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Dynamic testing of bone grafts

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The influence of cycling loading force on the substrate made of frozen bone grafts was investigated. Three layers of bone grafts were compacted in a spherical model of hip joint acetabulum and then subjected to a sinusoidal loading force. For each layer a series of $N = 30$ loading cycles were performed. The least impacted grafts were located in the upper part of the acetabulum, close to its opening, whereas the bed is the most compacted part. Compacting is a non-linear process which quickly loses its dynamics during subsequent cycles. Most of the compacting was observed during the first cycles and the deformation of bone grafts has clearly plastic character. Bone grafts initially compacted by orthopedist undergo further compacting when exposed to a cyclic load.

Key words: *impacted bone grafts, hip joint acetabulum*

1. Introduction

The main purpose of using grafts in revision procedures is the reconstruction of viable bone tissue around the acetabulum socket without losing its primary stability [1]–[8]. A process within the period that starts with obtaining a primary stability of the acetabulum fixed on the grafts and cement and ends with final remodelling of the grafts into viable osseous tissue is not fully elucidated. The impaction of morsellised bone grafts, as recommended by SLOOFF and LING, has significantly improved their survival in revision hip joint surgery [4], [8]–[10].

It is difficult to determine the optimal values of compacting force necessary for the stable fixing of acetabulum. The compacting of bone grafts is a complex process, in which correlation between several biological and mechanical factors must be taken into account. Compacted bone grafts should assure mechanical stability of the system of acetabulum–cement–bone grafts–acetabular bony bed but, on the other hand, excessive compacting may damage biological structure of grafts, thus disturbing its transformation into osseous tissue [11]–[13].

According to LING [5] a stable fixing of an implant is not only the main goal of this technique, but also a critical condition of successful transformation of grafts into tissue, while according to KÄRRHOLM [14] the proper stiffness of compacted bone grafts is of a primary importance. Several experimental studies describe a connection between the impacting of grafts and their density and hardness. However, no close correlation between those factors has been explicitly proved [15]–[18].

The mechanical properties of morsellised bone grafts compacted during revision hip arthroplasty have a significant influence on final results of operation [11], [19]–[22].

Most available research in this field was aimed at determining the properties of grafts as a function of their type and size as well as force values and the time of compacting [15], [16], [23]–[25]. Morsellised bone grafts described in [15], [16], [19], [20], [22], [23], [26] were tested using planar models, being considerably different from spherical layout of bone bed

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formed during arthroplasty. Equipment used for such research was only capable of static testing of samples. Under real conditions the grafts are subjected to dynamically changing forces.

The authors decided to experimentally test the properties of compacted bone grafts because of the following reasons:

- a growing number of loosen acetabula after revision hip arthroplasty,
- a shorter life of the hip replaced after revision hip arthroplasty than an initial one,
- main cause for revision hip arthroplasty is an acetabulum stability loss,
- the cause for such frequent failures is unknown.

2. Aim of research

The research should be aimed at identifying the factors, which have a decisive influence on the initial stability of artificial acetabulum. Taking into account the high costs of a primary, and in particular, a revision hip arthroplasty, the prolonged lifetime of such an implant may lead to considerable savings.

Our main goal was to determine the response of substrate made of frozen bone grafts to cyclic force of fixed magnitude. The tests had an important new aspect because they were carried out on a spherical model of acetabulum. The effects observed during the dynamic testing of bony bed made of compacted grafts are interesting because they appear in post-operation period, when the artificial hip joint is subjected to loading force. At that time further compacting of grafts can be observed as well as migration of polyethylene acetabulum, which may lead to its loosing [5], [14], [24], [27].

The main research goals are as follows:

- the analysis of the compacting process under conditions similar to clinical ones,
- finding the influence of a value of the force applied and the thickness of graft layer on a compacting process,
- assessing the quality of graft compacting.

3. Test stand and testing methodology

In an available literature on the properties of grafts, mainly planar models are described, in which the force is uniformly applied to the whole plane [22], [24]. Such layout can be easily modelled as a plane subjected to uniform pressure. In contrast to this common approach, we carried out our research on a spherical model, whose shape is much closer to that of real graft layer that is formed during revision hip arthroplasty.

For the experiments, bone grafts from femoral heads were used. After removing a cartilaginous tissue and defatting, the bones were ground down to create bone pieces whose diameter ranges from about 5 to 8 mm. Then the grafts were frozen. Their sterilization by ionizing radiation was not applied. Bone graft samples were prepared in a spherical vessel created inside a cylinder with 68-mm diameter (figure 1). Each sample has 3 layers of bone grafts compacted successively with rammers of decreasing diameter (down to 50 mm) until the necessary shape was obtained ready for artificial acetabulum to be cemented in. After initial compacting, bone grafts were subjected to the load changing sinusoidally with 1 Hz frequency. For every layer of grafts a series of 30 compacting cycles were performed and the force changes versus displacement were recorded.

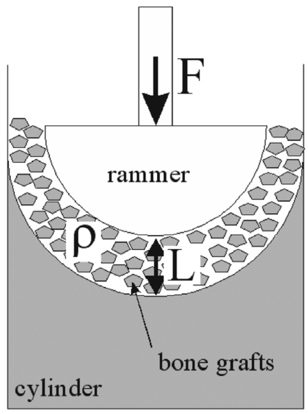

Fig. 1. Model of arrangement tested

Compacting process was carried out on an INSTRON 8501 Plus stress-testing machine. Static and dynamic loads of various shapes can be applied to a test stand by controlling the process, based on the force or displacement measurements. The measuring accuracy is 0.5% of measuring range in the case of loading force measurement and 0.01 mm for displacement measurement.

The model of acetabulum was mounted on a test stand and exposed to sinusoidally varying load applied by a rammer of 50-mm diameter mounted on mandrel attached to load cell of hydraulic actuator. The displacement of bone grafts was determined based on the position shift of table mounted on moveable crosshead.

4. Test results

On the basis of the data collected several charts were plotted. They represent the character of dynamic compacting process on Instron machine. If the rammer position for the points of a minimal load is known, it is possible to plot a graph showing the change of actual minimal rammer position with respect to minimal load position in the last cycle (figure 2). On this basis the compacting of the grafts achieved in consecutive cycles can be determined.

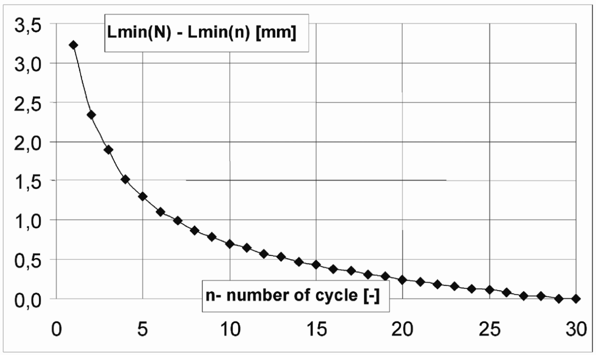

Fig. 2. Difference between minimal rammer positions in *n*-th and last cycles

Dynamics of the compacting process, defined as the increase in the value of minimal position of the rammer in consecutive cycles, is presented in figure 3. It was calculated as the difference between minimal positions of the rammer in n and $n-1$ cycles. On the basis of cyclic compacting process another graph was plotted, showing the difference between minimal and maximal rammer positions in a given cycle (figure 4). An increase in position was calculated as the difference between the positions corresponding to maximal and minimal (close to zero) force values.

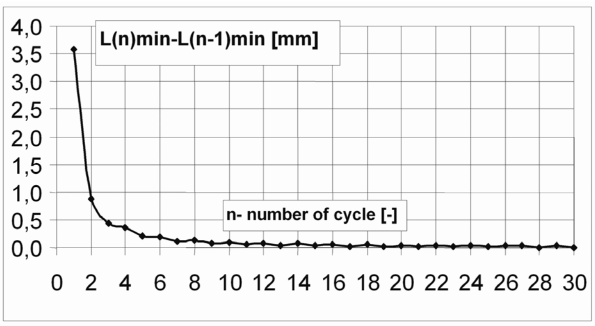

Fig. 3. Increase in depth of compacting in consecutive cycles

After the compacting of the first layer of bone graft the next two layers were placed inside the vessel and subjected to the same compacting procedure. The curves representing the difference between the positions of a rammer corresponding to maximal and minimal loads for three layers are presented in figure 4.

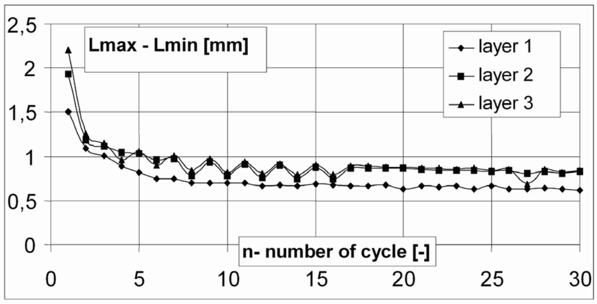

Fig. 4. Difference between maximal and minimal rammer positions in a given cycle

The process of compacting has the same character as the relations obtained for all the layers presented in figure 4.

5. Discussion

The impacting of grafts in spherical acetabulum preserves conditions similar to those during revision operations. In such a case, it is difficult to obtain the uniform impacting of grafts in the whole area of the model of acetabulum. Clinical observations as well as those during the experiments showed that the least impacted grafts were located in the upper part of the acetabulum, close to its opening, whereas the bed is the most compacted part.

The studies conducted were limited to strength tests of grafts of one size, similar to those performed by orthopaedists from the Military Medical Institute in revision procedures. During the process of compacting, the trabecular system is deformed, yet it can recover its previous state [22]. If the threshold values of compacting force are exceeded, the deformation of trabecular system cannot be reversed. The total volume of bone grafts decreases because of two main reasons. First, the distances between individual graft particles are reduced, and second, the size of particles is reduced as well. Such a reduction of dimensions can be observed in the range of elastic strain.

A dynamic compacting of bone grafts in hemispherical model shows the complexity of the process. The curve presented in figure 2 shows that compacting process has non-linear character and can be approximated by exponential function. It can be seen that the thickness of bone graft substrate subjected to compaction is reduced by 3.3 mm during 30 compacting cycles.

Dynamics of compacting process quickly decreases in every consecutive cycle, which can be seen in figure 3. The greatest shift in rammer position was observed during initial cycles and deformation had definitely elastic character. During the next cycles the rammer travels much smaller distance. Mixed, plastic-elastic character of compacting process in hemi-spherical model of acetabulum can clearly be seen in figure 4. It shows that the hysteresis of rammer position is much greater in the first cycles, because in those cycles most of the compacting takes place.

After a few cycles the compacting process stabilizes itself and only a slight increase in the displacement takes place. It can be seen that after 10 cycles the difference between extreme rammer positions becomes stable at the level of 0.65 mm and in the next cycles this is constant. This means that after about 10 cycles the compacting process has purely elastic character. Further penetration of a rammer inside bone graft structure is caused mainly by fat and water loss through the microchannels in epoxy resin used to make the cylinder and by an insufficient stiffness of a test stand.

It is obvious that compacted grafts reach the elasticity threshold, i.e., maximal force that causes only elastic strain. The difference between maximal and minimal rammer positions for two next layers becomes stable at the level of 0.85 mm, slightly higher than that obtained for single layer of bone grafts. This is caused mainly by the greater overall thickness of bone graft layer, which makes fluid displacement more difficult.

According to the test results it can be stated that bone grafts reveal elastic properties in a wide range of the forces applied, and the reaction time for the load applied approaches 1 minute. This was determined during static testing when a constant load was applied and the time necessary for the rammer to reach stable position was measured.

The authors stress that the primary stability of implant is the most important factor influencing the normal process of graft healing [5], [14]. A better impacting of grafts and their greater size can produce an improvement of implant primary stability [23], [24], [28], [29]. Besides, the quality of grafts used in revision operations and, in particular, the ratio of spongy layer to cortical layer are of a certain significance [24]. The use of cement seems to increase the implant stability through its penetration into impacted graft layer, producing a cement–grafts zone [11].

The experimental studies conducted have demonstrated that bone grafts preliminarily impacted by orthopaedist and subjected to cyclic weight bearing undergo further impacting process. The observations lead to a conclusion that bone grafts should be primarily impacted in such a way that the forces of prosthesis weight-bearing, acting on them, would not cause their secondary impacting resulting in the displacement of the seated acetabulum. In order to ensure a sufficient stability of the implant, the impacted grafts cannot be deformed during pushing-in and cementing the implant. After that procedure the stability of the implant is maintained not only by impacted grafts, but also by cement. This is mainly the strength of the impacted grafts that has a decisive influence on the stability of the host bone–grafts–cement–implant system created.

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