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Does a micro-grooved trunnion stem surface finish improve fixation and reduce fretting wear at the taper junction of total hip replacements? A finite element evaluation

Ariyan Ashkanfar[1*], David J. Langton[2], Thomas J. Joyce[1]

[1] School of Mechanical and Systems Engineering, Newcastle University, Stephenson Building, Claremont Road, Newcastle Upon Tyne, NE1 7RU, UK.
[2] North Tees Explant Centre (NTEC), University Hospital of North Tees, North Tees, UK.

Abstract

The generation of particulate debris at the taper junction of total hip replacements (THRs), can cause failure of the artificial hip. The taper surfaces of femoral heads and trunnions of femoral stems are generally machined to a certain roughness to enhance fixation. However, the effect of the surface roughness of these surfaces on the fixation, wear and consequently clinical outcomes of the design is largely unknown. In this study, we asked whether a micro-grooved trunnion surface finish (1) improves the fixation and (2) reduces the wear rate at the taper junction of THRs. We used 3D finite element (FE) models of THRs to, firstly, investigate the effect of initial fixation of a Cobalt-Chromium femoral head with a smooth taper surface mated with a Titanium (1) micro-grooved and (2) smooth, trunnion surface finishes. Secondly, we used a computational FE wear model to compare the wear evolution between the models, which was then validated against wear measurements of the taper surface of explanted femoral heads. The fixation at the taper junction was found to be better for the smooth couplings. Over a 7 million load cycle analysis *in-silico*, the linear wear depth and the total material loss was around 3.2 and 1.4 times higher for the femoral heads mated with micro-grooved trunnions. It was therefore concluded that smooth taper and trunnion surfaces will provide better fixation at the taper junction and reduce the volumetric wear rates.

Keywords: wear modelling, finite element analysis, total hip replacement, taper junction, surface roughness.

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[*] Corresponding author. Tel: +44 759 198 0781. E-mail address: ariyan.ashkanfar@gmail.com (A. Ashkanfar).

1 Introduction

The use of separate components (modularity) in total hip replacements (THRs) is very common, allowing flexibility intra-operatively to facilitate optimum prosthetic functionality and anatomical fit for individual patients. In addition, modularity allows the use of different materials for different components – e.g. cobalt-chromium (CoCr) for femoral heads due to good wear properties, and titanium (Ti) for femoral stems in order to encourage bone ingrowth. On the femoral side of a THR, the modular connection involves a taper junction between the femoral stem (trunnion) and the internal taper of the femoral head (see Figure 1).

Despite the many advantages of femoral component modularity, it introduces another contact interface which may lead to wear particle generation. Recently, many reports have identified THR failure with taper junction wear (Brock et al., 2015; Crowninshield et al., 2004; Esposito et al., 2014; Kop et al., 2012; Langton et al., 2012; Langton et al., 2016; Langton et al., 2008; Lavigne et al., 2011; Panagiotidou et al., 2013; Smith et al., 2005). This is fretting wear and is a result of contact stress and relative micromotion at the taper-trunnion interface of THRs (Delaunay et al., 2010). Wear at the taper junction depends on a number of factors including: head size (Langton et al., 2012), taper junction angular mismatch (Ashkanfar et al., 2017), implant alignment (Donaldson et al., 2014), assembly impaction (English et al., 2016), taper offsets (Langton et al., 2012) and taper length (Brock et al., 2015) as well as surface finish which is the focus of this study.

The taper surfaces inside CoCr femoral heads are typically manufactured with a smooth surface finish with a Roughness Average (R_a) of around 0.4µm (Munir et al., 2015). In contrast, trunnion surface finishes of femoral stems generally fall into two groups. Some stems such as the SROM (DePuy) and Exeter (Zimmer) have smooth trunnion surfaces with approximately the same R_a value as the female taper but others such as Corail (DePuy) have micro-grooves machined on the trunnion surfaces with an R_a value of more than 2.5µm (Munir et al., 2015).

The claimed benefit of such micro-grooves is to improve the integrity of the connection between the trunnion and a femoral head taper and enhance the fixation of the two components (Munir et al., 2015). In this study, we used finite element (FE) models of commercial THRs with different trunnion surface finishes, while considering plasticity in the FE analyses to investigate whether these claimed benefits of micro-grooves are correct. We also used a validated FE based wear model to simulate the wear at the taper junction of THRs to investigate whether such micro-grooves help to reduce the wear rate at the taper junction or not. The FE wear results were compared with CMM (Co-ordinate Measuring Machine) wear measurement of retrieved femoral head tapers to validate the computational wear analysis.

2 Method

2.1 Finite element model

Two femoral stem FE models, one with machined micro-grooves and the other with a smooth trunnion surface finish, both coupled with a 36 mm diameter CoCr femoral head with a smooth taper surface finish, were modelled in ABAQUS (6.14-3 ABAQUS Inc) (see

Figure 2). A base-locked taper mismatch – where the taper and trunnion surfaces engaged at the base of the interface– of 3´ between taper and trunnion was selected (see

Figure 2) (Ashkanfar et al., 2017). The key difference between the models was the trunnion surface roughness as shown in

Figure 2.

Both models were meshed with highly refined mesh at the taper interface, using eight-node bilinear hexahedral reduced integration elements (C3D8R). The elements at the contact interface were carefully matched and this was followed by a mesh study. The procedure of the mesh study is comprehensively explained in a previous paper (English et al., 2015). The approximate element size at the interaction for both models, although it was not necessary for the smooth coupling, was reduced down to 0.012 mm in order to model the micro-grooves accurately.

During hip replacement surgery, the head is impacted onto the femoral stem of the THR. The magnitude of the initial impaction force applied intra-operatively affects both the contact pressure and micromotion at the taper junction and ultimately the extent of any subsequent fretting wear. In a previous study (English et al., 2016), we showed that the impact duration for a polymer tipped impactor with a metal head was 0.7ms and also that 4kN impaction force is required to provide fixation and minimise the wear rate at the taper junction (see Figure 3). As such, a 4 kN initial assembly force, known as a medium impaction force (English et al., 2016), was applied to fix the head onto the stem prior to the wear analyses.

The impaction analysis was executed as a dynamic implicit analysis (see (English et al., 2016) and Figure 3 for full details). Furthermore, in this study, the plasticity included in the FE impaction analysis and simulated as an FE Elastic-Perfectly Plastic analysis, was undertaken to investigate whether any plastic deformation of the micro-grooves would occur due to the initial assembly force.

The loads and rotations of a walking step were assigned on the models as shown in Figure 4 and described earlier in detail in (Ashkanfar et al., 2017). These loading and boundary conditions create an efficient and realistic walking simulation which was applied to a dynamic implicit analysis step discretised into 10 equal time intervals over a 1.2 s period.

The combination of a CoCr femoral head fitted on a Ti femoral stem is commonly used in THRs. The material and contact interaction properties of CoCr and Ti were assigned on the femoral head and femoral stem respectively as presented in Table 1. Finite sliding with the penalty contact formulation in ABAQUS solver was used to model the friction at the taper junction with a friction coefficient of 0.21 (Fessler and Fricker, 1989).

2.2 Wear model

The Dissipated Energy wear law was used and implemented into FE analysis. A fretting energy wear coefficient of 1.31×10^{-8} MPa^{-1} for the CoCr alloy on the Ti alloy was used in this law (Zhang et al., 2013). As explained in (English et al., 2015), the Energy wear law was applied to a wear algorithm as a user plug-in for ABAQUS. The implementation and the method are comprehensively explained in a previous technical study (English et al., 2015). In the current study, this validated algorithm was further developed and used to compare the wear rates and wear pattern damage at the taper junction of THRs with either micro-grooves or a smooth trunnion surface finish. The volumetric wear rates and total volume loss were determined by a separate custom Python script based on the reduction of element volume at the interaction.

Due to the highly refined mesh assigned on the models in this study, the wear scaling factor – which represents a specific number of loading cycles to scale up the calculated single cyclic wear depth – was obtained to be 100,000 (see (English et al., 2015)). One million walking cycles per year patients' activity has been assumed in this study (Schmalzried et al., 1998).

In the computational wear model, a fraction of calculated wear depth at each analysis stage needs to be removed from the taper and trunnion surfaces (Ashkanfar et al., 2017). This “wear fraction” (English et al., 2015), depends on the specific materials being considered. The wear fraction for a CoCr femoral head and Ti trunnion material combination is mainly based on the theory of Ti hardening in-vivo (Moharrami et al., 2013). Put simply, at first, the Ti trunnion is worn by the harder CoCr head. However, over time an increasingly thick Ti oxide layer builds up. Once it reaches around 150 microns in depth, it has sufficient hardness at sufficient depth to begin to wear the CoCr alloy. This change in hardness, and thus wear, has been modelled computationally by varying the wear fraction during the wearing analysis as shown in Figure 5. While the concept of an apparently softer material wearing a harder material may seem counterintuitive, under fretting conditions (as would be the case in a taper-trunnion junction) such an effect has been seen in multiple tribological studies (Elleuch and Fouvry, 2005; Kayaba and Iwabuchi, 1981; Lemm et al., 2015; Varenberg et al., 2002). In such cases the differential wear has been attributed to “the formation of oxide debris which then became trapped in the contact area and embedded in the softer surface; the hard, embedded particles then abraded the harder” material (Lemm et al., 2015).

Due to the highly refined mesh at the interaction, the time taken for each wear analysis over 7 million walking cycles is around 1450 hours, executed on a 12-core Intel Xeon CPU at 2.6 GHz with 128 GB of RAM.

3 Results

3.1 Initial impaction analysis and the effect of plasticity

During the impaction analysis, 4kN impaction load with the load time history as shown in Figure 3 was applied on the top of the femoral head. The overall aim of machining grooves onto the stem trunnion stem is said to be that the grooves enhance the fixation at the taper junction (Munir et al., 2015). However, in this study, the result showed no Equivalent Plastic Strain (PEEQ, ABAQUS field output) as illustrated in Figure 3. Figure 6 details the contact pressure distributions along the trunnion surfaces. As expected, the maximum contact pressure was localised at the distal edge of the models due to the base-locked taper mismatches. The maximum contact pressures were approximately 196 and 385 MPa for smooth and micro-grooved trunnion surfaces respectively. These stresses illustrate that no plastic deformation could possibly occur based on the initial impaction assembly load for CoCr/Ti material combination.

3.2 Wear damage

The evaluation of the wear damage over a 7 million load cycle period is shown in Figure 7, comparing the smooth femoral head taper surface coupled with micro-grooved (Figure 7a) and smooth (Figure 7b) trunnions. As expected the wear depth evolves for both cases as the wear analysis progresses.

Accelerated increases in the wear depth can be seen for the femoral head taper which was coupled with a micro-grooved trunnion after 5 million load cycles where the relative micromotion at the interface starts increasing rapidly. This increase in the micromotion continues until the femoral head starts rotating on the femoral stem with a much larger scale than fretting relative micromotion at 6.8 million load cycles. The maximum wear depth increases from a value around 8.57 µm at 5 million load cycles to 21.44µm at 7 million load cycles (see Figure 7a). It should be noted that, as the sophisticated FEA model focussed on wear at the micro grooves with a resolution of 0.012 mm, so when the entire taper (approximately 10mm long) is shown as an image, as in Figure 7, areas of red (maximum wear depth) become difficult to discern on this macro scale. For the femoral head coupled with a smooth trunnion (Figure 7b), however, the wear depth increases at the distal edge of the contact interface to approximately 6.51 µm at 7 million load cycles. The wear damage at the interface is distributed more uniformly and circumferentially at the femoral head taper (see Figure 7b). This lower wear depth, compared with the femoral head coupled with micro-grooved trunnion stem, is mainly due to having more area in contact and subsequently a larger interface. The larger interface allows better fixation which could maintain the relatively small amounts of micromotion for a larger number of load cycles.

The volumetric wear rate over 7 million load cycles and the total volume loss are compared for both cases and are shown in Figure 8. For the head coupled with a micro-grooved stem trunnion, the volumetric wear rate is relatively constant over 4 million load cycles (approximately 0.08 mm^3/yr) and then rapidly increases to 0.12, 0.24 and 0.36 mm^3/yr over years 5, 6 and 7 respectively. This increase in the volumetric wear rate is due to the effect of loss of fixation which leads to a rapid increase in the relative micromotion and thus the material loss. The total volume loss is around 1.03 mm^3 over 7 million load cycles. It can be seen in Figure 8 that the initial wear rates for the head coupled with a smooth trunnion surface are slightly higher than the head coupled with a micro-grooved trunnion surface (0.19 mm^3/yr) as a smooth taper-trunnion coupling provides a greater surface contact area. Although these initial wear rates are higher, the fixation is better maintained over time at the taper junction. As the micromotion is maintained at its lower extent over a longer period of time the contact stress at the interface reduces slightly and this causes a reduction in the wear rates gradually over time (to around 0.04 mm^3/yr at 7 million load cycle). The total volume loss over 7 million load cycle is 0.76 mm^3.

3.3 Comparison of computational wear analysis with measurement of retrieved femoral tapers

Eight retrieved CoCr femoral heads (Articuleze), all 36mm in diameter with 12-14 smooth female taper surface finish and +5 head offset, and which had been mated with Corail Ti micro-grooved femoral stem trunnions, were available for inspection. The couplings produced on average 1.57′ taper mismatch at the taper junction (range 0.36′ to 3.47′). All eight prostheses were revised due to adverse reactions to metal debris. Samples had been *in-vivo* for 5.4 years on average (range 2.2 to 7.1 years).

A CMM (Legex 322, Mitutoyo) was used to measure the wear depth and volumetric material loss at these taper surfaces. A customised programme written in the CMM software, Mitutoyo ‘MCOSMOS’, was used to measure the surfaces and another customised Matlab program (The Mathworks, Inc.) was used to plot the wear patterns and calculate the volumetric wear. This method of taper measurement has been previously validated and published (Bone et al., 2015; Langton et al., 2012) and further explained in (Ashkanfar et al., 2017).

Figure 9 compares the computational FE wear pattern damage obtained in this study with CMM measurements of wear damage at the retrieved femoral taper surfaces. The FE wear model could be analysed at specific points (i.e. 2.5 million cycles) to allow a direct comparison with a specific hip implant’s time in vivo (i.e. 2.5 years). It can be seen in Figure 9 that the wear depths obtained computationally compare favourably with the CMM measurements for explants retrieved at 2.5, 5.8 and 7.0 years. Once again, note that due to the fine mesh size (0.012mm) of the FEA model, and the localised material removal from microgrooves, once the image is scaled up to show an entire taper, so areas of red (maximum wear depth) become difficult to discern on the FEA image. The average volumetric wear rate for the hip explants obtained from the CMM was 0.28 mm^3/yr, (range 0.04 to 1.67 mm^3/yr), while that from the FEA model was 0.26 mm^3/million cycles (figure 8). The close similarities shown between the numerical analysis and measured wear damage of retrieved prostheses demonstrates the effectiveness of the 3D FE wear model, the chosen loading and boundary conditions, and the wear algorithm; therefore, the computational analysis is validated.

4 Discussion

We have shown that the taper and trunnion surface finish influence the fixation and the amount of material lost at the taper junction of THRs. Kop et al. (2012) claimed that hip implants with micro-grooved trunnions showed higher fretting at the taper junction. Panagiotidou et al. (2013) observed severe damage at taper surfaces when mated with micro-grooved stem trunnions. Brock et al. (2015) showed a significantly higher wear rate where femoral heads were mated with rougher trunnions. Hothi et al. (2016) observed clear imprinting and severe damage of the grooves of the stem trunnion on many smooth CoCr femoral head taper surfaces.

The FE wear model and results presented in this study have identified a clear difference in the fixation, volumetric wear rates and surface wear damage between CoCr smooth femoral head tapers implanted with Ti stems with smooth or micro-grooved trunnion surface finishes. In this study, the wear patterns on both couplings identified much more severe damage at the inferomedial aspect of the interfaces. As such, the fundamental wear mechanism for both surface finishes are the same; however, it has been accelerated for the femoral head taper when mated with a micro-grooved stem trunnion. A comparison between the results over 7 million load cycles *in-silico*, showed that there is around 3.2 times higher linear wear depth and around 1.4 times higher total volume loss from the femoral head taper surface when mated with a rough micro-grooved trunnion stem. As the trend of the wear rates illustrates in Figure 8, these differences would be more pronounced over periods beyond 7 million load cycles.

As discussed, due to the Ti hardening *in-vivo*, which increases its hardness over the CoCr alloy, the CoCr alloy wears significantly more (Moharrami et al., 2013). In this study, the algorithm is able to consider the hardening of the Ti during the wearing analysis. As such, the harder micro-grooved trunnion stem imprints into the femoral surface as shown in Figure 7. Although this hardening happens for the smooth Ti trunnion stem as well, the surface damage is less extensive (see Figure 7).

Design variations such as taper-trunnion angular mismatches (Ashkanfar et al., 2017) and surface roughness (as explained in this study) as well as surgical variations such as the initial assembly load (English et al., 2016) can all have important effects on wear particle generation and thus on the longevity and clinical outcomes of THRs. In a previous study, we showed that at least 4kN initial impaction assembly is required to fix the components properly and minimise the wear rates at the taper junction (English et al., 2016). We also showed that a taper mismatch of less than 6′ reduces the wear rates significantly (Ashkanfar et al., 2017). A 3′ taper mismatch used in this study was considered to be close enough to the 1.57’ average mismatch (range 0.36′ to 3.47′) of the retrievals which is based on our previous work (Ashkanfar et al., 2017). In this study, we used these parameters (4kN assembly force and 3′ taper mismatch) to investigate the effect of the trunnion surface finish on the taper wear rate. It was shown that surface roughness does affect wear generation in THRs. The rougher trunnion surface finish showed higher wear rates at the taper junction. This effect would likely be more significant if lower initial impaction forces were applied and/or a larger taper mismatch existed at the taper junction.

From our earlier study (Ashkanfar et al., 2017) and this study we conclude that increasing angular taper mismatch and surface roughness could both increase the relative micromotion at the taper junction. Through fretting wear, this increase in the relative micromotion leads to an increase in the wear rates. These high wear rates, then, could potentially lead to failure of the hip, as has been reported in several studies (Brock et al., 2015; Crowninshield et al., 2004; Esposito et al., 2014; Langton et al., 2012; Langton et al., 2016; Panagiotidou et al., 2013).

A limitation in this study was that we did not have access to any retrieved CoCr femoral heads mated with a smooth Ti femoral stem trunnion with the same design topography and morphology as presented in this study, so as to directly compare with our computational wear model. However, as indicated by other studies (Brock et al., 2015; Kop et al., 2012; Panagiotidou et al., 2013), wear of tapers fitted on such stems is likely to be lower than when used with rougher stems, the same result as indicated by our computer model. Another limitation to this study is related to the use of a fixed friction coefficient during the wear analysis. We accept that a variation in the friction coefficient could have an effect on the results. However, the aim of our study was to investigate the influence of roughness. Moreover, these computer analyses are computationally intensive and takes months to complete. Studies into the influence of variation in friction will be the subject of future work. We also appreciate that there will be a range of activity levels across a population of patients who receive total hip replacements. In our study we have taken one million walking cycles as equivalent to one year of a patients' activity (Schmalzried et al., 1998). We accept that some patients will have higher activity levels. In such cases, this will simply quicken the rate of wear compared to our study. It will not affect the overall conclusion, comparing micro-grooved with smooth surface finishes.

A computational wear algorithm for the taper-trunnion junction of THRs has been developed and was then used to compare the effect of trunnion surface finishes on the wear at the taper junction of THRs. The computational model showed that, based on the hypothesis of Ti hardening *in-vivo,* the micro-grooved trunnion imprints into the CoCr head taper surface. The femoral head taper mated with the micro-grooved trunnion surface finish has a lower surface contact area and as such the wear rate is initially lower for this coupling but later increases more rapidly than the taper mated with a smooth trunnion surface finish. The opposite trend was observed with the smooth coupling design, an initially higher wear rate which gradually reduced throughout the 7 million cycle analysis. This was due to the fact that the relative micromotion at the taper junction remained low for a longer period of time due to having a larger surface area in contact.

From the comparison between different stem surface roughness couplings in this study we can conclude that a better fixation at the taper junction could be achieved if the taper and trunnion surfaces are manufactured to be as smooth as possible, in conjunction with a low taper angular mismatch. Providing proper fixation by means of initial impaction assembly force could also lead to a reduction in the relative micromotion and thus wear debris generation at this junction, which could subsequently increase the longevity of modular hip implants. Finally, from this FE wear analysis, we concluded that plastic deformation at micro-grooves at the trunnion stem surface was unlikely to occur with 4kN impaction assembly.

Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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Figures caption

Figure 1: CoCr femoral head and Ti femoral stem of THRs; 36mm femoral head with smooth taper surface finish mated with femoral stems with (a) micro-grooved trunnion stem and (b) smooth surface finish.

Figure 2: FE model and mesh distribution of the head and stem of THRs; smooth femoral head taper mated (a) with micro-grooved trunnion stem with 200µm spacing (Munir et al., 2015) and (b) with smooth trunnion stem; 5°36´ head taper angle (in red) and 5°39´ stem trunnion angle (in orange) (Brock et al., 2015) produced 3´ base-locked taper mismatches for both models.

Figure 3: Equivalent Plastic Strain (PEEQ) showed no plastic deformation at the grooves of the femoral trunnion stem associated with FE initial impaction Elastic-Perfectly Plastic analysis

Figure 4: Schematic presentation of the finite element loading

Figure 5: wear fraction between CoCr and Ti material combination over developed wear depths during the wearing procedure

Figure 6: Contact pressure (CPRESS) distribution over the interface of the trunnion stem associated with the initial assembly impaction (4kN) for (a) micro-grooved and (b) smooth trunnion surfaces

Figure 7: Evaluation of the wear pattern on the smooth head taper surfaces mated (a) with a micro-grooved and (b) with the smooth trunnion surface finish. Note that the specific wear depth (WD) values on the figure show the maximum wear depth at each stage of the analysis.

Figure 8: Volumetric wear rates and total volume loss over and after 7 million load cycles respectively

Figure 9: 36mm CoCr femoral head taper mated with Corail micro-grooved stem trunnion; (a) Finite Element analysis and (b) CMM wear measurement. Note that, the specific wear depth (WD) values have been added to help show the similarity in wear results between the FEA and CMM analyses.

Table 1: Material and contact interaction properties

		Young's Modulus (GPa)	Yield stress (MPa)	Poisson Ratio	Wear coefficient (MPa^{-1})	Friction coefficient
Head	Co-28Cr-6Mo	210	980	0.30	1.31e-8	0.21
Stem	Ti-6Al-4V	119	880	0.29		