and complications. To avoid the extensive bone augmentation procedure (4,5) due to the advanced involution, the ALL-ON-FOUR protocol was introduced by Maló (5,6). According to this concept, the fixed and immediately loaded prosthesis is supported by four implants in the anterior part of the complete edentulous jaw. The two posterior implants are placed in the interforaminal region, angled, to minimize the cantilever length; the two anterior placed axially, parallel to each other (7). Both finite analysis and retrospective studies (5) suggest that implants placed this way could be a good alternative, which can
safely support the fixed dentures. No clinically significant differences in success rates were found between these methods (8).

An idea presents itself that, the mechanical properties of the mandible could be affected by the procedure of pre-drilling and then, substituting the space with a different material characteristics. We were looking into the possibility of this process being able to weaken the jawbone against masticatory forces and if, it can affect its biomechanical properties, considering the possibility of three-dimensional torsion deformation of the mandible (9,10). We have been also investigating whether it represents a risk of pathological fractures for the patient, considering the fact, that the implants placed with ALL-ON-FOUR protocol are being immediately loaded with the provisional or definitive full-arch prosthesis in 48 hours after surgery (5,11). We considered the possibility if these micromovements can be recognized as harmful deleterious during osseointegration (12), however according to the experimental models of several authors, these micromovements were not proven to be harmful (13).

The basic hypothesis is that the implant placement weakens the biomechanical properties of the bone structure. Our objective is to investigate and compare the mechanical properties of the ribs, before and after implant placement.

**Materials And Methods**

Fresh, non-frozen, young domestic porcine ribs with soft parts (periosteum, attached muscles, fascia, fat) were obtained from an abattoir. The excess soft parts were removed with a sharp scalpel, however care was taken to ensure that the periosteum was left intact. The main reason for the selection of porcine ribs was the excellent homogeneity and thickness of cortical bone (14) which is similar to a human mandible (15). The animals were not sacrificed for the purpose of the experiment. The dimensions of the ribs (length, width, height) were measured with an analog caliper (Sigma-Aldrich Z136115). The porcine ribs were randomly divided into three groups. In the first group (Group 1, n=17) the implants were placed according to the ALL-ON-FOUR protocol: two implants were placed parallel medially (ICX TEMPLANT 4.1 mm x 10 mm, W & H Implantmed Classic SI-923), and two tilted implants were inserted laterally (ICX TEMPLANT 4.1 mm x 15 mm). In the second group (Group 2, n=16) the nests of the implants were pre-drilled (W & H Implantmed Classic SI-923) for the same type and size of implant, but left empty without implant placement. During pre-drilling and placing the implants, the manufacturer’s recommendations and the rules of the profession were kept in mind. No intervention was taken on the ribs in the control group (Group 3 n=18).

For the mechanical testing, each group was randomly divided into two parts. Half of the samples were tested with a static tensile - compression materials testing machine /Tinnius Olsen H5KT Atec, USA/, while the other half were placed under fatigue test by an *All-Electric* Dynamic Test Instrument (Instron ElectroPuls™ E3000, USA) (16).
Components were manufactured individually for the equipment, that were able to perform the three-point bending tests that were most widely accepted for fracture testing (17–20).

During the static load measurements, the bending deformation was increasing steadily on the bones. The according force was measured, digitized. The equipment recorded the position of the crosshead and the measured force. The maximum deformation was 10 mm, which was reached in 5 seconds. During the measurement an automatic halt was actuated, when the device observed a sudden decrease in the force.

The other part of the samples was examined by dynamic fatigue test. The dynamic test followed the arrangement of three point bending fatigue measurements. (21,22). Prior the dynamic tests, the stiffness of each ribs was determined by measuring the force-deflection curve between 0.2 and 0.8 mm deflection. After this process the fatigue test was performed on the samples, where the initial deflection was set to 2 mm, which was reached in 5 sec. The fatigue test was performed in deflection control mode. The fatigue signal was a sinus function with 20 Hz frequency at 0.5 mm deflection amplitude over 10,000 cycle. At the end of the fatigue process the load was decreased to 0 N in 5 sec.

The measured force values were subjected to Kruskal-Wallis non-parametric test and as post-hoc test Mann-Whitney non-parametric statistical tests were used. The significance level in these tests were set to 5% (p<0.05). SPSS statistical software (version: 25; IBM Co., Armonk, NY, USA) was used for the statistical analysis.

Results

Results of the static load test:

The graph in Fig.2 shows the measurement results of the static load tests: the first stage of the load-deflection curve can be described as an almost straight increasing line, which represents the flexible range of the rib. After the maximum force exerted, even a smaller force was sufficient for further deflection.

Mean maximum force (and standard error) was 298.9±30.95 N in the control, 287.1±25.93 in the pre-drilled and 280.29±27.51 N in the implanted group. No significant differences were found in the data (p =0.979, Kruskal-Wallis test).

The area under the curves on the 1st diagram (S) describes a quantity, which correlates with the toughness of the ribs, and can be calculated with the following formula:

$$ S = \int_{0}^{1} F(x) \cdot dx $$

Figure 4 shows the S values in Nmm registered during the test.
Mean S value was 1701.37±166.335 Nmm in the control, 1175.77±128.832 Nmm in the pre-drilled and 1235.56±248.392 Nmm in the implanted group. There is no significant differences between the groups in the calculated S toughness related values (p=0.16, Kruskal-Wallis test).

Results of the dynamic fatigue test:

To analyze the results of the dynamic fatigue tests the Kruskal-Wallis statistic test (control vs. 1, 2) was performed on the measured force values measured for maximum deflection (2.5mm) at specified times (100th, 2000th, 9000th cycles). The results are shown in Fig. 5.

At the 100th cycle the average measured force values were: 0.5766±0.033 kN in the control, 0.4030±0.081 kN, in the pre-drilled, 0.4991±0.073 kN in the implanted group. The statistic test showed significant difference for the measured values between the groups (p=0.014, Kruskal-Wallis test).

At the 2000th cycle the average measured force values were: 0.3896±0.027 kN in the control, 0.2800±0.056 kN, in the pre-drilled, 0.3530±0.049 kN in the implanted group. The statistic test showed a significant difference for the measured values between the groups (p=0.015, Kruskal-Wallis test).

At the 9000th cycle the average values were: 0.2999±0.015 kN in the control, 0.2227±0.042 kN, in the pre-drilled, 0.2840±0.042 kN in the implanted group. The statistic test showed a significant difference for the measured values between the groups (p=0.026, Kruskal-Wallis test).

The difference between the groups was tested with Mann-Whitney test. This showed a significant difference in the measured force values between the control and drilled ribs 100th cycle (p = 0.001, Mann-Whitney U test), which difference remains consistent at the 2000th cycle (p = 0.002, Mann-Whitney U test) and 9000th cycle (p = 0.005, Mann-Whitney U test).

The difference between the control and the implanted ribs in terms of mechanical properties (that is related to the measured force values) is not significantly different in any of the cycles examined (100th cycle p = 0.243, 2000th cycle p = 0.447, 9000th cycle p = 0.72, Mann-Whitney U test), furthermore the summary graph, figure 5, shows that they exhibit very similar mechanical properties from cycle 9000.

No significant difference was found between the drilled and implanted ribs in the post-hoc test at 100th cycle (p = 0.33, Mann-Whitney U test) 2000th cycles (p = 0.136, Mann-Whitney U test), at 9000th cycles (p = 0.094, Mann-Whitney U test).

Discussion

The purpose of this study was to examine and discuss the deterioration of bone mechanical properties as a function of bending forces before and after implant placement in order to seek answer to the question, whether implant placement can weaken the bone structure.
Static load tests showed significant differences between the groups tested. In the case of intact bone samples, the load curves shown in Figure 2 are continuous, and the sudden reduction in force associated with fractures is observed only over a large deformation of ~ 6.6 mm. The maximum force observed for the intact bones is in the range of 200-800 N with an average maximum force of 299 ± 31 N. Typically, the maximum force values were achieved with 1.5 to 3 mm deflection.

For the drilled samples, the resistance force maximal decreased (170-390N), relative to the control samples, which is well observed in Figure 2. Most measurements show single or gradual fractures in the 2.4-5mm deflection range, well below the damage limit of the intact bones. The maximum force observed was 287 ± 26 N.

The reduction of the damage limit clearly shows the weakening of the mechanical properties of the bone, which is partly due to the lack of material and partly due to the decrease in the effective bone thickness in the drilled region.

According to our static load tests, filling the pre-drilled nest with implants did not improve the mechanical resistance of the bones.

For the implanted samples the maximum force measured was in the range 175-380 N, the mean maximum force decreased to 280 ± 28 N. The deflection values corresponding to the first partial fracture are in the range of 1.6-4.5 mm, which is smaller compared to the intact and drilled bone values. Partial cracks were observed between the two middle implants during the load. The appearance of a crack was often accompanied by a sound effect.

The earlier cracks appear to be due to the fact that the holes are filled with harder material than the spongy bone, consequently local stresses at the implant-bone interface are exerted during loading.

If the local stress value is greater than the strength of the cortical bone, a crack appears (23), but the macroscopic fracture of the bone does not occur (24). As the deflection increases, the force-deflection curve shows small breaks, indicating the appearance of new cracks. The local fractures provide stress relaxation, resulting in a higher deflection values for appearance of macroscopic fracture at 7,3-9,5 mm compared to the drilled bone. Due to this phenomenon, the toughness of the implanted specimens will be higher than that of the drilled specimens. For fatigue tests, constant force was applied throughout the experiments. To achieve the same deformation, a lower force at a higher cycle number was required for each sample, as shown in Figure 5.

For fatigue tests, the same temporal function of deflection was applied throughout the experiments. To achieve the same deflection at a higher cycle number, a lower force was required for each sample, as shown in Figure 5. Initially, the decrease in the force values is greater, and with higher cycle numbers, the reduction of the force slows down. This phenomenon shows the weakening of the mechanical structure due to bending cycles. Each cycle causes micro-cracks in the bone, which reduces bone stiffness (25). However, macroscopic fractures did not occur at the set deflection values and cycle numbers.
For all fatigue tests, the force required for a pre-set deflection was the highest for intact bone and the lowest for drilled bone. This significant weakening is due to the reduction of local bone volume.

In the case of implanted bones, the maximum force values for a given deflection are between the values of the intact and the drilled bone. Initially, the difference compared to intact bone is greater, but with a higher number of cycles this difference disappears.

Local stresses at the implant bone interface result in earlier appearance of micro-cracks, similar to those observed with static measurements. When stress is relaxed by the appearance of microcracks, the mechanical properties of the implanted bone will become closer to the intact bone. This is due to the fact that the effective bone thickness has been restored with the implant, which takes a part of the load in the bone.

Overall, the results of our mechanical examinations showed that the placement of the holes in the bone significantly reduces the stiffness and mechanical strength and stiffness of the bone, which leads to the appearance of macroscopic fractures even at smaller deformations. The implants partially restore the integrity of the bone and increase the load-bearing capacity against the macroscopic fracture compared to the drilled samples. However, the implanted bone does not reach the mechanical parameters of intact bone.

**Conclusion**

This topic was explored by finite element analysis, and many studies have been conducted on the relationship between the bone and implants under the All-on-four protocol.

According to Sannino, distal implants placed at 15, 30, and 45 degrees, with a greater angle at the implant-bone interface, exert the greatest stress, but this mechanical stress value is still lower than what the implant and bone can withstand (26).

The three-point bending tests which we performed has previously been only conducted, in the literature, with intact bones and not pre-drilled and implanted ones (20,27,28).

It is important to note that these measurements were performed on non-osseointegrated samples. In the event when osseointegration occurs, mechanical properties are expected to improve further. However, our experiment shows that local mechanical stresses appear at the bone-implant interface, which reduces the force required to cause fractures. A limitation of our study is that the bending forces applied in the tests occur only in extreme cases in clinical circumstances. However, the cyclicity and the magnitudes were in accordance with physiologically observable chewing movements. A further limitation of our research is that, the protocol developed and applied by us does not allow the implant-bone interface to be investigated in a direct way, unlike as we have seen with the finite element analysis tests.

The results of our experimental model testing concluded that during dynamic fatigue testing of natural and implanted ribs, compared with the highlighted cycles of 100, 2000 and 9000, the p-value determined
by the Mann-Whitney Post-Hoc test increased continuously (samples from the two different groups starting to show similar properties). After the 9000 fatigue cycle, the implanted samples exhibited almost the same mechanical properties as the control samples, which suggests that implantation have stabilized the skeletal bone structure.

In the light of our results, it can be stated that the pre-drilled bone was much weaker in both static and dynamic tests than the natural or implanted specimens. In everyday dental practice, it can be concluded that, if a patient loses even one of the four implants (peri-implantitis or connective tissue encapsulation following insufficient osseointegration) placed during the All-On-Four protocol, the stabilizing effect of the implants cannot be expected. If the jaw structure is weakened this way, it is less resistant to the loads of the physiological mastication movements and other hazards, such as traumatic injuries.

Declarations

1. Ethics approval and consent to participate

Not applicable

2. Consent for publication

Not applicable

3. Availability of data and materials

Not applicable

4. Competing interests

The authors declare that they have no competing interests

5. Funding - No funding

6. Authors' contributions

Author 1: Contributed to conception, acquisition, and interpretation, drafted the manuscript, gave final approval. agrees to be accountable for all aspects of work ensuring integrity and accuracy

Author 2: Contributed to conception, drafted the manuscript, critically revised the manuscript, gave final approval. agrees to be accountable for all aspects of work ensuring integrity and accuracy

Author 3: Contributed to conception, drafted the manuscript, critically revised the manuscript, gave final approval. agrees to be accountable for all aspects of work ensuring integrity and accuracy

Author 4: Contributed to analysis, critically revised the manuscript, gave final approval. agrees to be accountable for all aspects of work ensuring integrity and accuracy
Author 5: Contributed to conception, interpretation, drafted the manuscript, critically revised the manuscript, gave final approval. agrees to be accountable for all aspects of work ensuring integrity and accuracy

7. Acknowledgements

All authors gave their final approval and agree to be accountable for all aspects of the work. All authors read and approved the final manuscript.

The authors declare that they have no competing interests

References

1. Clavero J, Lundgren S. Ramus or chin grafts for maxillary sinus inlay and local onlay augmentation: comparison of donor site morbidity and complications. Clin Implant Dent Relat Res. 2003;5(3):154–60.
2. Trisi P, Rao W. Bone classification: clinical-histomorphometric comparison. Clin Oral Implants Res. 1999 Feb;10(1):1–7.
3. Kuchler U, von Arx T. Horizontal Ridge Augmentation in Conjunction with or Prior to Implant Placement in the Anterior Maxilla: A Systematic Review. Int J Oral Maxillofac Implants. 2014 Mar;29 Suppl:14–24.
4. Urban IA, Monje A. Guided Bone Regeneration in Alveolar Bone Reconstruction. Oral Maxillofac Surg Clin North Am. 2019 May;31(2):331–8.
5. Malo P, Rangert B, Nobre M. “All-on-Four” immediate-function concept with Branemark System implants for completely edentulous mandibles: a retrospective clinical study. Clin Implant Dent Relat Res. 2003;5 Suppl 1:2–9.
6. Rasouli R, Barhoum A, Uludag H. A review of nanostructured surfaces and materials for dental implants: surface coating, patterning and functionalization for improved performance. Biomater Sci. 2018 May;6(6):1312–38.
7. Bevilacqua M, Tealdo T, Pera F, Menini M, Mossolov A, Drago C, et al. Three-dimensional finite element analysis of load transmission using different implant inclinations and cantilever lengths. Int J Prosthodont. 2008;21(6):539–42.
8. Malo P, de Araujo Nobre M, Rangert B. Short implants placed one-stage in maxillae and mandibles: a retrospective clinical study with 1 to 9 years of follow-up. Clin Implant Dent Relat Res. 2007 Mar;9(1):15–21.
9. Daegling DJ, Hylander WL. Biomechanics of torsion in the human mandible. Am J Phys Anthropol. 1998 Jan;105(1):73–87.
10. Seong W-J, Kim U-K, Swift JQ, Heo Y-C, Hodges JS, Ko C-C. Elastic properties and apparent density of human edentulous maxilla and mandible. Int J Oral Maxillofac Surg [Internet]. 2009;38(10):1088–93. Available from: http://europepmc.org/articles/PMC2743800
11. Maló P, de Araujo Nobre M, Lopes I. A new approach to rehabilitate the severely atrophic maxilla using extramaxillary anchored implants in immediate function: A pilot study. J Prosthet Dent [Internet]. 2008 Nov;100(5):354–66. Available from: https://doi.org/10.1016/S0022-3913(08)60237-1

12. Sugiura T, Yamamoto K, Horita S, Murakami K, Tsutsumi S, Kirita T. Effects of implant tilting and the loading direction on the displacement and micromotion of immediately loaded implants: an in vitro experiment and finite element analysis. J Periodontal Implant Sci. 2017 Aug;47(4):251–62.

13. Kourtis LC, Carter DR, Beaupre GS. Improving the estimate of the effective elastic modulus derived from three-point bending tests of long bones. Ann Biomed Eng [Internet]. 2014;42(8):1773–80. Available from: https://doi.org/10.1007/s10439-014-1027-3

14. Friberg B, Sennerby L, Roos J, Johansson P, Strid CG, Lekholm U. Evaluation of bone density using cutting resistance measurements and microradiography: an in vitro study in pig ribs. Clin Oral Implants Res. 1995 Sep;6(3):164–71.

15. Lee S-W, Kim S-G. Membranes for the Guided Bone Regeneration. Maxillofac Plast Reconstr Surg [Internet]. 2014/11/12. 2014 Nov;36(6):239–46. Available from: https://www.ncbi.nlm.nih.gov/pubmed/27489841

16. Horita S, Sugiura T, Yamamoto K, Murakami K, Imai Y, Kirita T. Biomechanical analysis of immediately loaded implants according to the “All-on-Four” concept. J Prosthodont Res [Internet]. 2017 Apr;61(2):123–32. Available from: https://www.sciencedirect.com/science/article/pii/S1883195816300706

17. Jiang F, Rohatgi A, Vecchio KS, Cheney JL. Analysis of the dynamic responses for a pre-cracked three-point bend specimen. Int J Fract. 2004;127(1):147–65.

18. Leppanen O, Sievanen H, Jokihaara J, Pajamaki I, Jarvinen TLN. Three-point bending of rat femur in the mediolateral direction: introduction and validation of a novel biomechanical testing protocol. J Bone Miner Res. 2006 Aug;21(8):1231–7.

19. Ayagara AR, Langlet A, Hambli R. On dynamic behavior of bone: Experimental and numerical study of porcine ribs subjected to impact loads in dynamic three-point bending tests. J Mech Behav Biomed Mater [Internet]. 2019;98:336–47. Available from: https://doi.org/10.1016/j.jmbbm.2019.05.031

20. Sadeghi H, Espino DM, Shepherd DET. Fatigue strength of bovine articular cartilage-on-bone under three-point bending: the effect of loading frequency. BMC Musculoskelet Disord [Internet]. 2017 Apr;18(1):142. Available from: https://www.ncbi.nlm.nih.gov/pubmed/28376781

21. Mori S, Burr DB. Increased intracortical remodeling following fatigue damage. Bone. 1993;14(2):103–9.

22. Zioupos P, Hansen U, Currey JD. Microcracking damage and the fracture process in relation to strain rate in human cortical bone tensile failure. J Biomech. 2008 Oct;41(14):2932–9.
24. Vashishth D, Tanner KE, Bonfield W. Experimental validation of a microcracking-based toughening mechanism for cortical bone. J Biomech [Internet]. 2003;36(1):121–4. Available from: https://doi.org/10.1016/s0021-9290(02)00319-6

25. Keaveny TM, Wachtel EF, Kopperdahl DL. Mechanical behavior of human trabecular bone after overloading. J Orthop Res. 1999 May;17(3):346–53.

26. Sannino G. All-on-4 concept: a 3-dimensional finite element analysis. J Oral Implantol. 2015 Apr;41(2):163–71.

27. Jamsa T, Jalovaara P, Peng Z, Vaananen HK, Tuukkanen J. Comparison of three-point bending test and peripheral quantitative computed tomography analysis in the evaluation of the strength of mouse femur and tibia. Bone. 1998 Aug;23(2):155–61.

28. Turkozan NY, Mammadov C. Biomechanical properties of the body and angle of the sheep mandible under bending loads. Dent Traumatol [Internet]. 2011 Jun;27(3):179–83. Available from: https://doi.org/10.1111/j.1600-9657.2011.00977.x

Figures

![Figure 1](image-url)
Experimental layout. A: supporting platform with point support rollers; B: pork rib segment; C: pressure head of the mechanical tear / break device with the roller used for point loading. D: distance between support points (standard 40 mm). E: vector of the force acting on the bone segment.

Figure 2

Measurement results of the static load tests. A: Static load diagram of the control group. B: Static load diagram of the pre-drilled ribs. C: Static load diagram of the implanted ribs

Figure 3

Blue: control, Orange: Pre-drilled, Yellow: implanted
The occurrence of the maximum static load force values: Blue: control, Orange: Pre-drilled, Yellow: implanted

**Figure 4**

Occurrence of various toughness ranges in the study groups. Blue: control, Orange: Pre-drilled, Yellow: implanted
Figure 5

The force values measured for maximum deformation (2.5mm) depending on the number of cycles Blue: control, Orange: Pre-drilled, Yellow: implanted