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Fatigue failure in the cement mantle of a simplified acetabular replacement model

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Abstract

Although the role of fatigue failure in aseptic loosening of cemented total hip replacements has been extensively studied in femoral components, studies of fatigue failure in cement mantle of acetabular replacements have yet to be reported, despite that the long-term failure rate in the latter is about three times that of femoral components. Part of the reason may be that a complex pelvic bone structure does not land itself readily for a 2D representation as that of a femur.

In this work, a simple multilayer model has been developed to reproduce the stress distributions in the cement mantle of an acetabular replacement from a plane strain finite element pelvic bone model. The experimental multilayer model was subjected to cyclic loading up to peak hip contact force during normal walking. Radial fatigue cracks were observed in the vicinity of the maximum tangential and compressive stresses, as predicted by the FE models. Typical fatigue striations were also observed on the fracture surfaces post cyclic testing. The results were examined in the context of retrieval studies, 3D FE analysis and in vitro experimental results using full-sized hemi-pelvic bone models.

Keywords: Fatigue; Bone cement; Acetabular replacement; In vitro experiment

1. Introduction

Late failure of implants in the absence of infection, known as "aseptic loosening", has been identified as the most common cause for long-term instability leading to gross migration of the implants and failure of total hip replacements (THRs) [1,2]. Fig. 1 shows a schematic of a cemented THR, where the femoral head and acetabular cup are fixed with bone cement. The role of fatigue failure in aseptic loosening of cemented THRs has been studied extensively in femoral components [3–12]. Maloney et al. [3] observed cracks in retrieved cement mantles; Topoleski et al. [4] reported a fractographic study of ex vivo cement mantles and showed remarkable similarity in fracture surfaces between in vivo and in vitro specimens. Jasty et al. [5] observed fatigue striations in femora retrieved at post-mortem from otherwise satisfactory total hip arthroplasties. The significance of this latter work lies in the evidence of fatigue failure from symptom free patients at periods of between 2 weeks to 17 years post-operation, suggesting fatigue as one of the possible failure mechanisms that *initiates* the failure of the cement fixation. In addition to retrieval studies [3–6], in vitro fatigue testing of femoral implants has also been carried out [7–9]. An experimental model [7,8] was developed to represent a cemented femoral implantation with "windows" that permit monitoring of fatigue crack growth in situ. Multiple microcracks were observed with over 80% in the cement mantle. Radial cracks were observed in transverse cross-sections of implanted femora [9]. Finite element methods have also been used to simulate the fatigue damage accumulation in the cement mantle [10–12]. Stolk et al. [10] developed a finite element algorithm that simulated creep and fatigue damage accumulation in acrylic bone cement. Damage development in tubular cement specimens and cement

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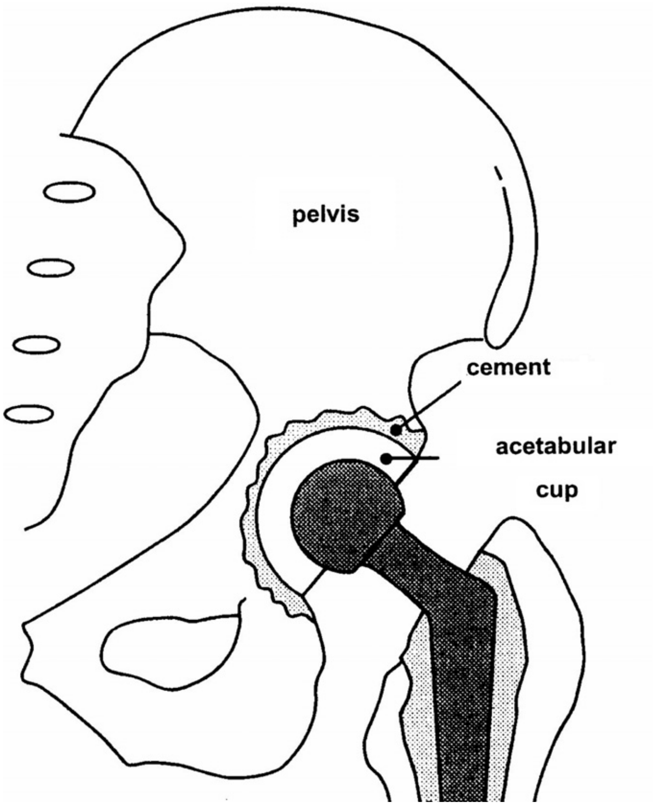

Fig. 1. A schematic of a cemented acetabular replacement in a total hip replacement [10].

mantles around femoral implants was successfully simulated. Although numerous experimental studies of microcracking in bulk cement provide essential information on the crack initiation and growth in cement specimens, the conclusions drawn from these experiments are often difficult to apply to the cement mantle in cemented joint replacements, as the stress state in a cement mantle is inevitably multiaxial and variable, could not be adequately represented by material testing of cement specimens. Consequently, in vitro fatigue experiments of cemented implants are preferred, as the loading conditions are closer to those in vivo.

Evidence from retrieval studies and in vitro experiments seems to support the hypothesis that cement mantles fail by fatigue. For femoral components, the accumulated damage failure scenario is thought to be one of the most prominent ones in cemented THRs [13]. Mechanical damage in the form of microcracks accumulates under cyclic loading conditions, cracks coalesce and form macrocracks, leading to disintegrition of the cement mantle and eventually to gross loosening of the implant. Although the late loosening rate of acetabular cups has been reported to be three times that of femoral components 20 years after operation [14], mechanistic studies of fatigue failure in the cement mantle of acetabular replacements have yet to be reported. Structurally, an acetabulum is more complex than a femur, in that the 3D structure of pelvic bone does not permit a ready 2D representation as that of a femur [15].

In this work, we present a simple multilayer model that would reproduce similar cement stress distributions as those in the cement mantle of an acetabular replacement from a plane strain FE pelvic bone model. Cyclic loading was applied to the experimental multilayer model where a dominant radial crack was grown, as predicted by the FE analysis. Crack morphologies were also examined using microscopy post fatigue testing. The results were discussed with regard to retrieval studies, in vitro experimental results, as well as 3D FE analyses.

2. Finite element studies

2.1. The pelvic bone finite element model

The plane strain finite element model of a natural hip joint was adapted from Rapperport et al. [16]. Generated from a roentgenogram of a 4 mm slice normal to the acetabulum through the pubic and ilium, the model was divided into 24 regions of different elastic constants with isotropic material properties assumed in each region. The main regions were cortical bone, subchondral bone, trabecular bone and cartilage. The trabecular bone region was further divided into smaller regions to account for the different densities of the bone in different areas within the region. A standard ultra high molecular weight polyethylene (UHWMPE) cup was secured with bone cement and the cup was in articulation with a spherical femoral head of Co–Cr alloy. The diameter of the replacement head was 28 mm while the thickness of the UHWMPE cup was 10 mm. The cement mantle was assumed to be uniform

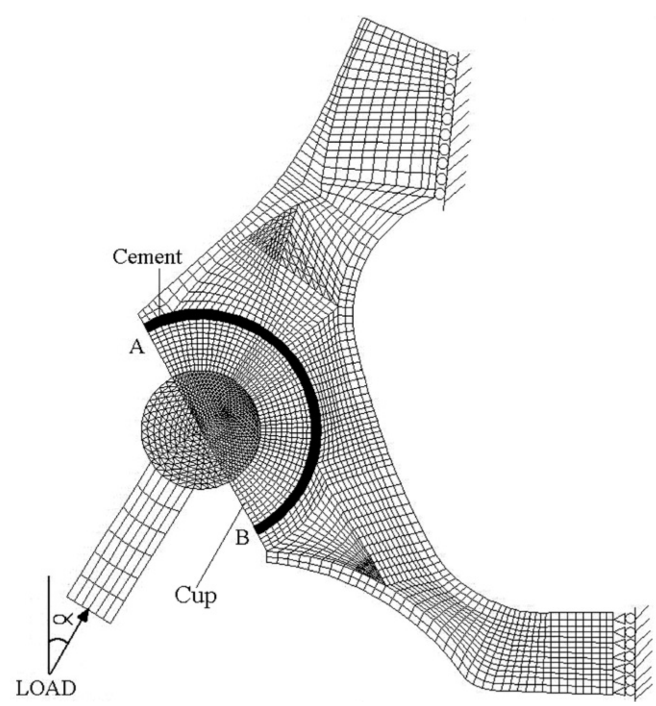

Fig. 2. The meshed plane strain pelvic bone model with a cemented acetabular implant.