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Ceramic–ceramic coupling in total hip arthroplasty

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Based on positive clinical experience with the taper lock of ceramic heads in total hip replacement, the conical fixation was also chosen for modular cup inlay made of alumina ceramic and polyethylene. For a comparative assessment of inlay fixation, new ceramic and polyethylene inlays with a taper lock were biomechanically tested and compared with clinically proven system with a snap lock mechanism. With regard to the prevention of dislocation and relative movements the same level of safety was found. Measurements of the damping characteristic of the acetabulum replacement showed that there is no considerable shock-absorption for a metal backed polyethylene inlay and there are no differences in this respect between ceramic and polyethylene inlays.

Keywords: acetabular cup, ceramic–ceramic coupling, modular inlay testing

1. Introduction

Wear particle-induced osteolysis is widely regarded as the leading long-term problem associated with total hip arthroplasty. Histological analyses of the tissue surrounding implants have implicated particulate polyethylene as the most prevalent material inducing osteolysis. Improvements and alternatives to the current technology of articulating metal or ceramic femoral heads with polyethylene acetabular cups are therefore being sought in an attempt to mitigate the osteolysis problem by reducing the amount of wear debris generated at the head cup interface. One potential alternative is the use of ceramic cups with ceramic heads, a concept first introduced by Boutin in 1971. The ceramic–ceramic combination has shown excellent biocompatibility, a stable frictional torque over time and minimal wear debris, estimated to be less than 0.5% of metal–UHMWPE and 1 to 2% of ceramic–UHMWPE combinations [3, 5, 12]. Contrary to reports on metal–polyethylene articulations, where osteolysis is frequently described, in ceramic–ceramic couplings this complication is uncommon. Ceramic wear particle consisting of fine grains collected within macrophages was found in revised cases, although no or only very few foreign-body giant cells were seen in any case [4, 5]. Comprehensive material research and clinical experience gained for more than 20 years have shown the alumina–alumina ceramic combination as a safe and reliable articulation system in total hip replacement with extreme low wear rates, no tissue reactions and – looking to other systems – comparable clinical long-term results. On the other hand, the specific properties of this material combination need to be considered in clinical use and particularly in the design of implant components.

2. Modular acetabulum cups

In the past, the weakest argument for use of modular cups was the modular polyethylene liner. Disassembly of the insert and accelerated wear of polyethylene have been reported [7, 13]. Today, the modular cup design permits the alternative, indication-specific use of various bearing combinations, for example alumina–alumina ceramic, alumina ceramic–polyethylene or metal–polyethylene, providing an alternative which avoids polyethylene wear and is particularly suitable for younger, active patients. Nevertheless, the thickness of the liners and a tight, durable locking mechanism of the inserts appear to be still an important design feature, particularly when using inlay materials with extremely different mechanical properties such as those of ceramic and polyethylene (Fig. 1). In the following the integrity of the locking mechanism for a press fit cup with modular alumina ceramic and polyethylene inserts will be addressed.

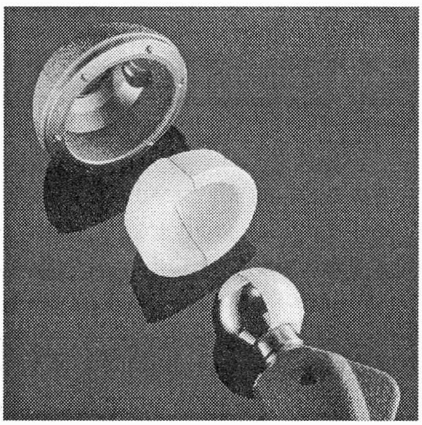

Fig. 1. Modular acetabulum cup for polyethylene and Al_2O_3–ceramic inlays. A tight locking mechanism of the insert is given by a taper lock design which has been adapted to the different material properties

3. Inlay testing

Apart from tribological wear tests, which are adequately described in the literature for the Al_2O_3–Al_2O_3–ceramic wear couple and have been confirmed by many years of clinical experience [4, 5, 6, 8, 12], the ceramic inlays in combination with the new press fit cup design were subjected to various static and dynamic fracture tests. In all cases, the minimum values found – static fracture load: $\geq$ 46 kN and fatigue stress: maximum load 20 kN over 10×106 cycles – were exceeded. These minimum values which were also applicable to ceramic spherical heads can be regarded, on the basis of clinical experience to date with failure rates below 0.02%, as adequate and as ensuring a high level of safety. Dynamic load tests with the polyethylene inlay also showed no failure mechanisms within the minimum values applicable to ceramic inlays. The high interfacial friction of the taper lock reliably prevents even very small relative movements at the inlay–metal cup interface, so that wear and fretting cannot be observed.

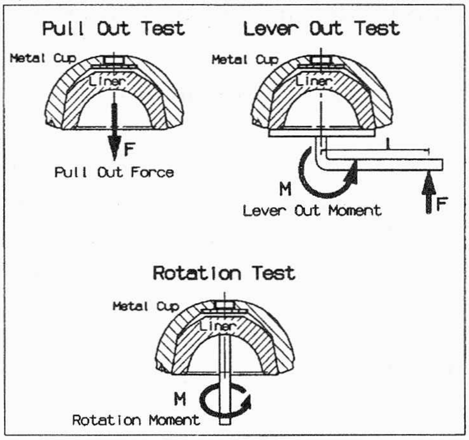

Fig. 2. Inlay test methods. Cup size: 48/50 mm; inner diameter – 28 mm, *F* – applied load, *M* – applied moment

The design-specific match between inlay and metal cup is just as important for secure inlay fixation as for the static and dynamic limiting load capacity of the inlay. While axial press out or pull out tests are a good guide to the efficiency of this connection, additional tests which better simulate the real load situation, for example the lever out test and rotation test, are required for a critical analysis (Fig. 2). For a comparative assessment of the inlay fixation, the new ceramic and polyethylene inlays with taper lock were compared with a clinically tested system with a snap lock mechanism. The tests were carried out on the one hand under dry conditions and on the other hand in the Ringer solution at 37 °C to simulate the effect of body fluid on a MTS Mini Bionix testing machine.

4. Results

4.1. Pull out test

Compared with the pull out strength of the clinically tested press fit cup snap lock connection, the pull out loads of the taper lock are substantially lower both for the ceramic inlay and for the polyethylene inlay under dry conditions, but increase to substantially higher values under the influence of fluid and heat (37 °C). If the minimum force of 129 N and maximum force of more than 1000 N determined by Tradonsky [7, 9] for various modular cups are used for comparison, the taper lock with an average pull out strength of 400 N has good fixation stability. When revisions are necessary, however, the ceramic inlay can be easily released from the taper lock by the application of short force pulses. As the *in vivo* loading of the systems is complex, the results do not imply the clinical safety of any interlocking mechanism, but rather provide a basis for comparison with clinically proven designs.

4.2. Lever out test

In contrast to the results in the pull out test, the torques required for levering out the inlay indicate a substantial superiority of the taper lock over snap lock mechanisms used to date (Fig. 3). For the ceramic inlays, the test runs were terminated at a torque of 150 Nm since failure of the taper lock would have been achievable only

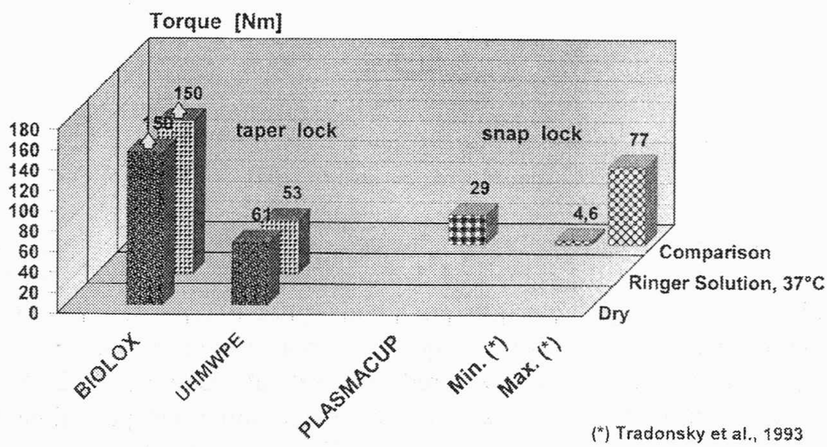

Fig. 3. Results of the lever out test. The taper lock proves to be very secure in the lever out test owing to the large inlay contact surface achieved. For the ceramic inlays, the tests were terminated at a torque of about 150 N since dislocation prior to destruction of the material was not expected

through plastic deformation of the metal cup or destruction of the Al_2O_3 ceramic inlay. For the polyethylene inlays, material deformation and hence failure of the taper lock occurred at torques between 50 and 100 Nm, which however was several factors higher compared with the results for inlay connections used to date. This is essentially due to the maximum congruence achieved in the taper lock with optimal force transmission between inlay and cup.

4.3. Rotation test

Testing of the inlay rotational stability was carried out under various load conditions, with stability in this case being considered directly after insertion of the inlay (unloaded) and under an axial articular load of 3 kN. For the ceramic inlays, the test-related maximum rotational torque of 35 Nm was reached in virtually all cases without prior failure. Only under dry test conditions and in the absence of an articular force did rotational failure occur at 28.5 Nm. Measured against the resulting frictional torques, these extremely high rotational torques give a safety factor for the ceramic inlay of more than 7 assuming dry friction and of more than 70 in the case of fluid friction. On the other hand, the fixation stability to rotational torques was found to be lower for the polyethylene inlays. The rotational torques measured under an articular load of 3 kN reached values of 10 Nm under dry test conditions and 7.5 Nm under the influence of fluid. Assuming mixed friction in the artificial joint, an antirotation safety factor of between 2 and 10 is thus reached for the polyethylene inlay. Compared with all other loads, the polyethylene inlay with taper lock is therefore the most sensitive to rotation about the inlay axis.

5. Discussion

On the basis of the taper lock mechanism, which is advantageous for a ceramic inlay, a polyethylene inlay was developed for the investigated modular press fit cup system. Compared with the snap-lock mechanisms in standard use today, this polyethylene inlay has at least the same level of safety with regard to the prevention of dislocation and relative movements. The results of pull out, lever out and rotational tests show the high short term inlay locking capacity of the new modular press fit cup system, whose taper lock mechanism is strongly attributed to the specific design and material parameters. Unfortunately it is not completely understood how much force a cup liner assembly should be able to withstand *in vivo,* but in comparison to clinically proven systems the test results provide a good measure of system integrity.

The modular press fit cup system therefore provides an acetabular replacement which combines the excellent tribological properties of alumina ceramic with a microporous pure titanium coating which is optimal with regard to osseous integration. The extent to which the substantially higher stiffness of the ceramic inlay influences the osseous reaction at the implant–bone interface can, in the end only, be determined by comparative clinical studies. However, biomechanical analyses indicate that the force induction into the osseous structures of the acetabulum are unlikely to differ from that in the case of polyethylene under normal loads. Measurements of the damping characteristic of the acetabular replacement showed that, regardless of the inlay used, the energy absorption in the implant system is negligibly small, so that there are no differences in this respect between the ceramic and polyethylene inlays and the metal-backed polyethylene inlay has no significant shock-absorbing property.

Rather, what is decisive is the total stiffness of the force transmission chain, which is assumed to be low in comparison with the stiffness of the implant materials used and therefore dominates the damping behaviour and the shock absorption (Fig. 4).

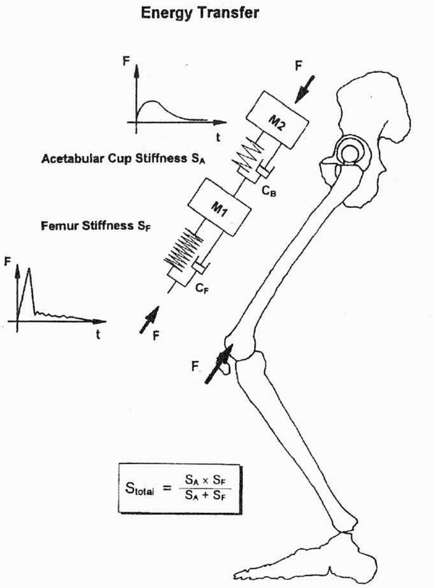

Fig. 4. Schematic diagram showing the total stiffness. In simplified form, the total stiffness may be regarded as a series of connected springs. This results in an extremely small effect of the implant stiffness – regardless of whether a ceramic or polyethylene inlay is used. The stiffness characteristics of the total force transmission zone is dominated by the lowest individual stiffness, in the present example by the stiffness of the femur

Very generally, with the given low stiffness of the force transmitting tissue structures, there is only a slight effect of the comparatively high implant stiffnesses, even when the stiffnesses of the ceramic and polyethylene inlays differ by a factor of 50.

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