STRENGTH TESTS OF FROZEN COMPACTED BONE GRAFTS IN THE MODEL OF HIP JOINT ACETABULUM

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Abstract: In the paper the experimental results of mechanical tests of the bed made of compacted frozen bone grafts are presented as the function of weight load applied. The tests were performed on grafts impacted by orthopaedist, reproducing the procedure of revision prosthetic arthroplasty in a spherical model of hip joint acetabulum made of epoxide resin. The extent of strains produced was determined depending on the value of the applied force of static character within 0.3kN to 3.0 kN value range. The tests were carried out on a stand equipped with an Instron 8501 Plus strength-testing machine. By means of computed tomography the densities of bone grafts were determined in the impacted layer of grafts after completion of the cycle of strength tests.

Introduction

The filling of bone bed defects by impaction of bone grafts is the basis of the activities performed during revision hip acetabulum prosthetic arthroplasty. Appropriately modelled spherical bed of bone grafts is the bed for cementing of artificial acetabulum. The quality of bone graft bed impacting is of decisive importance for the primary stability of the reconstructed biomechanical system that includes artificial acetabulum/cement/bone grafts/patient's bone. Preliminary impacting of the grafts is decisive of stable fixation of acetabulum prosthesis on them and of the possibility of weight loading of the joint within a definite range of force values.

Bone graft impacting is performed in three stages, which are not precisely defined in available literature. Initially, the grafts are forced into cavernous defects or formed in segmental defects. Forcing in of the grafts into defects is connected with the second stage that is compacting, or increasing of their density. Only the last stage, that is impacting, makes possible to obtain the expected stiffness and hardness of the grafts. In the initial period, setting of the grafts takes place that reproduce the spherical surface of bone bed, while the final stage includes their impacting. Applying a force to the graft layer decreases its height and volume increasing thereby graft density.

The aim of the studies carried out was to determine the factors affecting acetabulum stabilisation in the cement bed and frozen bone grafts and to find which of them are of decisive importance for the change of artificial hip joint functionality.

The experimental studies described included modelling, under laboratory conditions, of one of significant elements of revision artificial hip joint acetabulum implantation procedure, i.e. graft impacting. During modelling of the impaction process of graft layer in a vessel of hemispherical shape, the reaction of the impacted grafts to forces of various values was assessed under conditions similar to clinical ones. The reaction of bone graft bed to forces similar to those of hip joint weight loading was also of significant importance from the standpoint of patient's rehabilitation after surgery.

Applying various forces to the grafts, we tried to find out the conditions of their optimal impaction on a hemispherical bed in order to obtain a homogenous environment of a definite biomechanical strength.

Determination of the force values necessary for bone grafts impacting is an extremely complex task, in which the interrelations of numerous aspects, both biological and mechanical, must be considered [3, 4, 5]. On the one hand, impacted bone grafts should provide mechanical strength of the system created, while on the other, the impaction process must not cause destruction of graft biological structure. During impaction deforming occurs of bone graft trabecular system, which can return within a definite weight load range to its primary status. When borderline pressure force values are exceeded permanent deformation of the trabecular system occurs, with its destruction. This happens due to exceeding of bone grafts elasticity limits.

Materials and Methods

In the literature concerning the properties of bone grafts studies are mainly described carried out on flat models, in which the pressure applied to the tested grafts was uniform over the whole surface area [1, 2, 8, 11]. Such a system could be relatively easily modelled as a plane subjected to pressure of uniform value. Most of those studies were experimental tests performed on animals [8, 9, 10].

Contrary to those works [6, 7] the studies described here were performed on a model reproducing the actual shape of graft layer developing during revision hip arthroplasty.

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Bone grafts obtained from femoral heads were used for the studies. After removal of cartilaginous tissue and defatting, the grafts were frozen.

Individual tests were performed in a cylindrical vessel of 68mm diameter. A schematic drawing of the study model is presented below (Fig. 1).

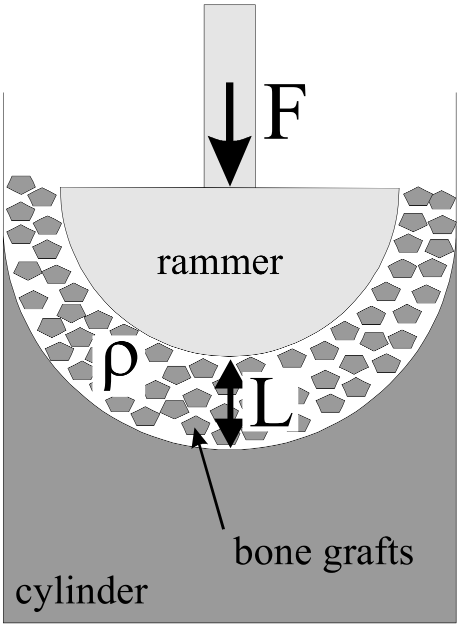


Figure 1: Model of the study system

In view of X-ray examinations scheduled in later stage of the study, the vessel was made of two-component epoxide resin. Morsellised grafts of 5x5 mm dimensions were placed in the vessel and impacted in layers. Each sample was prepared from three layers of grafts impacted in turn with rammers of decreasing diameters until obtaining of the desired shape for cementing of artificial acetabulum. The grafts were impacted by hand by an experienced orthopaedist using a rammer and a 700g orthopaedic hammer.

The tests of bone graft impacting were carried out on a strength-testing stand based on an INSTRON 8501 Plus universal strength-testing machine presented in Fig.2.

The stand makes possible to apply static or dynamic (sinusoidally variable) weight loads using process control by means of strength channel or displacement channel. The accuracy of weight loading force measurement was 0.5% of the extensometer's head measurement range (the head with ±5 kN range was used) while the displacement was measured with 0.01 mm accuracy.

In order to determine the relationship between the quality of graft impaction and the value of forces and number of impaction cycles, the density of the grafts was measured during the studies, in successive phases of the experiment. Graft density was measured by the method of computed tomography, dividing the space under question into five measurement zones, as presented in Fig. 3. The first and fifth zones were the areas of acetabular entrance, where poorest graft compaction was found clinically. The volumetric measurements of the grafts are presented in Hounsfield units (HU).

Figure 2: Instron 8501 strength-testing machine

Most tests were carried out with spiral scan with 0.62m mm layer thickness and 1024 x 1024 pixel matrix and 25 cm field of view.

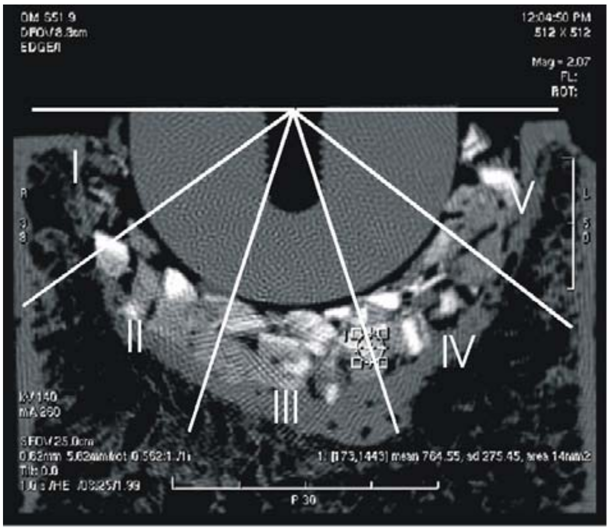


Figure 3: Tomographic picture of the study model.
(A schematic presentation is visible of the division of the compacted grafts into five zones in which density measurements were performed)

Results

After preliminary impacting of three layers of grafts of about 1cm thickness, they were subjected to kneading with a saw-shape force of maximal values alternating from 0.3kN to 3kN. The weight load applied was of static character. The force applied to the central part of the rammer of 50mm diameter was gradually increased to the maximal value and then the pressure was discontinued. Altogether, six independent tests were performed for various force values and the study results are presented in Fig. 4 and 5.

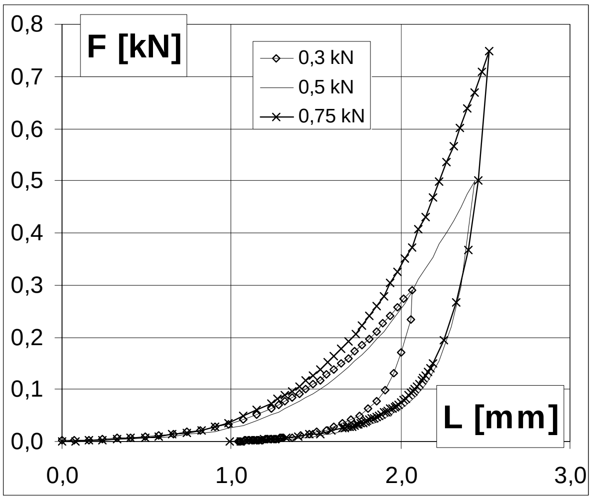


Figure 4: Characteristics of force changes as function of rammer displacement for F_{max}=0.3, 0.5 and 0.75kN

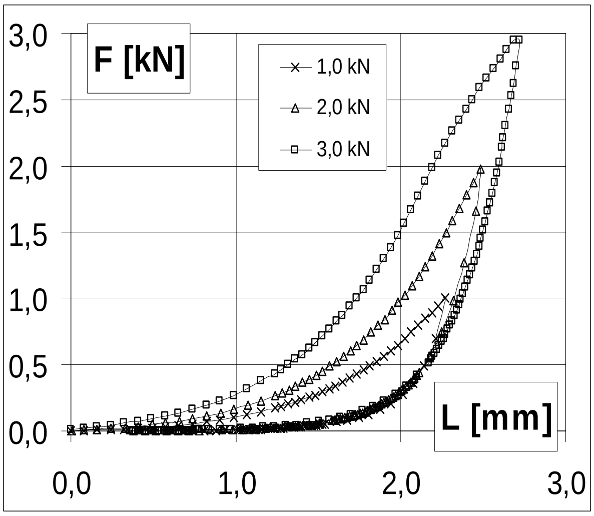


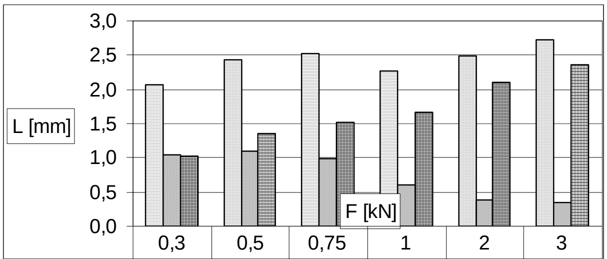
Figure 5: Characteristics of force changes as function of rammer displacement for F_{max}= 1, 2 and 3 kN

Every time the displacement of the rammer was measured in relation to the baseline position, which was accepted as zero and therefore all characteristics have a common point at the origin of coordinates.

Some hysteresis was observed in the rammer displacement during increasing and then decreasing the force. With reduction of the kneading force from maximum to zero it was observed that with F=0 the rammer failed to return to its initial position.

In Fig. 6 some characteristic values are presented suggesting the effectiveness of bone graft compacting. The following values were accepted, expressed in millimetres:

- **Lmax** – rammer displacement for the maximal force value (maximal compressing of the grafts)
- **Lmin** – rammer displacement for the minimal force value close to zero (minimal compressing of the grafts – the remainder, hysteresis, after cessation of force effect)
- **(ΔL=Lmax – Lmin)** – difference between the maximal and minimal displacement showing the extent of elastic strain.



F [kN]	0,3	0,5	0,75	1	2	3
Lmax	2,06	2,44	2,52	2,27	2,48	2,72
Lmin	1,04	1,09	0,99	0,61	0,38	0,36
Lmax-Lmin	1,026	1,35	1,53	1,66	2,10	2,36

Figure 6: Comparison of displacement values at characteristic points of the cycle (L_{max} and L_{min}) for various impacting forces

After performing the strength tests, the quality of the compacted grafts was checked by measuring their density in selected measurement zones, as shown in Fig.3. The measurement was carried out and the mean value ρ and variance σ in Hounsfield units were determined. The results were presented as table and bar chart (only the mean value) in Fig. 7. This is an example of density distribution in spherical model of hip joint acetabulum.

Zone I		Zone II		Zone III		Zone IV		Zone V	
ρ[HU]	σ[HU]	ρ[HU]	σ[HU]	ρ[HU]	σ[HU]	ρ[HU]	σ[HU]	ρ[HU]	σ[HU]
-258,8	476,7	260,3	546,1	685,4	533,7	191,7	681,6	203,4	311,1

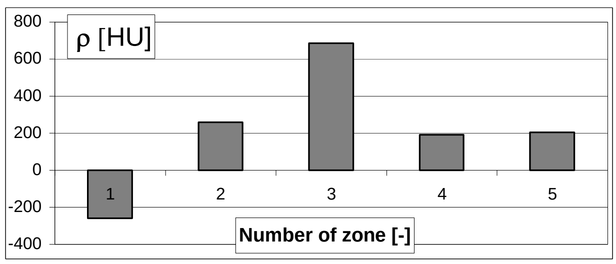


Figure 7: Distribution of density of bone grafts in five zones

Discussion

On the basis of the observations of kneading characteristics patterns in Fig. 4 it was found that in the first phase of the cycle, with application of a slight force (about 100 N) the rammer sank at the depth of 1.5 mm.

After reaching the maximal force value (F=0.3 kN), rammer displacement (L_{max}) was 2.06 mm (Fig. 6). After weight load discontinuation the rammer failed to return to its initial position but remained in displacement L_{min}=1.04 mm. The difference between positions with application of the maximal and zero forces (ΔL) was the effect of bone graft elasticity. This might be interpreted that the grafts were compacted by 1.04 mm and partially (1.03 mm) underwent elastic strain (2.06-1.04=1.03). In successive cycle with application of F=0.5 kN force value the grafts were kneaded by 2.44 mm and after weight load discontinuation the rammer remained in displacement L_{min}=1.09 mm. The value of elastic strain in this cycle increased and was 1.35 mm. With increasing the impacting force up to 3 kN, the maximal displacement (L_{max}) of the grafts increased with simultaneous reduction of the minimal displacement (L_{min}). Some non-monotonicity of the process occurred with weight loading with F=1 kN force. The strain of graft layer was lower than with 0.75 N force value, possibly due to homogenization of the impacted bone mass and due to beginning resistance of trabecular bone fragments contained in the impacted grafts. After exceeding of 1 kN load value the process of graft compaction started again.

Despite gradual increasing of the impacting force from 0.3 to 3 kN the effectiveness of graft compaction decreased. With force increasing, elastic strain (ΔL) constituted an ever greater part of the total strain while plastic strain (L_{min}) decreased. With 3 N force value the displacement value was as high as 2.72 mm but after force discontinuation the rammer returned almost to its initial position. Fig. 6 shows that only the first three cycles (for 0.3, 0.5, and 0.75 kN force values), out of six impaction cycles performed, caused a rather significant graft subsidence due to force effect. The next three cycles (1, 2, and 3 kN) caused significant strain of the graft bed due to pressure, but after force effect cessation the bed returned to its initial status. Slight plastic strain in those cycles was the effect of pressing fluids out of the impacted grafts through pores in the vessel made of epoxide resin.

The total compaction of the grafts after six cycles was 4.47 mm with 3.12 mm achieved after the first three cycles with the maximal force of 0.75 kN.

The model of acetabulum with compacted grafts was subjected to CT examination in order to determine the degree of graft compaction. After six weight loading cycles with force values from 0.3 to 3 kN it was disclosed that the greatest compaction of the grafts occurred in zone 3 on the acetabular fundus and its value was 685.4 Hounsfield units. In zones 2 and 4 the density was almost three times lower than in the central zone. In zones 1 and 5, in which poorest graft compaction was usually observed, the results of density measurements were very divergent. In zone 5 the result was comparable to that in zone 4, while in zone 1 negative mean value pointed to presence of air spaces in the graft layer, in spite of application of such a great force.

Conclusions

Static compacting of bone grafts in hemispherical model of acetabulum confirms the complexity of the phenomena occurring during static impacting. After preliminary impacting by orthopaedist further impacting of grafts proceeds with pressure of low value (0.3 kN).

The bed of compacted bone grafts has a very wide range of plastic-elastic properties. The greatest plastic strains occur within force range from 0.3 kN to 0.75 kN. After exceeding 0.75 N pressure force, further increasing of force value causes strain of only elastic character. It can be assumed that this is the elasticity limit of grafts impacted in a spherical vessel, i.e. this is the highest stress producing only elastic strains.

Osseous bed stiffness depends on the values of forces applied during impaction process and on the location of grafts around the acetabulum. CT examinations demonstrated a correlation between the density of bone grafts and their mechanical strength.

During graft impacting (effects of external forces), compaction is non-uniform and asymmetrical particularly in zones 1 and 5 at acetabular entrance. Non-homogenous density of the bone grafts was observed in CT examinations in individual measurement zones. The highest density values were observed in acetabular fundus. The lowest density values were found in superficial zones.

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