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The effect of different assembly loads on taper junction fretting wear in total hip replacements

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ABSTRACT

Variability in the magnitude of the impaction force applied by surgeons to assemble a hip prosthetic head to a femoral stem could be a cause of increased wear in taper junctions. This study investigates the effect of varying the magnitude of the assembly force on fretting wear at the taper over a 10 year period using a 3D finite element model and wear algorithm. It is demonstrated that an increase in assembly force results in a reduction in fretting wear and it is recommended that surgeons should apply an impact force of at least 4 kN to minimise wear rates. The wear patterns and wear rates presented are comparable with observation and measurement of those seen in retrieved prostheses.

1. Introduction

Total Hip Replacements (THRs) normally comprise of three components, an acetabular cup, femoral head and stem (Fig. 1). The modularity of the THR allows flexibility intra-operatively to facilitate optimum prosthetic functionality and anatomical fit for the patient. The femoral head is assembled to the stem by means of a taper fixation.

As well as the benefits associated with modularity there are inherent difficulties associated with the release of wear debris at both the acetabular cup-head articulating surface and the head taper-stem trunnion junction which has led to adverse soft-tissue reactions (ASTR) in recipients [1,2]. ASTR has predominantly been linked to wear at the articulating surfaces, however, recent reports show that ASTR has occurred in patients with Metal-on-Plastic (MoP) [3] and Metal-on-Metal (MoM) prostheses [1,4] implicating metallic wear debris produced by fretting at the head – trunnion taper junction. Langton, et al. [5] hypothesised that taper junction material loss was primarily due to mechanical fretting wear and not corrosion, contrary to the opinion of Malviya, et al. [6], Goldberg, et al. [7], and Gilbert, et al. [8].

1.1. *Femoral head and stem assembly*

The assembly of the femoral head onto the stem trunnion at surgery is achieved by impaction by the surgeon using a mallet and polymer tipped impactor (Fig. 2). It is known that the magnitude of this impaction force affects the initial taper strength (taper lock) and it has been postulated that attaining maximum fixation is crucial in minimising problems associated with these tapers such as corrosion, fretting and micromotion. A number of experimental studies have investigated parameters that affect taper fixation [9–12] with the axial taper ‘pull-off’ force being used as the measure to assess taper strength. All of these studies involved (at least) the simulation of the assembly and disassembly of cobalt chrome alloy heads with titanium alloy stem trunnions.

The magnitude of the impaction forces used in the studies were determined initially using tests in [9], [10], and [12] where surgeons were required to apply an impact typical of that used intra-operatively to assemble the head to the stem. The average of the measured forces from the three studies were approximately 5000 N (1 surgeon × 11 impacts) [10]; 1633 N, Standard Deviation 422 N (8 surgeons × 5 impacts each) [12]; and 4409 N (10 surgeons × 1 impact each) [9]. Rehmer, et al. [11] used impact forces of 2000 N, 3000 N and 4000 N (“to cover the typical range of force applied by surgeons”) describing them as light, medium and firm hammer blows for seating the femoral head on to the stem. A linear relationship was found by Heiney, et al. [9], Pennock, et al. [10], and Rehmer, et al. [11] such that increased impaction resulted in increased pull-off forces (with the ratio between pull-off and impaction being around 0.4 [10] and 0.48 [9]). Lavernia, et al. [12] found much reduced pull-off forces where biological debris (blood, fat) existed on the taper during assembly. Pennock, et al. [10] and Rehmer, et al. [11] stated multiple impacts did not increase taper strength, whereas Heiney, et al. [9] advised two firm blows would attain maximum fixation. Pennock,

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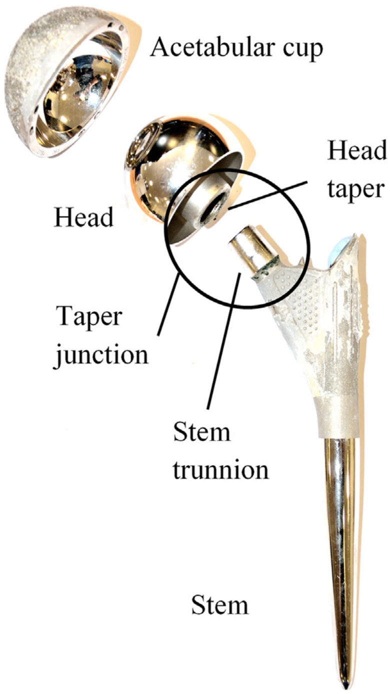

Fig. 1. A commercial THR.

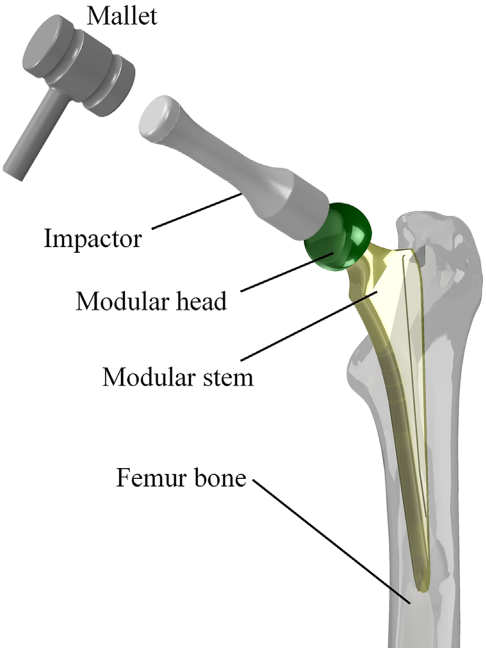

Fig. 2. Total hip replacement in situ, impaction of the modular head onto the stem trunnion.

et al. [10] suggested that surgeons should apply an in-line maximum impaction but Heiney, et al. [9] and Rehmer, et al. [11] recommended a firm blow (4000 N) so as not to risk damage to the femur. However, Mroczkowski, et al. [13] used an impact load of 6700 N and hand assembly to represent the "extremes of what may be seen clinically" in an experimental study into the effect of impact assembly on fretting corrosion of hip tapers.

These studies highlight the non-standard nature of the surgical assembly process for the prosthetic femoral head and stem with evidence of significant variation by surgeons with regard to impaction force and technique used. This variation occurs due to a surgeons differing experience; the type of head (metal or ceramic); and the quality of the bone stock of the patient. In addition, manufacturers guidelines are vague, with statements such as 'slightly' or 'firmly' impacted the norm to describe the magnitude of any impaction force to be used.

There is evidence that the magnitude of the impaction force used affects taper fixation [9–11], further, [9–11,13] suggest that the extent of taper fixation may have an effect on corrosion, micromotion and fretting wear. However, the effect of variability of impaction forces on fretting wear at the taper junction is still unclear [14]. As such, this study investigates the effect of varying the assembly forces from a 'hand press' force up to a 'high impaction' force (6 kN) on the extent of any subsequent fretting wear at the taper junction over a period of 10 years. The investigation used a 3D finite element (FE) model with a wear algorithm based on the dissipated energy wear law [15]. The assessment of wear in this study is solely based on mechanical wear (fretting) as being the primary mechanism causing damage at the head-trunnion taper junction. The results obtained have been compared favourably with observation and also measurement of fretting wear damage of available retrieved prostheses. Recommendations have been made with regard to surgical process when assembling the head to the stem so as to minimise fretting wear and thus help prolong prosthesis life.

2. Wear

The dissipated energy wear law used in this study bases the calculation of volumetric wear on the interfacial shear work being the predominant parameter determining wear. Based on this, the linear wear depth W_d occurring at the taper junction can be obtained using Eq. (1),

$$W_d = \alpha \tau s \tag{1}$$

where, α is the energy wear coefficient (determined experimentally), τ is the contact surface shear stress and s is the relative displacement between the contacting surfaces. In order to calculate wear at the taper junction numerically, the method used here is to first calculate the wear depth that would occur during one walking load cycle. Due to the complex load-time history this is facilitated by discretizing the loading cycle into a number of time intervals n and calculating (then summing) the contribution to the wear depth of each specific time interval i over the cycle. As such, the wear depth for a single cycle of loading (the cyclic wear depth W_c) can be calculated using Eq. (2),

$$W_c = \sum_{i=1}^{n} \alpha \tau_i s_i \tag{2}$$

where τ_i is the surface shear stress and s_i is the relative displacement, both calculated at the end of a specific time interval i. The cyclic wear depth W_c will be very small and if unmodified will have negligible influence on the evolving taper junction surface geometry due to wear. As such, a 'wear scaling factor' β is employed to increase W_c to a value which would have occurred over a much larger number of loading cycles. The value of β used in this study was specified as 10^5 based on findings from convergence studies undertaken in [15] on the effect of β on calculated wear depth for a specific number of loading cycles. The total wear depth W_d that is generated over a specified total number of loading cycles N can be determined from Eq. (3),

$$W_d = \sum_{j=1}^{(N/\beta)} \beta \sum_{i=1}^{n} \alpha \tau_{i,j} s_{i,j} \tag{3}$$

where j is a specific analysis 'stage' reflecting the evolution of wear; N is the total number of loading cycles and β is the wear