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Research paper

Influence of geometry and materials on the axial and torsional strength of the head–neck taper junction in modular hip replacements: A finite element study

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ABSTRACT

The assembly force is important in establishing the mechanical environment at the head–neck taper junction of modular hip replacements. Previous experimental results of the assembled taper junctions with different material combinations (Co–28Cr–6Mo and Ti–6Al–4V) reported similar axial strengths (pull-off loads), but lower torsional strengths (twist-off moments) for the CoCr/CoCr junction. However, mechanics of the junction and the strength behaviour have not been understood yet. A three dimensional finite element model of an isolated femoral head–neck junction was developed to explore the assembly and disassembly procedures, particularly the axial and torsional strengths for different material combinations and geometries. Under the same assembly load, the contacting length between the CoCr head and titanium neck was greater than that of in CoCr/CoCr. The contact length in the titanium neck was more sensitive to the assembly force when compared to the CoCr neck. For instance, with increasing the assembly force from 1890 to 3700 N, the contact length increased by 88% for CoCr/Ti and 59% for CoCr/CoCr junctions. The torsional strength of the junction was related to the lateral deformation of the neck material due to the applied moment. The angular mismatch existing between the head and neck components was found to play the main role in the torsional strength of the junction. The smaller mismatch angle the higher torsional strength. It is suggested to consider reducing the mismatch angle, particularly in CoCr/CoCr junctions, and ensure a sufficiently high assembly force is applied by impaction for this combination.

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1. Introduction

Modularity at the head–neck junction of total hip replacement (THR) implants may result in fretting wear which occurs when two contacting metallic components are subjected to tangential oscillatory movements (Jauch et al., 2011). Given the presence of a corrosive medium all around the implant, shear stresses induced under fretting conditions may disrupt the passive layer of the metal (Mathew et al., 2009; Zhu et al., 2009); and thus, accelerate corrosion at the head–neck interface (Rodrigues et al., 2009; Hussenbocus et al., 2015). This combined failure mechanism, known as fretting-corrosion (Higgs et al., 2013; Swaminathan and Gilbert, 2012; Gill et al., 2012), contributes to a degradation process which reduces the integrity of the implant structure and releases metal particles that can adversely affect the surrounding tissues (Cobb and Schmalzreid, 2006; Cooper et al., 2012; Sansone et al., 2013; Doorn et al., 1998; Papageorgiou et al., 2007). Due to the taper design and manufacturing tolerances, there is always an angular mismatch between the head and neck components (Bisseling et al., 2013). Depending on the taper angle of each component, such an angular mismatch can cause the head–neck junction to have its main contact at the bottom or top of the trunnion, known as distal and proximal contacts, respectively. It is reported by previous research that fretting-corrosion damage is more severe in the distal contact designs (Hothi et al., 2014; Nassif et al., 2014). Furthermore, Goldberg et al. (2002) developed a multi-centre retrieval study to investigate the effect of different metallurgical and geometric parameters on the fretting and corrosion damage in the head–neck junction. This study revealed that although the corrosion damage was more severe in the distal contacts, the damage caused by fretting was almost equal for both distal and proximal mismatches.

The potential for fretting to occur is dependent on the strength of the head–neck junction achieved during the assembly process, as well as the complex loads applied during physical activities (Mroczkowski et al., 2006). The ability of the taper junction to resist torsional loads appears to be just as important as the ability to resist the axially applied forces (Farhoudi et al., 2015; Jauch et al., 2014).

Various parameters which contribute to the strength of the head–neck junction have been investigated in previous studies. Pennock et al. (2002) investigated the effect of varying the impaction force, repeated impactions, and fluid contamination on the disassembly strength of Morse-type tapers. A linear relationship was found between the impaction and uniaxial disassembly forces. Lieberman et al. (1994) analyzed the head–neck taper interface in forty-eight implants with three different designs of retrieved hip prostheses. Where the femoral head and stem were still connected together, pull-off loads were measured through a disassembling process. It was found that micro-motion is the main factor that contributes to the fretting and corrosion. They concluded that improvement of the design and tolerance of the head–neck junction can increase the strength and thus reduce the micro-motion which can then alleviate the fretting and corrosion. Jauch et al. (2011) investigated the influence of material combinations and assembly conditions on the magnitude of micro-motion at the head–neck interface for two combinations of CoCr head-Ti neck and CoCr head-CoCr neck. They found that using a titanium neck and contaminated interference (some of the neck adapters were contaminated by porcine bone chips) increases micro-motion between the head and neck which can result in increasing the risk of fretting and corrosion. Rehmer et al. (2012) experimentally investigated the effect of assembly force and material combination on the axial and torsional strength of the head–neck junction for three combinations of CoCr head-Ti neck, CoCr head-CoCr neck and ceramic head-Ti neck. The CoCr/CoCr combination was found to have a lower torsional strength than CoCr/Ti. However, the mechanical mechanism and reasons for this behaviour were not investigated.

Due to the conical geometry, frictional contact, and complicated nature of mechanical loadings, finite element (FE) modelling is a convenient and effective method to interrogate the mechanical environment of the head–neck junction. To date, there have only been a limited number of FE studies in this area. Zhang et al. (2013) developed a 2D axisymmetric model for the head–neck junction; however, the gait forces and moments are not axisymmetric. The FE model developed by Dyrkacz et al. (2015) ignored the existing mismatch angle between the head and neck components, although they reported that micro-motion was dependent on the head size, assembly force, taper size and materials combination. However, based on the previous research, mismatch angle plays an effective role in the mechanical behaviour of the junction; and hence, its inclusion in the model is necessary. Donaldson et al. (2014) performed a stochastic finite element simulation on the head–neck junction to predict the fretting work (frictional work which is done over cycles of gait) which was correlated with three parameters: angular mismatch, centre offset and body weight. For verification, an axial impaction load was applied at 45° off-axis to two sets of taper-trunnion pairs made of Al 6061 at a 3:1 size scale. Since the FE model included different materials (CoCr head and Ti neck) and dimensions in comparison with the verification experiments, the fretting prediction results may not be completely reliable.

In this study, a three dimensional FE model of an isolated femoral head–neck junction was developed to simulate the real geometry of the head and neck components with a nonlinear frictional contact and elastic–plastic properties of the mating materials. The main aim was to investigate the mechanics of the head–neck junction in order to understand which parameters contribute to the axial and torsional strength of the interface. The FE model was verified by experimental assembling and disassembling tests conducted by Rehmer et al. (2012). Two further combinations of CoCr head-Ti neck and CoCr head-CoCr neck were investigated in this study with the same geometries of the models that were used in Rehmer's tests (Rehmer et al., 2012), but with different mismatch angles.

2. Materials and methods

A three dimensional (3D) finite element model of an isolated head–neck junction was generated using ABAQUS 6.13 (Fig. 1). In order to verify the model, a set of experimental test results on assembling and disassembling of the head and neck components was replicated (Rehmer et al., 2012). A 12/14 taper was modelled and two material combinations were