Surface roughness of debonded straight-tapered stems in cemented THA reduces subsidence but not cement damage

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Abstract

Although stress analyses have shown that the mechanical endurance of cemented femoral THA reconstructions is served by stems that firmly bond to their cement mantles, retrieval studies suggest that this may be difficult to achieve. Clinical studies with roentgen stereophotogrammetric analyses have shown that stems may gradually debond from their cement mantle. Accepting the fact that stem debonding is unavoidable, stem subsidence and cement stresses can be reduced by increasing stem–cement friction, as indicated by finite element stress analyses. Hence, it can be hypothesized that debonded stems with high surface roughness values would damage the cement mantle to a lesser extent as compared to polished ones. To confirm this hypothesis, tapered stems with polished and rough surface finishes were implanted in cement mantles and cyclically loaded for 1.7 million times. It was investigated how surface roughness affected the damage in the cement mantle, and how it was related to prosthetic subsidence.

The polished taper subsided considerably more than the rough one (630 vs. 270 μm at the end of the experiments). In addition, it was found that the polished taper displayed step-wise subsidence, which is probably due to the interaction of stick–slip processes at the interface, associated with creep of the acrylic cement. The rough taper subsided monotonously. Scanning Electron Microscopic (SEM) analysis of the taper–cement structures showed that the rough taper was completely debonded from the cement mantle, creating a gap at the interface, and that many large cement cracks and particles were created. Around the polished taper, only a few cracks were found and the taper–cement interface seemed undamaged.

It was concluded that an increased surface roughness does not necessarily lead to a reduction in cement damage. On the contrary, compared to polished ones, debonded rough stems may produce more cement cracks and acrylic cement debris, and provide routes to transport these wear products. Hence, after failure of the stem–cement interface, straight–tapered stems with an increased surface roughness accelerate the failure process due to inferior fail-safe features. Consequently, in vivo subsidence patterns at the stem–cement interface should be considered in combination with the surface finish of the implant. An amount of post-operative subsidence of a rough stem may be much more damaging for the reconstruction than the same amount for a polished stem.

1. Introduction

Although the end-stage of failed cemented femoral Total Hip Arthroplasty (THA) manifests itself predominantly at the cement–bone interface, the failure process may be initiated elsewhere in the structure and can develop along a variety of failure scenarios [1]. The two most important failure scenarios concerning cemented femoral THA involve accumulated damage and particulate reactions. The former one relates to gradual accumulation of mechanical damage in the materials and at the interfaces until they fail. The implant becomes mechanically loose, produces micro-motions at the cement–bone interface, which leads to bone resorption and soft tissue interposition and ultimately to gross loosening. The second failure scenario is based on the biological response at the cement–bone interface to wear particles. These particles may be generated at the articulating surfaces (polyethylene), at the stem–cement interface (metal or acrylic bone cement), or may be produced by cement failure. When these particles reach the endosteal bone, they initiate an inflammatory response resulting in local bone resorption, and gradually debond the cement–bone interface.

This study concentrates on the damage accumulation failure scenario. Laboratory experiments [2] and finite element analysis (FEA) studies [3–6] have demonstrated

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that this failure scenario is promoted by stem–cement debonding, due to elevated stresses in the cement mantle. One way to avoid these stress elevations is to prevent stem debonding. However, whether a permanent stem–cement bond can be obtained remains questionable, and debonding seems a rule rather than an exception [7–9]. The alternative to this concept is to accept that stem–cement debonding does occur, and minimize its effect. Recent finite element analyses indicate that this can be accomplished by increasing stem–cement interface friction [6, 10]. Increased stem–cement friction limits the effects of stem debonding by reducing the cement stresses and stem subsidence, and therefore represses the damage accumulation failure scenario. Clinical studies have confirmed that high amounts of gradual stem subsidence is correlated with high probabilities of revisions [11]. Hence, it can be hypothesized that debonded stems with high surface roughnesses would damage the cement mantle to a lesser extent as compared to polished ones. The purpose of this study was to test this hypothesis. Laboratory experiments were performed with tapered stems with polished and rough surface finishes which were implanted in cement mantles and dynamically loaded. It was investigated how surface roughness affected the damage in the cement mantle, and how it was related to prosthetic subsidence.

2. Methods

Using a brass metal mould, two tapers with circular cross sections were implanted in a cement mantle (Fig. 1). The only difference between the two tapers was the roughness of the surface. Average $R_s$ values, measured with a Mytutoyo Texture Surftest 201 (Veenendaal, Netherlands), were 0.033 (S.D. = 0.0025) and 9.96 (S.D. = 0.70) $\mu$m for the highly polished and rough taper, respectively. The proximal part of the taper was fixed to the actuator of the testing machine, which ensured axial–central placement of the taper in the cement mass. Taper and mould were designed in such a way, that a uniform cement thickness of 10 mm was obtained. The taper had a top angle of 8° and a length of 125 mm. The cement mantle was 80 mm in height. After polymerization, the cement mantle with the taper could easily be extracted from the mould and was stored in saline solution for more than 1 month at a temperature of 37°C. To be able to determine the effect of the cyclic fatigue load on the strain levels in the cement mantle, six uni-directional strain gauges were attached to the surface of the cement mantle to measure the hoop strains. Drift in the gauges during the experiments, two additional (dummy) gauges were attached to a small unloaded piece of acrylic cement. The strain gauges were sealed with a layer of silicon rubber and the structure was placed in a 38°C bath of saline solution. The cyclic micro-motion and the subsidence of the tapers with respect to the top level of the cement mantle were measured using an extensometer with a resolution of 0.5 $\mu$m (Fig. 1).

The tapers were exposed to a compressive sinusoidal load ranging from zero to 7 kN at a frequency of 1 Hz. This load enforced immediate failure of the taper–cement interface. The tests were terminated deliberately after 1.7 million loading cycles. The structures were cross-sectioned at four locations along the axis (Fig. 1), using a water-cooled ceramic saw, and prepared for Scanning Electron Microscopic (SEM) analysis. The sections were analyzed with respect to cement damage and interfacial width, relative to unloaded controls.

3. Results

The roughness of the surfaces not only affected the amount of subsidence, but also the subsidence patterns of the tapers within the cement mantles. A schematic representation of the subsidence patterns is shown in Fig. 2. The rough taper subsided gradually in the cement mantle, whereas the polished one displayed step-wise subsidence patterns. The total subsidence after 1.7 million loading cycles was about 630 and 270 $\mu$m for the polished and rough tapers, respectively (Fig. 3).

Despite the different surface roughnesses of the two tapers, the cyclic subsidence amplitudes were very similar.
Cyclic hoop strain amplitudes increased from proximal to distal, and were larger around the rough taper. The hoop strain amplitudes around the polished taper changed considerably during the testing period (Fig. 6). The step-wise subsidence of the polished taper had considerable effects on the dynamic strains, resulting in a wave-like pattern of the cyclic hoop strain amplitudes. After the polished taper had slipped suddenly, the cyclic hoop strain amplitudes were reduced. Afterwards, the amplitudes increased until the taper slipped again. The wave-like pattern in these cyclic strain patterns could not be derived from the cyclic subsidence amplitude pattern (Fig. 4). The cyclic hoop strain patterns generated around the rough taper showed a much more gradual pattern in time. Initially, these cyclic hoop strains increased with time, particularly in the tip and middle region. This could be caused by higher cyclic motions of the taper relative to the cement mantle in these regions. After about 250,000 loading cycles, the cyclic strain amplitudes decreased again, indicating that the relative motions decreased again. These changes in cyclic motions were not detectable in the pattern of the cyclic subsidence amplitude of the rough taper (Fig. 4).

SEM analysis of the cross sections revealed considerable differences between the polished and rough taper with respect to debris formation, interfacial width, and number of cracks in the cement mantle (Fig. 7). In the unloaded control sections, the interface around the polished stem could be identified as a line without irregularities (Fig. 7a). Around the rough stem, however, the cement and metal had not fused completely, leaving gaps of up to about 10 μm (Fig. 7b). Around both unloaded control tapers, a small number of radially oriented cracks in the cement mantle were found. Almost all of them originated at the outer surface of the mantle. These cracks are probably caused by stresses generated in the shrinkage phase shortly after curing of the cement.
In the loaded specimen with the polished taper, the interface morphology had not changed, acrylic cement debris was absent, and only a few additional cement cracks had been generated as compared to the unloading control specimen. These additional cracks were generally associated with pores or contaminants present in the cement mantle (Fig. 7c). Around the loaded rough taper, a considerable amount of acrylic debris was generated, an interfacial gap had been created, and numerous cracks in the cement mantle had been formed (Fig. 7d and e). On both the polished and rough surface patches of thin bone cement films were present, indicating that metal–cement as well as cement–cement friction was generated at the interface. At each of the four sections of the rough taper, the interface was completely debonded, leaving a gap of about 10–20 μm between the taper and the cement. Cement particles were captured in these gaps at the taper–cement interface, particularly in the tip region. At the debonded interface, numerous cracks were found initiated around the asperities of the surface roughness profile and generally oriented in radial direction. The orientation of these cracks can be explained by the fact that the unbonded tapers generate relatively high hoop stresses in the circumferential direction when the tapers subside in the cement mantle, thereby creating cracks perpendicular to the circumferential direction.

4. Discussion

This study was performed to determine the long-term effects of prosthetic surface roughness on the failure process of cement THA reconstructions after stem–cement
debonding. Although the differences in mechanical behavior between the two tapers were extensive, it should be noted that only two tapers were considered. It should also be appreciated, that the laboratory model used represented a simplification of reality. Only a straight tapered stem with no geometrical inhibition against subsidence was used and the stems were forced into the cement mantle by relatively high forces to accelerate the failure.

Fig. 7. SEM micrographs of the sections; the markers represent 10 µm. (a) The interface in the control specimen of the polished taper could be identified as a line. (b) The interface in the control specimen of the rough taper had not fused completely, leaving gaps of up to about 10 µm. (c) In the loaded specimen with the polished taper, a crack has been generated, associated with a big pore in the cement. (d) In the loaded specimen with the rough taper, a gap at the interface was formed and radial cracks were generated. (e) In the loaded specimen with the rough taper, acrylic cement particles were captured between the taper and the cement mantle.
process. In addition, only an axial load with no bending component was applied and no bone around the cement mantle was represented. The cement mantle was tested after one month of polymerization. It is known that bone cement creeps quicker shortly after polymerizing [22]. In that respect the viscoelastic behavior contributing to prosthetic subsidence is underestimated in the present study. The load was applied in a continuous manner, whereas normally patients will have alternating periods of activity and rest. During these rest periods the stresses are allowed to relax to some extent, and facilitate subsidence after which loading is initiated again. As a consequence of these assumptions and limitations of the model, this study only provides information about the trends, rather than the precise effects of prosthetic surface roughness on the failure process of cemented reconstructions.

It was shown that a polished taper can subside substantially within a cement mantle without causing significant damage to the cement material. It appeared that the subsidence occurred step-wise rather than in a continuous fashion. The SEM analysis of the slices of the structure with the polished taper showed that the number of cement cracks was very small. Hence, it is unlikely that the subsidence of the polished taper was caused by cement failure. A more probable explanation for this phenomenon is the occurrence of creep of the acrylic cement. Earlier studies have indicated that cement creeps [12–13]. Creep of the cement mantle, which is a time-dependent phenomenon, would facilitate the subsidence of the taper with time without generating cement fractures. The step-wise pattern of the subsidence is probably caused by stick–slip processes at the interface, interacting with the creep process of the cement mantle.

The subsidence of the rough taper was less as compared to that of the polished one. One could speculate that the subsidence of the rough stem was prohibited by the asperities of the roughness profile or by debris products captured at the taper–cement interface. Unlike the polished taper, which did not have these irregularities, the rough taper could subside only after local destruction of the cement mantle. Therefore, the rough stem seemed to subside by rasping its way through the cement mantle. It should be kept in mind that the rough taper had a roughness value of almost 11 μm, which is relatively rough as compared to commonly used prosthetic components with a mat surface finish which have a surface roughness in the order of 1–2 μm. Hence, the differences between commercially polished and mat stems may be considerably less than those between the tapers studied here. However, in their multi-center study, Malchau et al. [14] showed that polished Exeter stems had significantly higher survival rates as compared to stems with the same shape, but with a mat surface finish. This indicates that the mechanisms found in this study may play a dominant role in the failure process of cemented THA reconstructions, even when the surface roughness is much less than applied in this study.

Cyclic hoop strain amplitudes in the cement were consistently higher around the rough stem. This does not necessarily indicate that the strains in the cement mantle around the rough stem were higher, because only the amplitudes were measured in the experiments, without consideration of the absolute strain levels. However, it does suggest, contrarily to what one would expect, that the rough taper shows a higher cyclic slip in the cement mantle. Two mechanisms for this phenomenon, which probably interact, are suggested. First of all, the damaged cement mantle becomes less stiff and therefore stretches more when an external load is applied. Secondly, the particles at the interface may serve as roller bearings, resulting in a decrease of frictional forces at the interface and an increase in local cyclic motion.

The study showed that a higher prosthetic surface roughness does not reduce the damage generated in the cement mantle. There was no indication that the rougher surface raised the friction and reduced cement stresses. In fact, the hypothesis stating that debonded stems with high surface roughness values would damage the cement mantle to a lesser extent as compared to polished ones, as posed in the introduction, was contradicted. This seems to oppose result as produced by FEA studies [3–6]. However, FEA studies generally simulate variation of friction without changing the surface roughness. If higher friction is generated without changing the surface roughness by, for example, using varying material combinations, the results of the FEA studies would be applicable. However, if friction is increased by increasing the surface roughness the effects of increased friction are overruled by those of the surface roughness itself as shown in this study and global FEA models are less useful to analyze the localized effects around the asperities of the surface profile. In that case, a local FEA model such as presented by Verdonschot et al. [23] (1998) would be more appropriate.

Compared to polished ones, debonded rough stems may produce more acrylic cement debris, and provide routes to transport these wear products [9]. In addition, the wear products captured at the stem–cement interface, and the asperities of the roughness profile, may serve as stress risers from which cement cracks originate. Hence, after debonding of the stem–cement interface, the particulate debris and the damage accumulation failure scenarios are both promoted by an increased stem roughness.

Recently, Roentgen Stereophotogrammetric analysis (RSA) has been introduced to monitor the in vivo motion patterns of implants [11, 15]. These studies indicate that a higher amount of gradual stem subsidence is correlated with high probabilities of revision. To enable interpretation of these migration values a separation should be made between stem–cement and cement–bone migration because different failure mechanisms play a role at these
different interfaces. This study only concerned the mechanics of the stem–cement interface and it illustrates that stem–cement subsidence patterns should be considered in combination with the surface finish of the implant. An amount of post-operative subsidence of a rough stem may be much more damaging for the reconstruction than the same amount for a polished stem.

A considerable amount of work has been performed to improve the interfacial bond between the stem and the cement mantle. Cementing techniques [16], surface roughness patches [17], textures [18], and pre-coatings [7, 19–21] have been considered to create a reliable and endurable fixation. However, as long as the bond between the stem and the cement mantle cannot be secured for the complete lifetime of the implant, not just the bonding strength, but also the fail–safe mechanism against the effects of debonding should be considered. Although the interface may be stronger with a rough surface, which postpones debonding, its fail–safe mechanism against the effects of debonding is inferior to that of a polished stem. In the end, this may accelerate its overall failure rate, particularly when a stem is straight tapered, with no geometrical inhibition against subsidence. Consequently, in vivo subsidence patterns at the stem–cement interface should be considered in combination with the surface finish of the implant. An amount of post-operative subsidence of a rough stem may be much more damaging for the reconstruction than the same amount for a polished stem.

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