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Does surface roughness influence the primary stability of acetabular cups? A numerical and experimental biomechanical evaluation

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ABSTRACT

Most acetabular cups implanted today are press-fit impacted cementless. Anchorage begins with the primary stability given by insertion of a slightly oversized cup. This primary stability is key to obtaining bone ingrowth and secondary stability. We tested the hypothesis that primary stability of the cup is related to surface roughness of the implant, using both an experimental and a numerical models to analyze how three levels of surface roughness (micro, macro and combined) affect the primary stability of the cup. We also investigated the effect of differences in diameter between the cup and its substrate, and of insertion force, on the cups' primary stability. The results of our study show that primary stability depends on the surface roughness of the cup. The presence of macro-roughness on the peripheral ring is found to decrease primary stability; there was excessive abrasion of the substrate, damaging it and leading to poor primary stability. Numerical modeling indicates that oversizing the cup compared to its substrate has an impact on primary stability, as has insertion force.

1. Introduction

Total hip arthroplasty (THA) was defined as the "operation of the century" in a paper published in 2007 by Learmonth et al. [1], due to the excellent and long-lasting clinical and radiological results. Long-term stability of acetabular implants depends on their primary stability following implantation [2–6]. This is because long-term stable osseointegration of the porous-coated acetabular cups depends on bone ingrowth within their porous surface [5]. Primary stability is therefore vital to avoid micromotion, which, if excessive, can limit bone ingrowth [7]. This rigid initial fixation of uncemented cups is usually obtained via appropriate impaction and/or screws. Screws could provide strong fixation but involve a potential risk of vascular complications, and their use has declined in the last decade [8]. Impaction currently seems to be the best option for firm fixation. To achieve natural retention of the cup within the acetabulum, the implant must be hemispherical with a flattened dome [2,5,9]. This design maximizes the contact area between the implant and bone and achieves optimal distribution of stresses. However, in vivo assessment of press-fit stability is relatively imprecise and only based on the surgeon's experience, without any real quantitative evaluation of stability [10]. Thus, to evaluate primary stability in acetabular press-fit cups, mechanical testing and numerical studies were developed and carried out on different substrates such as artificial bone [2,4–6], animal bone [2,11] or human bone [3,12–15]. The tests can be divided into cyclic axial loading [12,13], tangential and rotational stability [2,5,6], and pull-out tests [6]. A complementary approach to analyze primary stability is the finite element (FE) method, which can accommodate large variations in geometry (reaming of the acetabulum) and material properties. FE analysis permits the study of the bone/cup interface (such as contact or strain data) [16–19]. The few studies that backed their numerical model with mechanical testing used cyclic axial loading tests [16,19], not the most accurate representation of a surgeon's hand movements during an operation, to test the stability of the cup immediately after impaction. Yet accurate and reproducible evaluation of the primary stability of press-fit acetabular cups, while complex and dependent on a variety of parameters, is crucial to optimize design.

New press-fit acetabular cups using porous materials of varying degrees of roughness are being developed, and we tested the hypothesis that their primary stability would be impacted by this surface roughness. To evaluate how the primary lateral stability of three press-fit acetabular cups of identical design was affected

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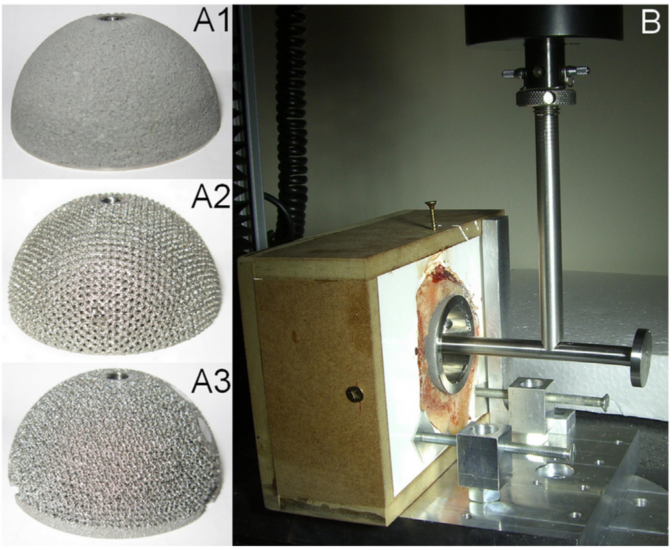

Fig. 1. The cups tested: A1: with smooth surface; A2: with macro-spikes of titanium; A3: with macro-spikes and a smooth equatorial surface. B: tangential stability (TS) test.

by their differing surface roughness, we used first an experimental set-up and second finite-element analysis. We further investigated the influence of the sizing of the cup compared to its substrate and of the insertion force used.

2. Materials and methods

Our experimental study used reproducible materials, starting with an artificial homogeneous material (sawbone) followed by bovine bone, to assess both the effect of the cups' macro-roughness and the effect of the insertion force on their primary stability. A related numerical analysis on sawbone was then performed to obtain contact information not accessible via experiments and which might elucidate the contact and interaction mechanisms between an inserted press-fit cup and its substrate, as well as how differences in cup diameter might affect primary stability.

2.1. Experimental part

Three geometrically identical press-fit cups, of differing degrees of surface roughness (Fig. 1A), were compared for primary stability. We tested a standard press-fit cup (A1), considered as the micro-roughness cup, with a conglomeration of titanium balls (diameter 300 μm) covered with a hydroxyapatite coating (70 μm thickness), and two new-generation cups: one with macro-roughness (A2) and the other with combined macro- and micro-roughness (A3). The first (A2) has 1 mm high titanium macro-spikes spaced 0.7 mm, and the second (A3) is a combination of A1 and A2: smooth (similar A1) around an equatorial ring (5 mm wide) and abrasive (spikes 1 mm high) everywhere else. Moreover, the cups with macro-roughness (A2 and A3) offer surface porosity within their surface, to enhance the osseointegration of the prosthesis during secondary stability. Six cups in each of the three materials were obtained from Adler Ortho® (Milano, Italy). External diameters were 54 mm for A1 and A3 and 55 mm for A2.

Two different substrate materials were used. Sawbones® (Malmö, Sweden) provided polyurethane foam blocks of $130 \times 130 \times 40\,\text{mm}^3$, with a density of $0.32\,\text{g/cm}^3$, simulating cancellous bone in a reproducible, clean and artificial material. Then, specimens of proximal bovine humerus, more similar to human bone with the presence of fluids and already used for analysis of cup impaction [20], were obtained and cut with a handsaw into blocks of approximately $80 \times 140 \times 50\,\text{mm}^3$. On the advice of the implant designers, all blocks were under-reamed 1 mm compared to the external size of the cups, with surgical reamers (holes of 53 mm diameter for A1 and A3, and 54 mm diameter for A2). Blocks of bovine bone were frozen at −20 °C immediately after reaming. The day before the experiments, the bovine bones were defrosted at room temperature and placed in wooden boxes of size $130 \times 180 \times 70\,\text{mm}^3$ filled with Fascast polyurethane resin (Axson Technologies®). The bone surrounding the reamed holes was far enough from the resin not to be affected by the thermal effect of hardening. Cups' insertion was done using the testing machine detailed below, that does not reproduce the dynamic characteristics of the clinical environment. But we opted for a controlled insertion force to obtain test repeatability. As a first experimental campaign, A1 and A2 cups were implanted with a force of 1800 N, as per the literature [2,19]. Next, to investigate the influence of insertion force on primary stability, the A2 cups were subjected to two different insertion forces, first 1800 and then 4000 N, to enhance cup implantation (just beneath the surface). A3 was then compared to A2 via a second experimental campaign where an insertion force of 4000 N was used to give a more realistic representation of the appearance of the cup after insertion.

Two tests for tangential stability (TS) and pull-out (PO) were designed and performed using the materials testing system Instron (INSTRON 5566A). An experimental setup specifically manufactured for this study was designed so as to hold every substrate on the test platform during both tests. All cups underwent preloading of 4 N. In the TS test, cups were pulled down at an angle of 90° using a metallic rod (the impactor) threaded into the cup (Fig. 1B), in order to produce a tangential load on the cup (the load is applied 60 mm from the cup edge). The objective here was to obtain the closest match with the surgeon's hand movement during a THA. The PO test involved pulling the cup out vertically, thus with the same orientation as for insertion but in the opposite direction. The crosshead was moved at a rate of 1 mm/min for each test, and the maximum load required to extract each cup from its substrate was recorded (load precision ±0.5%). Each test was repeated three times for each type of cup (A1, A2 and A3) on each support (sawbone and bovine bone), for both PO and TS. In addition, two insertion forces were tested on A2, for all configurations. A total of 48 tests were thus performed.

2.2. Numerical part

Using the finite-element code ABAQUS (ABAQUS V6.11; Simulia Corp., Providence, RI, USA), we created a 3D model of a block of sawbone measuring $130 \times 130 \times 40\,\text{mm}^3$ with a central hemisphere hole of 54 mm diameter, identical to that used for A2 in the experiments. The goal was to obtain information on the contact between the cup and its substrate. The block was discretized into 20,375 tetrahedral linear elements. The cup was modeled as a rigid hemisphere with an external diameter of 54.5, 55 or 55.5 mm, which represents an oversizing of 0.5, 1 and 1.5 mm, respectively. The block of sawbone was assumed to have linear isotropic elastoplasticity: elastic properties obtained from the manufacturer Sawbone® with Young modulus $E = 284$ MPa and Poisson coefficient $\upsilon = 0.3$, and plastic properties obtained from Calvert et al. [21]. Displacements were prescribed to zero on the base of the block and on its lateral faces. The cup was placed on the block in contact with the periphery of the hole. A reference point (RP), situated 60 mm from the cup edge, was used to apply the load, as in the experiments. The experimental protocol was numerically reproduced with quasi-static resolution: