Journal of Bone Research

Watral et al., J Bone Res 2017, 5:1
DOI: 10.4172/2572-4916.1000172

Research Article Open Access

Stability Studies of Acetabular Cup in Artificial Hip Joint Models

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Received date: January 17, 2017; **Accepted date:** February 7, 2017; **Published date:** February 10, 2017

Abstract

Purpose:

The article presents the results of stress testing of an artificial cup fixed in a model containing a fragment of an animal hip. The main objective of the study was to determine the effect of the angle of cup fixing on its stability.

Methods:

In the model investigated, a polyethylene acetabulum was cemented on a base made of impacted frozen bone grafts by experienced orthopedists. In this way, the test conditions were similar to those in clinical trials. The model prepared in this manner was subject to cyclic loading followed by a trial to tear off the cup, performed on an INSTRON machine.

Results:

As a result, a set of characteristics was obtained which illustrate the dependency of acetabular cup displacement as a function of the shearing force for different inclination angles of cup fixing and varying thickness of graft layers.

Conclusion:

One conclusion was that the fixing angle of 60 degrees in relation to the vertical axis Z_m of the global coordinate system provided significantly better stability that the angle of 30 degrees. It was also noted that the layer thickness of frozen grafts was another factor influencing the value of the shearing force applied to the cup.

Keywords: Acetabular cup; artificial hip joint models; arthroplasty; osteolysis

Introduction

Since its introduction 30 years ago, the application of impacted allografts to supplement acetabular bone defects has become a standard procedure in revision total hip arthroplasty treatment. Revision arthroplasty, a method introduced by Sloof et al., aimed at the reconstruction of acetabular bone defects, which enabled stable and anatomical implantation of the revision acetabular cup [1]. The same method, albeit with some modifications, is also applied in revision hip arthroplasty with bone defects within the femur [2].

The initial period after the surgery is aimed at the protection of the cup-cement-grafts-bone structure in order to ensure an uninterrupted rebuilding process which provides biological stability of the pan after the transplantation. Restoration of mechanical, stable support in the initial period is necessary for successful revision procedures with bone grafting, which then allows for reconstruction of the transplantation. The final stability of the acetabular cup can be perceived as a race of reconstruction processes won against osteolysis. The layer thickness of grafts and the correct placement of the cup, including the proper inclination and rotation, are further important factors ensuring successful treatment. Migrations of the acetabular cup indicate some disturbance in the reconstruction process, but do not necessarily lead to stability impairment. Current research on the subject, published worldwide, was aimed at the recognition of properties which character is impacted bone grafts based on the type and size of the graft, as well as the magnitude and duration of the impact. Bone grafts with various mechanical properties and structures were typically impacted in a vessel prepared for that purpose. The authors of the present work conducted their studies on a model of animal hip joint, thus reducing some significant differences between laboratory and clinical conditions. Contrary to prior research [3], the authors' studies were carried out on a model which reflected the real shape of the graft layer formed during the procedure of hip joint revision. Research in this field is of vital importance because of the substantial costs connected with both revision and primary hip arthroplasty procedures. Knowledge acquired from such research may constitute a source of financial savings and may extend the time of proper endoprosthesis functioning.

Aim of Study

The studies performed on animal hip joints are aimed at determining the factors which influence the stability of acetabular cup in cement and frozen bone grafts. A further goal is to learn which of these factors have substantial influence on the alignment of artificial joints. The analysis of the studies carried out on hip joints models after revision arthroplasty procedures will provide information on optimal parameters for acetabular cup implantation, as well as the magnitude and direction of the forces applied on artificial joints at the early rehabilitation stage. A particular study aim is to investigate the influence of the inclination angle on the stability of acetabular cup.

Materials and Methods

Stress and endurance testing of calf hip joint models was performed on a test stand with an Instron 8501 Plus machine. Cyclic loading of the hip joint model with polyethylene acetabular cup was applied to check its strength against tension. Figure 1 presents the hip joint model applied during testing.

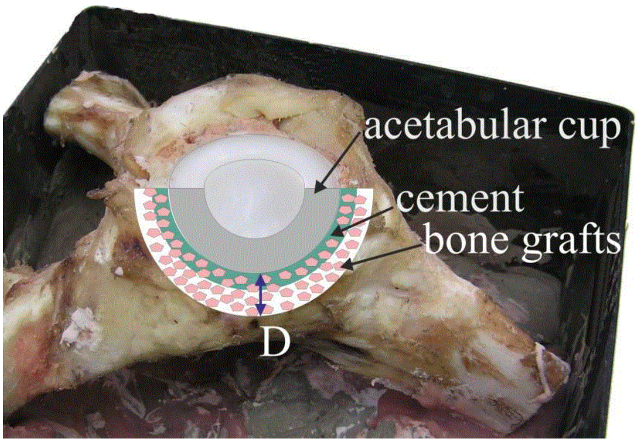

Figure 1: Calf bone after revision arthroplasty, cross-section.

Bone grafts obtained from femoral heads were applied in all experiments. Fragmented bone grafts were prepared by means of cartilaginous tissue removal. Bone marrow and adipose tissue was removed by rinsing the grafts in physiological saline at 70 degrees. Bone grafts of irregular shape and a size of 5-7 mm were applied in the studies. Varied grafts size enabled their accurate compaction by filling void space between larger grafts with smaller ones. Dried grafts were stored in a freezer at -25°C without prior sterilisation.

Each sample tested comprised three layers of grafts, compacted successfully with rammers of decreasing diameter until the desired shape for the artificial acetabular cup was achieved. The grafts were compacted manually with a 0.7 kg orthopedic hammer until the desired thickness D of 5-10 mm was obtained, as shown in Figure 1.

The hip models for testing were prepared in a cuboidal frame made of steel sheet whose base was filled with Ceresit CX-5 installation cement. The calf acetabula were glued into the cement frame using fast-bonding duracryl. Afterwards, the revision procedure of polyethylene acetabular cup implantation was performed. Bone socket defects of the cup were performed by means of drilling the acetabulum with a 60 mm reamer. The proper layer of bone grafts was then impacted manually and the polyethylene acetabular cup was cemented onto it. At the end, a cyclic force F was applied to the acetabular cup on the Instron machine in N cycles.

The studies were performed for:

Two values of graft layer thickness (D=5 or 10 mm).

Three different angles of the force which corresponded to three different inclination angles of the acetabular cup.

The intraoperational acetabular cup inclination of 60°, 45° and 30° corresponds to a cup slope angle β of 30°, 45° and 60° respectively, measured from the vertical axis Z_m of the global coordinate system Figure 2a. During laboratory testing, this was modelled by applying the force at different angles in a local coordinate system (X_p, Y_p, and Z_p) related to the acetabular cup, as shown in Figure 2b. For instance, a loading force applied along the local axis Y_p (the normal in relation to the cup opening) corresponds to a cup fixed at 45° with respect to the global vertical axis Z_m. The test set-up shown in Figure 2b is equivalent to a force applied vertically in relation to the cup opening, while a cup fixed at 30° and 60° signifies a loading force at $+15^{\circ}$ and -15° from the normal, respectively.

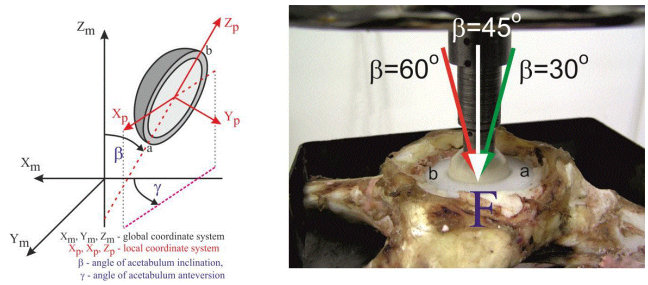

Figure 2: Acetabular cup fixing angles in a global coordinate system (X_m, Y_m, Z_m) (a) directions of applied loading force corresponding to different cup slope angles (β) (b).

Freely available HIP98 computer software was applied to determine the component values of forces which affect the hip joint during normal human activities [4]. In this way, force components were calculated which affect the cup at different cup slope angles in relation to the local coordinate system (X_p, Y_p, Z_p) during walking in a patient weighting 80 kg. The force components calculated are shown in Table 1.

β[°]	60°	45°	30°
FX_p [N]	412	412	412
$-FY_p$ [N]	1575	1353	1039
FZ_p [N]	649	1034	1349

Table 1: Calculated component values of a hip joint loading force.

The force components calculated have the greatest values for the fixing angles 45° and 60° for the Y_p component and 30° for the Z_p component.

Stress testing which consisted in cyclic loading of the cup at different angles with an F force of 1 kN, sinusoidal properties and a frequency of 5 Hz for N=100000 cycles was conducted in the test set-up as shown in Figure 2b.

In the first stage of testing, the models were grouped in terms of layer thickness D of the bone grafts and the angle β of cup fixing in relation to the global coordinate system of an individual. The testing results are provided in Table 2 along with their descriptions. Subsequent experiments are numbered from 1 to 6.

Sample No	Grafts layer thickness D [mm]	Cup fixing angel β [°]	Force value F[kN]	Number of cycles N[-]	Cup displacement after 100 000 cycles L0[mm]
1	5	45	0	0	0
2	5	45	1	100 000	0.26
3	5	60	1	100 000	0.30
4	5	30	1	100 000	1.76
5	10	60	1	100 000	0.47
6	10	30	1	100 000	0.73

Table 2: Test results for different grafts layer thickness and angle of cup fixing.

After stress testing, the quality of cup fixing was checked by means of endurance testing. The cup was subject to a shearing force F_c applied each time to the same side at the edge of the cup, as shown in Figure 3.

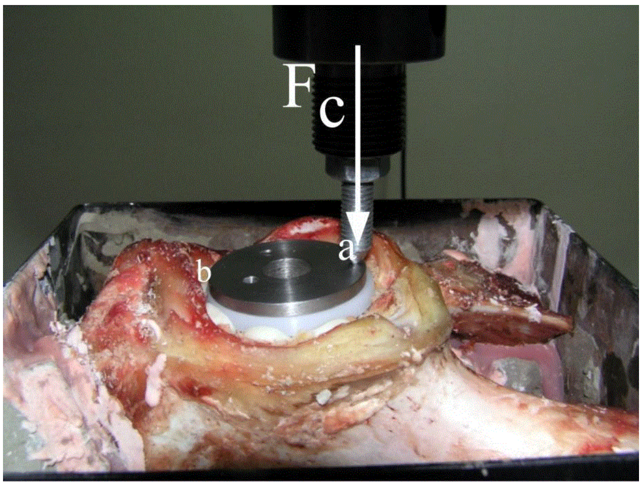

Figure 3: Cemented acetabular cup subjected to a shearing force.

Minor cup displacement was observed in the direction of the force during cyclic loading. Displacement values L_0 measured for particular samples are shown in the last column of Table 2. The value of the displacement observed depends on the thickness of the bone graft layer and the magnitude of the loading force [5].

Results

The measured values of the change in the shearing force F_c as a function of cup displacement L are shown in Figure.4. The results obtained were comparatively analyzed, with similar metrological properties of tested models used as the criteria. Figure 4 illustrates the process of tearing off the acetabular cup, i.e. the value of the force F_c as a function of cup displacement L for samples from 1 to 6 (Table 2). The influence of cyclic load on the cup stability was compared in sample 1 and 2 for the same layer thickness of bone grafts (β=45°).

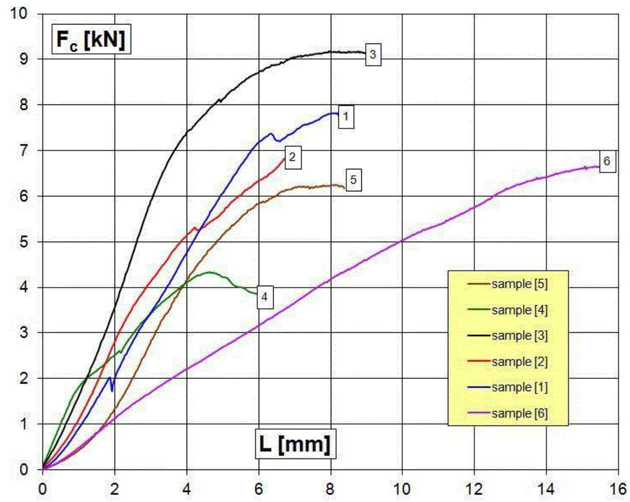

Figure 4: Shearing force as a function of cup displacement for Samples from 1 to 6.

This summary of samples shows the influence of cyclic loading on the cup stability in relation to the case where the cup was "torn off" immediately after cementing.

No considerable difference between samples 1 and 2 is visible in Figure 3 when comparing the plots of the shearing force as a function of cup displacement. The final stability of the acetabular cup fixing on a layer of bone a graft which was subject to prior loading is similar to that which was not exposed to external force.

Samples 2, 3 and 4 (Table 2) illustrate the cases where the cup fixing angle β was changed from 30° to 60° for the same layer thickness of bone grafts (D=0.5 cm).

When comparing the resulting plots, one can observe that the application of cyclic load increased the stability of the acetabular cup fixed at the angle β=60°. Decreasing the angle to 30°, in turn, makes the cup least stable – it is "torn off" when exposed to a force of about 4 kN. Further samples 5 and 6 (Table 2) compared the influence of the acetabular cup fixing angle when the bone graft layer was twice as thick (D=1 cm).

As in the case depicted in Samples 3 and 4, the fixing angle of 60° yielded better results in terms of acetabular cup stability than the 30° fixing angle. When comparing samples of identical angles and different layer thickness, it can be seen that the inclination of plots decreases as the layer thickness increases, which indicates worse stability.

Discussion

Acetabular pan defects still constitute a major technical problem during primary and revision hip arthroplasty procedures. Inadequate coverage of acetabular hip prosthesis with bone sockets or metal

Citation: J Plominski, Z Watral (2017) Stability Studies of Acetabular Cup in Artificial Hip Joint Models. J Bone Res 5: 172. doi: 10.4172/2572-4916.1000172

implants which complement the defects leads to poor long-term results. The desire to obtain full mechanical support for artificial acetabulum often leads to its excessively steep fixing, which can lead to dislocation and early loosening caused by forces affecting the superior-anterior surface of the acetabulum. Many hoped that the use of metal implants will provide the desirable effect. However, cases of their suitability were scarce [6].

Stability testing of polyethylene acetabulum cemented on impacted bone grafts in a natural animal hip joint reduced the gap between laboratory and clinical conditions. This provided an opportunity to directly test the influence of graft layer thickness and the fixing angle on the stability of the cup primary arrangement. One condition of long-term positive results of revision arthroplasty with bone defect compensation using bone grafts is the acquisition of good primary stability of the acetabular component and uninterrupted graft rebuilding process. The primary stability of the acetabular cup depends on the quality of graft impacting and on the proper arrangement of the cup. Graft impacting which provides mechanical support for the cup depends on the quality of the bone cup. Quite often, poor bone quality makes achieving the optimal graft impacting impossible [7].

The authors encountered similar technical problems while impacting grafts where a metal net was applied to fill the bone defects. However, the elasticity of such grafts makes proper impacting impossible. In both cases, this results in an early dislocation of the cup in the graft layer and causes its subsequent loosening.

The mechanical impacting quality of grafts depends on their size and composition. The authors believe that mechanical preparation of the bone layer affects the possibility of loading without the risk of loosening the artificial acetabulum. Many authors point out that the elastic properties of bone grafts are determined by their primary impacting [8].

However, long-term observations indicate other reasons which appear to be of vital importance for long-term acetabulum stability. That is why the Authors sought other dependencies, focusing their efforts on the proper positioning of the implanted acetabular cup.

Based on stress testing of acetabular cup fixing, an influence of the fixing angle β on the primary stability was determined (simulated in the experiments by the angle at which the loading force F was applied) and the layer thickness D of the grafts used.

The comparison of the results from stress testing for samples 1 and 2 (Table 2) revealed that a force of 1 kN applied for 100000 cycles perpendicularly to the cup normal does not cause excessive settlement of the grafts (0.26 mm). This is probably caused by the graft layer which is not too thick and which has been penetrated and stiffened with bone cement.

When one analyses the results for samples 2, 3 and 4 (Table 2), it i possible to evaluate how the fixing angle of the cup influences its displacement (Table 2) and stability. Based on sample 2, 3 and 4, a dependency between cup displacement and its fixing angle for the same layer thickness of grafts was found.

The reduction of the inclination angle to 30 degrees produces rapid growth in the cup displacement, caused by a much weaker compaction of grafts in the superior part of the cup. The studies revealed that a lower positioning angle of the cup results in its greater dislocation. This is caused by the principle that cementing the cup at the angle of 30° is not profitable. When applying the force at an angle of 30°, the transverse component of the force causes strong graft impacting in the direction of the force. However, some detachment of the bone graft from the bone base occurs on the opposite site at the same time. After such loading, the stability of the cup is decreased significantly and it becomes all the more likely to be torn off. A positioning angle of 60°, in turn, improves the compaction of grafts, which results in better cement penetration into the grafts and, as a consequence, improves the stability of the cup when compared with the angle of 45°. This implies that fixing the acetabular cup at the angle β=60° partially improve its stability, whereas an angle of 30° makes the cup less stable than in the case of 45°.

Stability testing of a cemented polyethylene acetabular cup on bone grafts also indicates the importance of the thickness of cement layer. This is especially important in a thin graft layer.

For a graft layer thickness of 0.5 cm, the application of a cyclic load has very limited influence on the magnitude of the force required to tear off the acetabular cup. Hence, it can be concluded that cement which penetrates a thin graft layer prevents further compaction and contributes to the primary stability. On the other hand, such a deep cement penetration into the graft layer prevents remodeling of the grafts, which may later result in implant displacement.

Finally, the shearing force plots for samples 5 and 6 were compared for identical angles as in samples 3 and 4, but with a somewhat thicker (D=1 cm) graft layer. Here, the fixing angle 60° also yielded better results in terms of stability than the fixing angle 30°. When comparing samples of identical angles and different layer thickness, it can be seen that the inclination of plots decreases as the layer thickness increases. For a graft layer with a thickness of 0.5 cm, the shearing force is approximately twice as big as in the case of D=1 cm. This demonstrates higher probability of cup loosening with a thicker layer of grafts.

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