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.

Keywords: Fretting wear modelling; Finite element analysis; Total hip replacements; Assembly force.

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

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junction. Langton, et al. [5] hypothesized 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].

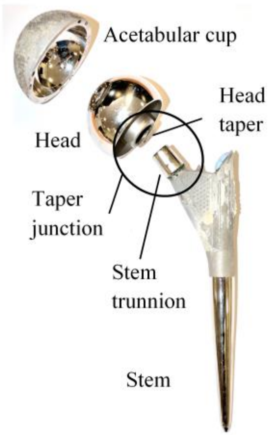

Fig. 1: A commercial THR.

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 minimizing 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.

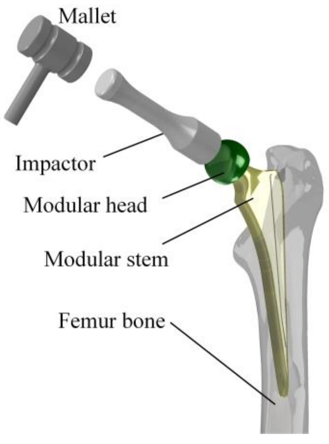

Fig. 2. Total hip replacement in situ, impaction of the modular head onto the stem trunnion.

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 5000N (1 surgeon × 11 impacts) [10]; 1633N, Standard Deviation 422N (8 surgeons × 5 impacts each) [12]; and 4409N (10 surgeons × 1 impact each) [9]. Rehmer, et al. [11] used impact forces of 2000N, 3000N and 4000N ("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, 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 (4000N) so as not to risk damage to the femur. However, Mroczkowski, et al. [13] used an impact load of 6700N 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,

$$W_d = \alpha \tau s \quad (1)$$

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,

$$W_c = \sum_{i=1}^{n} \alpha \tau_i s_i \quad (2)$$

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 scaling factor. The total wear depth W_d (for a specified number of loading cycles) is removed from the current model taper surfaces to update the model geometry. The fraction of W_d removed from each surface is dependent on the material combination in contact and is facilitated by the use of a 'wear fraction'. For a cobalt chrome alloy head and titanium alloy stem, the wear fractions have been specified as 0.9 and 0.1 respectively following work by Bone, et al. [16] and Langton, et al. [1] who found that the cobalt chrome contact surface was seen to wear around ten times more than the titanium alloy. This is further supported by Bishop, et al. [17] and explained by Moharrami, et al. [18] as occurring due to the preferential oxidation of titanium alloy over cobalt chrome thus increasing the hardness of the titanium alloy trunnion which then wears the un-oxidised CoCr head taper surface.

The approach is described and illustrated in detail in a previous study [15]. The energy wear coefficient used in this study (α=1.31×10^{-8}MPa^{-1}) was obtained by Zhang, et al. [19] for Co-28Cr-6Mo on Ti-6Al-4V from fretting wear measurements using a pin on disk apparatus with linear reciprocating motion.

3. Surgical impaction forces

3.1 Impaction tests

In order to accurately simulate the assembly of the head and stem intra-operatively using finite element analysis (FEA), several experimental impaction tests were performed to determine and quantify typical force magnitudes, impact times and load-time relationships. Pull off tests were performed to determine the strength of the subsequent fixations. The results from these tests (in addition to data from the literature) were used to quantify and specify the impact loads applied in this numerical wear study.

3.1.1 Surgical technique

Several primary and revision surgeries were attended at Broadgreen Hospital, Liverpool, UK (2014-2015) to observe surgical technique specifically related to head-stem assembly. It was noticeable that there were differences in the number of impactions used by surgeons in order to fix the head onto the stem trunnion. However, for purposes of this FE study, it has been demonstrated [10, 11] that it is the peak force applied (from multiple impacts) that solely affects taper strength and as such a single peak assembly force will be used in this study.

3.1.2 Impulse time

A drop tower was used to determine the impulse time associated with a particular impact (Fig. 3). Representative test samples of the head and stem were manufactured based on the dimensions and (taper) tolerances of a commercial THR (Fig. 4). In surgery a drift is used as an intermediary tool between the hammer and the prosthesis femoral head so as to facilitate access, however, the impulsive load transfer would be the same as that created by the experimental set-up shown here in Figure 3. A peak impact force of 4 kN was applied by the drop mass to the test assembly. The measured impact duration for a polymer tipped impactor with a metal ‘test’ head was 0.7 ms (Fig. 6).

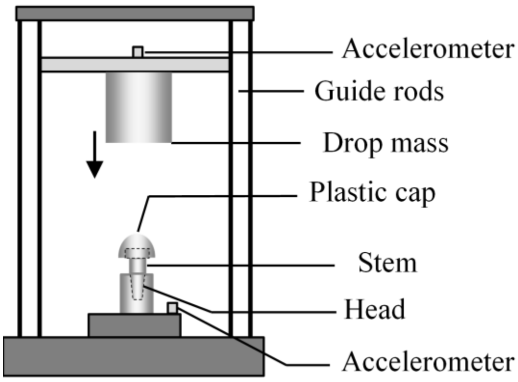

Fig. 3. Drop rig to investigate impulse time.

3.1.3 Impact force magnitude and load-time history

In addition to the impact loading data obtained from literature, further experimental tests were undertaken to quantify the load-time history for different impacts which physically could be described as ‘low to high’. Simple test pieces were used to replicate the femoral head and stem trunnion (see

Fig. 4). The test pieces were assembled (just into contact) and then fixed onto a single-pedestal load cell. Different loadings (namely “hand-press, low, medium and high impaction”) were applied to the test pieces based on previous observation of surgical technique. For all impaction cases a mallet and impactor were used as shown in Fig. 4, in addition, a ‘’hand press’’, although rare in clinical practice, was performed too. For each loading scenario, the tests were performed several times to determine an approximate maximum force magnitude and loading history.

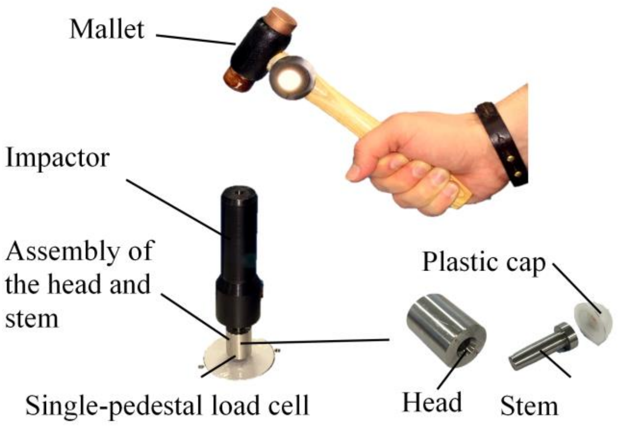

Fig. 4. Impaction experiment on single-pedestal load cell.

For the ‘hand press’ assembly case, the loading duration was recorded for around 2 seconds with the load-time relationship shown in Fig. 5 with a peak force measured as 160N. In addition, based on the findings of the tests, peak forces of 2, (3, 4) and 6 kN have been defined for the “low”, “medium” and “high” impaction cases respectively with their load-time histories defined as shown in Fig. 6 with impact durations of 0.7 ms.

3.2 Pull-off test

A Tinius Olsen tensile testing machine (H50K-S UTM Benchtop Tester) was used to determine the magnitude of the pull-off forces required to disassemble the test pieces previously described. An average pull-off force of around 45% of the impaction force was recorded for all of the different test assemblies, which correlates closely with [9-12].

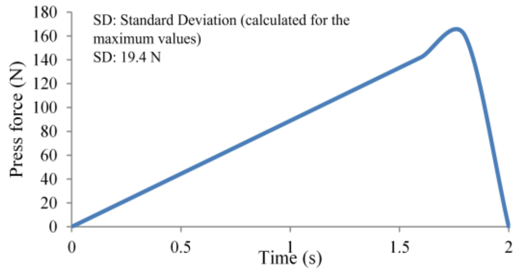

Fig. 5. Approximate 'hand press' load-time history.

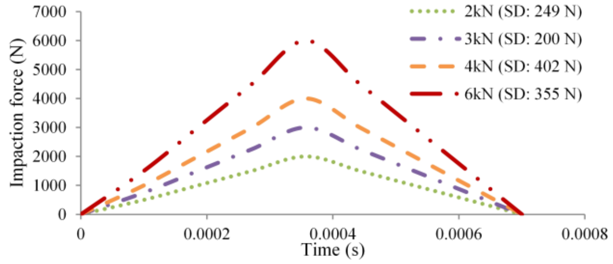

Fig. 6. Approximate average impaction force load-time histories

4. Finite Element Model

4.1 Geometry, FE Mesh and Materials

The taper junction geometry of a commercial THR was used in this study with a 3D FE model created with the head taper and stem trunnion modelled as a perfect fit with a zero taper mismatch angle (see Fig. 7). The head and stem trunnion were assembled and meshed in preparation for analysis in ABAQUS (version 6.13-1 ABAQUS Inc) using eight-node bilinear hexahedral, reduced integration elements (C3D8R). Following mesh convergence studies (paying particular attention to the edge of the taper contact) an element size of 0.2 mm was found to provide a converged solution at the taper interface so as to ensure accurate and smooth evolution of wear.

The cobalt chrome alloy femoral head and titanium alloy stem were modelled as deformable, linearly elastic and assigned material properties as shown in Table 1. The contact interaction was modelled as 'finite sliding' using the 'penalty' contact formulation in ABAQUS, a constant isotropic coefficient of friction of 0.21 was used [20].

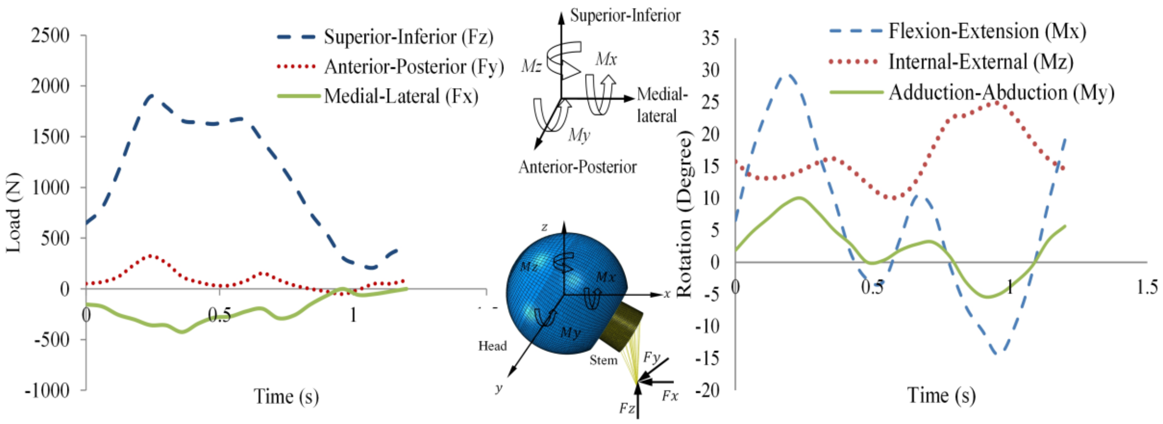

Fig. 7. FE model, loading and boundary conditions.

Table 1. Material properties of THR components.

	Material	Young's Modulus (GPa)	Poisson's ratio	Density (kg/m^3)
Head	Co-28Cr-6Mo	210	0.3	7800
Stem	Ti-6Al-4V	119	0.29	4400

4.2 Loading Conditions

The loading applied to the models in this study included an initial impact to simulate the 'assembly of the head onto the stem trunnion', and then time variant physiological loading cycles and rotations to approximate hip loading during walking for the 'wear analysis'. The inclusion of any bearing surface friction forces have been excluded from the analysis as their effect are seen to be small in comparison to the physiological loading; in addition, the bearing friction forces would have the same effect on each model as the femoral head size is fixed. As such their exclusion here will have no effect on the findings of this parametric study. Their exclusion facilitates the development of a much more efficient finite element simulation in that the acetabular cup need not be modelled or the resulting head-cup contact interaction.

Each 'assembly event' was executed as a separate dynamic implicit analysis (known as 'phase 1' of the wear methodology described in [15]). The load histories detailed in Fig. 5 and 6 were used in the 'assembly analyses' with the head and stem just contacting prior to loading.

For the 'wear analyses' (known as 'phases 2 and 3' in [15]) the models were initially assembled using the axial displacements determined from 'phase 1' where the head is forced onto the stem trunnion. These axial displacements create an overlapped mesh (interference fit) in the head-stem contact zone (simulating the taper fit or 'locking effect'). A dynamic implicit analysis is executed to model the walking cycle with the boundary conditions, *in-vivo* hip loading and rotations applied to the models as described in [15, 21] and shown here in Fig. 7. The load-time histories were discretized into 10 equal time intervals during the 1.2 second cycle time period. Further, an average of 1 million walking steps per year has been assumed in this work [22] with the 'wear analyses' executed to simulate 10 years walking activity.

4.3 Modelling of the taper 'locking effect' and the 'transition point'

Phase 2 of the methodology [15] consists of two ABAQUS analysis steps; step 1, a static overlap contact analysis (to model taper fixation) and step 2, a dynamic implicit analysis (to model the walking cycle). The static overlap analysis provides a mechanism to model the initial taper 'locking effect' (due to impaction) and then the gradual reduction in taper strength that occurs due to progressive fretting wear. The reduction in taper strength is facilitated by the removal of overlap based on calculated wear and the subsequent updating of contact surface coordinates. It has been shown in [15] and can be seen in Fig. 9 that the contact conditions prevalent at the contact interface at the end of the static overlap analysis in phase 2 are the same as those determined from the separate dynamic implicit analyses which simulated the assembly events in phase 1. This demonstrates the appropriateness of utilizing overlapped meshes to model taper fixation. In addition, a theoretical solution for taper contact pressures based on work by Burr [23] provides agreement with the FE results produced from the overlapped contact analysis (Fig. 8).

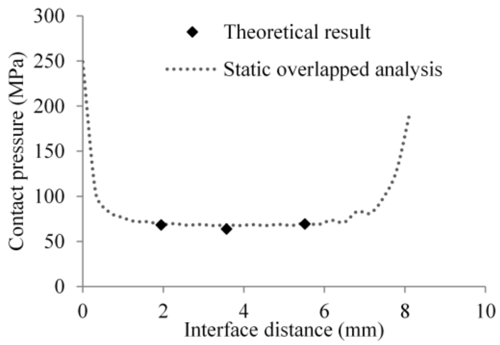

Fig. 8. A comparison between theoretical and FE results (the 'interface distance' is defined on Fig. 9)

Once all of the overlap has been removed from the model, the wear analysis moves into phase 3 whereby only the dynamic implicit analysis step is required, this point in the methodology has been defined as the 'transition point'. At the transition point, it can be hypothesised that the taper locking effect generated at the initial assembly of the head and stem has been removed from the model.

5. Results

Contact pressure, stresses and relative micromotion are all key parameters affecting the generation of fretting wear. The calculation of fretting wear in this study is based on interfacial shear work, however, shear stress distributions are difficult to interpret in the context of wear with two components acting tangential to the contact surface. As such, for clarity, contact pressure (and relative micromotion) distributions have been presented here instead.

The results for the more typical impactions of 4 kN and 6 kN are presented over 10 million cycles of loading (10 years). The 'hand press, 2 kN and 3 kN' impactions are presented over 6 million cycles (6 years) as subsequent to this their taper connections become loose and large scale rotation of the stem trunnion in the femoral head occurs. This rotation creates solution convergence problems due to difficulties in pairing nodes at the contact interface.

The time taken for each analysis 'stage' (0.1 million cycles in this study) was on average 6 hours, resulting in a total time of 600 hours for an analysis of 10 million walking cycles. All analyses were executed on a 64-bit Windows 7 professional operating system with twin dual six-core processor Intel Xeon CPU platforms at 2.60 GHz with 128 GB of RAM.

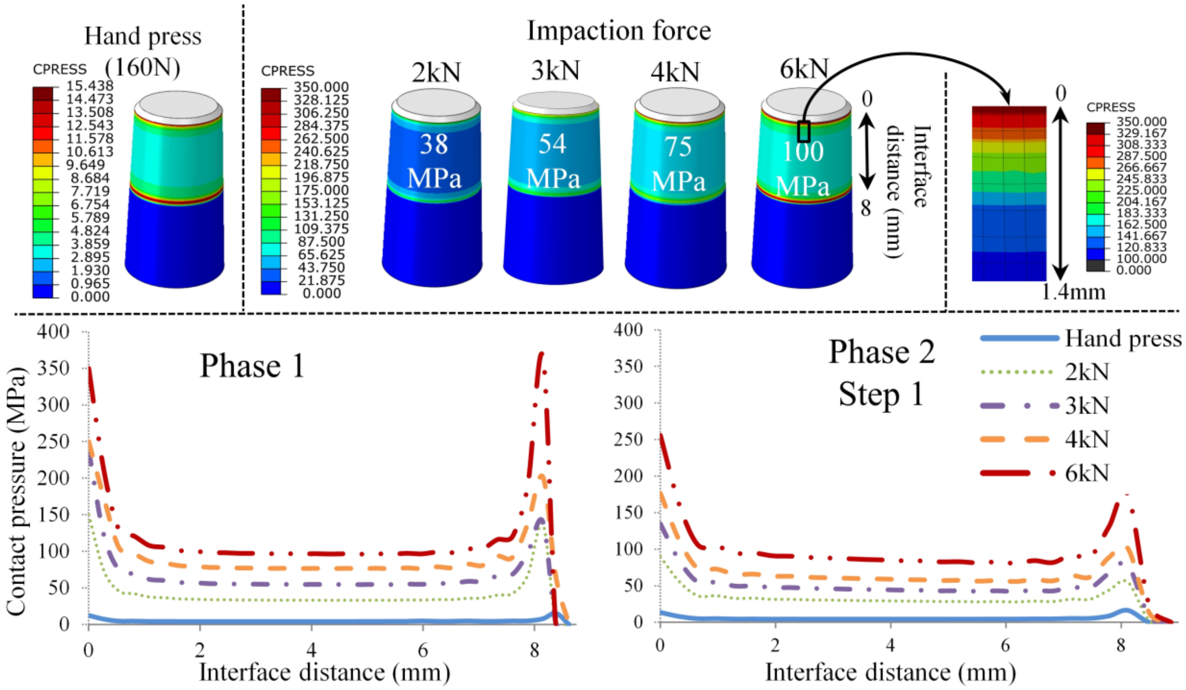

Fig. 9. Variation of contact pressure (MPa) on stem trunnion for different assembly loads

5.1 *Finite element modelling of the initial 'assembly events' (phase 1)*

The effect of increasing the assembly force from "hand press" (160 N) to "high impaction" (6 kN) is seen to increase the magnitude of the resulting contact pressures generated at the taper interface (see Fig. 9). Maximum values for contact pressure are localized at the proximal and distal edges of the contacting surfaces for all cases due to the abrupt change in contact conditions occurring at these positions. An increase in the impaction force also results in an increase in the axial displacement of the head onto the stem and subsequently greater mesh overlap at the commencement of the wear analyses (phases 2 and 3).

5.2 Variation of contact pressure and relative micromotion during the wear analysis (phase 2 and 3)

Fig. 10 and 11 detail the contact pressure and relative micromotion distributions along the head taper and stem trunnion surfaces respectively during phases 2 and 3 of the wear analysis. The distributions are shown after the last time interval of the loading cycle. Further, it should be noted that the contour range levels presented for the different impaction models are different so as to facilitate detailed contour plots showing the variation in contact pressure and relative micromotion at the taper interface.

The 'hand-press' load case, Fig. 10 (a), shows a fairly constant pressure distribution throughout the duration of the analysis, whereas the 2kN impaction model, Fig. 10 (b), shows a reduction in pressure on both the inferior and superior sides of the taper occurring between 4 to 6 million cycles of load. Fig. 10 (c), (d) and (e) demonstrate a reduction in contact pressure (specifically in phase 2) as the wear analysis progresses. Considering the 4 kN load case (Fig. 10 (d)), the pressure is seen to reduce from an approximate 'overall' surface value of 60MPa after 2 million cycles to around 20 MPa after 10 million. For all cases, in general, overall higher contact pressures are seen on the taper as the assembly load increases. More specifically, the maximum contact pressures for the 'hand-press and 6 kN' loading cases are seen to be 55 MPa and 124 MPa respectively. Further, higher contact pressures overall are seen on the inferior taper surface at the end of each analysis studied albeit being higher on the superior surface after 2 million cycles (for the 3, 4 and 6 kN models). In addition, the contact pressure is seen to reduce significantly over the duration of the analyses on the superior side of the taper for all models. Distal and proximal edge loading is prevalent on the superior taper sides for all cases producing maximum edge contact pressures of 55 MPa, 91.8 MPa, 103 MPa, 115 MPa and 124 MPa.

Fig. 11 (c), (d), (e), and to some extent Fig. 11 (a) and (b), demonstrate a general overall increase in relative micromotion as the wear analyses progress. Considering the 4 kN and 6 kN load cases (Fig. 11 (d) and (e)), the relative micromotion is seen to increase from an approximate 'overall' average value of 3 μm after 2 million cycles (for both) to around 40 μm and 50 μm after 10 million cycles. Lower 'initial' relative micromotion values (at 2 million cycles) are seen on the taper as the assembly force increases. More specifically, this can be seen clearly by considering the maximum values for relative micromotion for the 'hand-press and 6 kN' loading cases at 2 million cycles which are 34 μm and 3 μm respectively. Further, as the impaction force increases the models are seen to stay in phase 2 of the analysis for a longer period of time too.

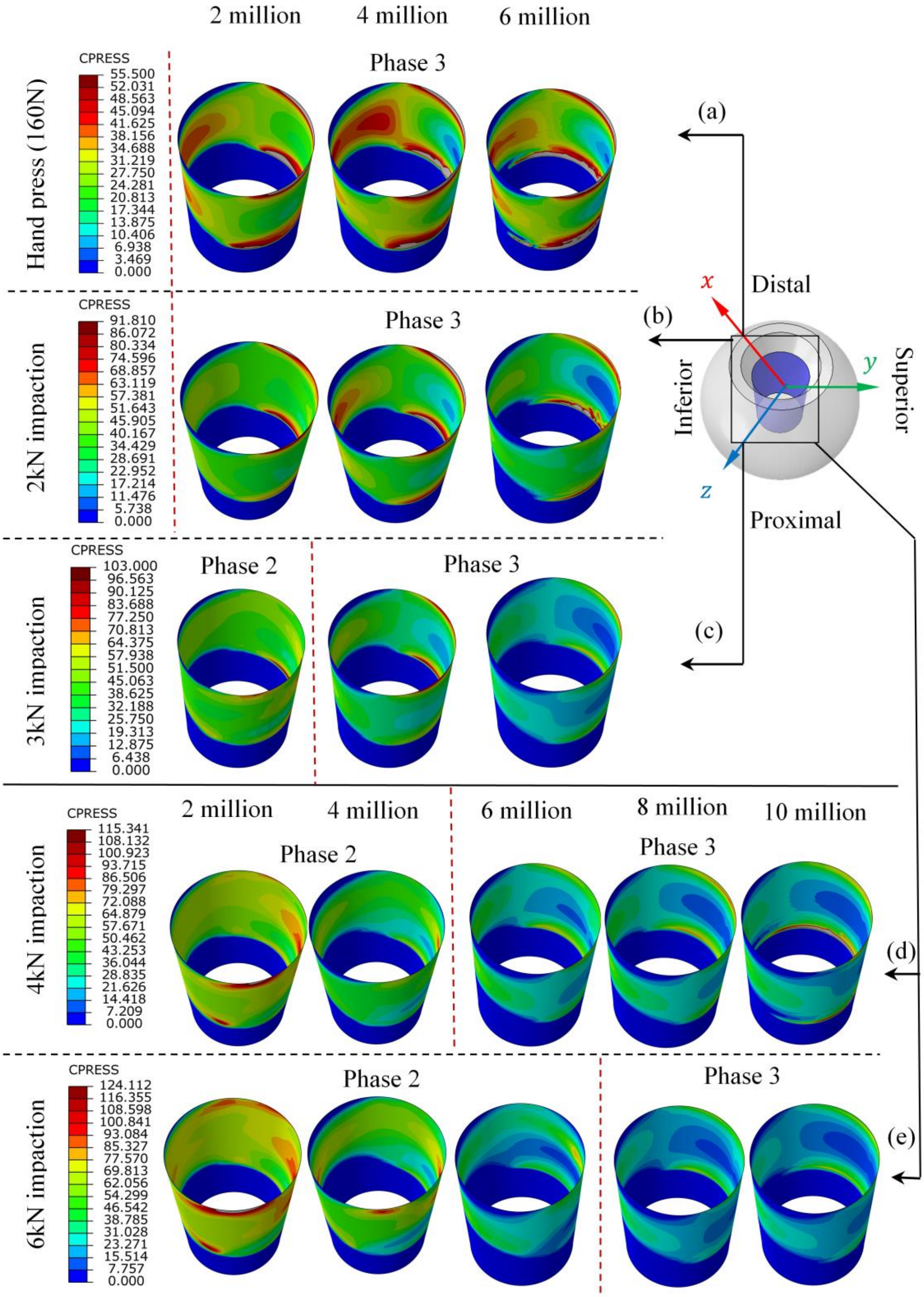

Fig. 10. Variation of contact pressure on head taper surface during wear analysis in MPa, row (a) for hand press, (b), (c), (d) and (e) for different impaction forces.

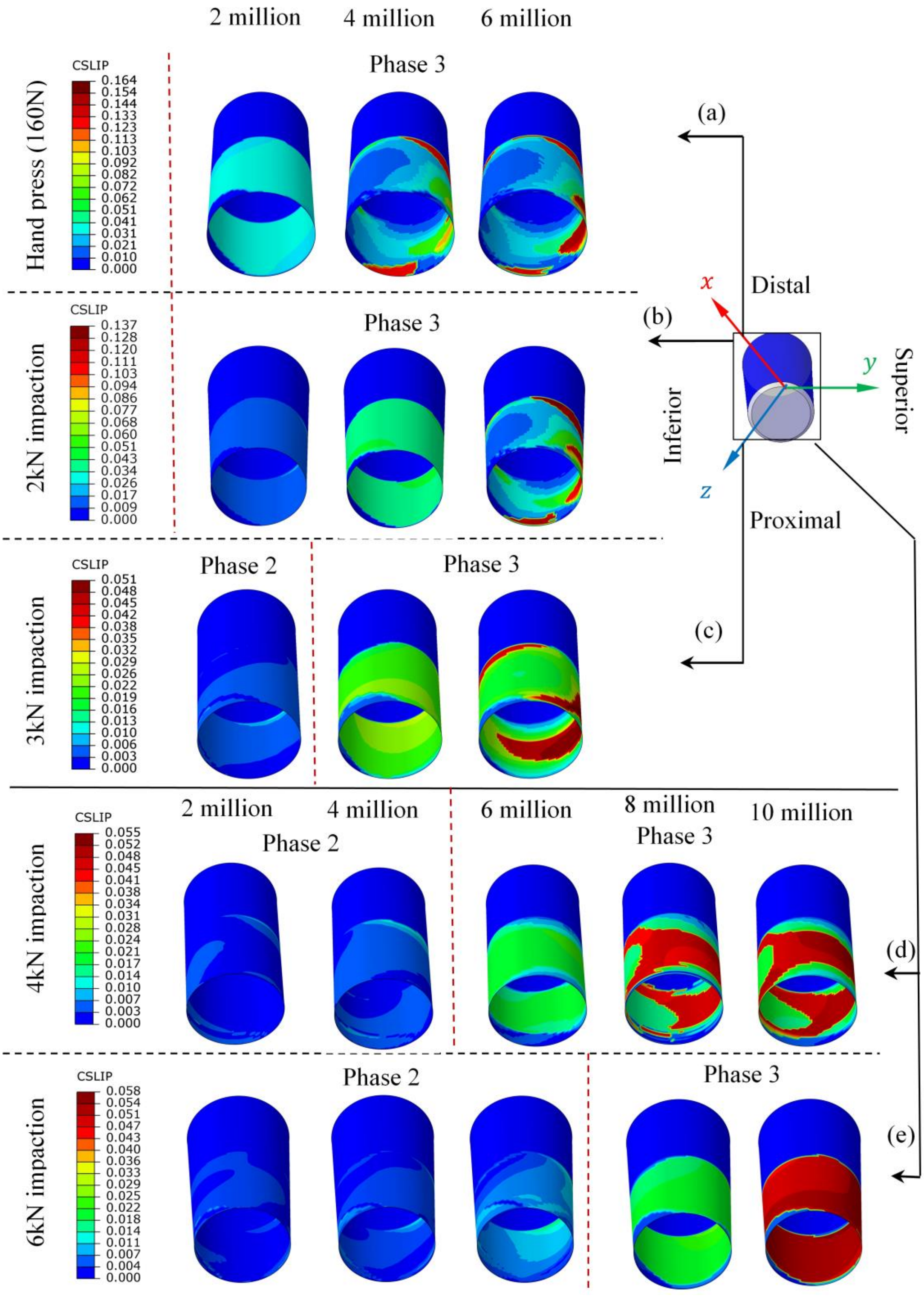

Fig. 11. Variation of relative micromotion on stem trunnion during wear analysis in mm, row (a) for hand press, (b), (c), (d) and (e) for different impaction forces.

5.3 Evolution of wear pattern damage (phase 2 and 3)

Fig. 12 details the evolution of wear along the head taper over a period associated with either 6 or 10 million load cycles (approximately 6 or 10 years of walking activity respectively) following the application of varying head-stem assembly forces. It can be seen for all load cases that the wear depth, as expected, increases as the analysis progresses. For example, for the 4 kN impaction the approximate overall average wear depth over the taper surface is around 0.5 μm after 2 million cycles increasing to 8 μm after 10 million cycles (ignoring edge wearing). In addition, for all cases, the taper wear evolves to similar patterns over the duration of the analyses with maximum wear occurring at the distal and proximal edges at the inferior side of the tapers. Similar maximum values of edge wear were determined for the 4 kN and 6 kN impaction models at 10 million cycles with values around 13.5 μm and 11.1 μm . By considering the results for wear depth after 6 million cycles, the approximate overall average wear over the taper surfaces is seen to reduce with increased impaction with values ranging from 9 μm (hand-press) to around 3 μm (4 kN and 6 kN impaction models). A comparison of wear depth at 10 million cycles between the 4 kN and 6 kN models show values of 9μm and 6μm respectively indicating again a reduction in wear with increased assembly force.

5.4 Volumetric wear rates for different impaction loads

Fig. 13 shows the variation in volumetric wear rate over the period of 6 million load cycles (hand press , 2 kN and 3 kN models), and 10 million load cycles (4 kN and 6 kN models). In general it can be seen that the magnitude of the impaction force does not have a significant effect on the initial wear rates which are all around 0.15 mm^3/yr. However, larger impaction loads maintain the models in phase 2 of the methodology for a longer period of time resulting in less wear at any specific time in the analysis. The wear rate in phase 2 remains relatively constant throughout at around 0.12 mm^3/yr although there is a slight reduction in wear rate seen due to the decreasing contact pressure at the interface as the analysis progresses (ie. for the 6 kN model, the wear rate reduces from 1.5mm^3/yr in year 1 to 1mm^3/yr in year 6). In comparison, dramatic increases in wear rate are seen in phase 3 for the hand-press and 2 kN models which occur over a short period of time, whereas a ‘steady’ (but significant) increase in wear rate is seen for the 3 kN, 4 kN and 6 kN models.

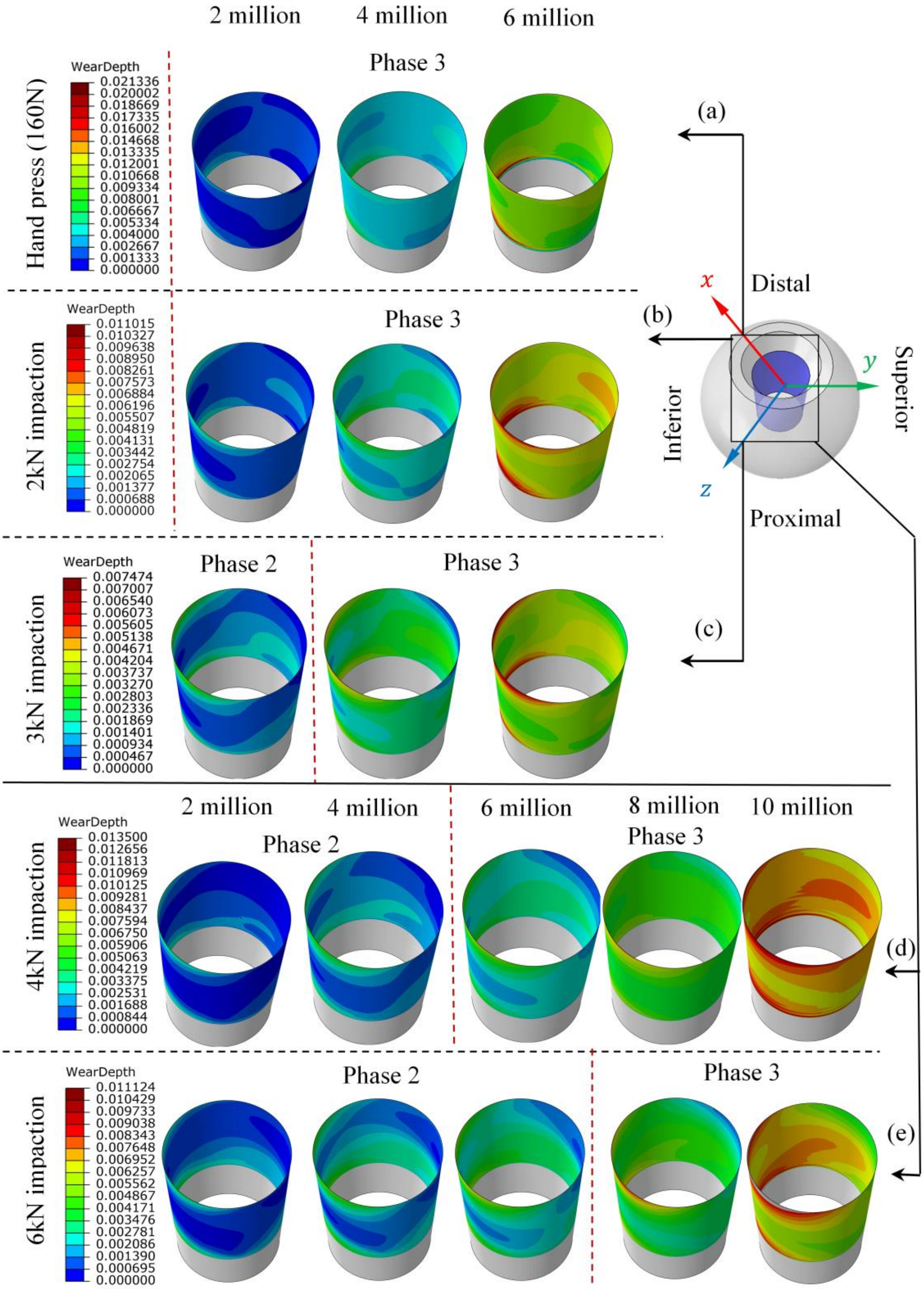

Fig. 12. Evolution of wear pattern on head taper surface during wear analysis in mm; row (a) for hand press, (b), (c), (d) and (e) for different impaction forces.

Table 2 details the 'average' volumetric wear rates for the different assembled models over the analysis periods studied. The 'average' wear rates are seen to reduce from 0.423 mm^3/yr for 'hand-press' to 0.128 mm^3/yr for the 6 kN impaction model calculated over a 6 year time period (a 69.7%

reduction). There is a reduction in the average volumetric wear rate from 0.236 mm^3/yr to 0.173mm^3/yr over the 10 year time period for the 4 kN and 6 kN impaction models respectively (a 26.7% reduction).

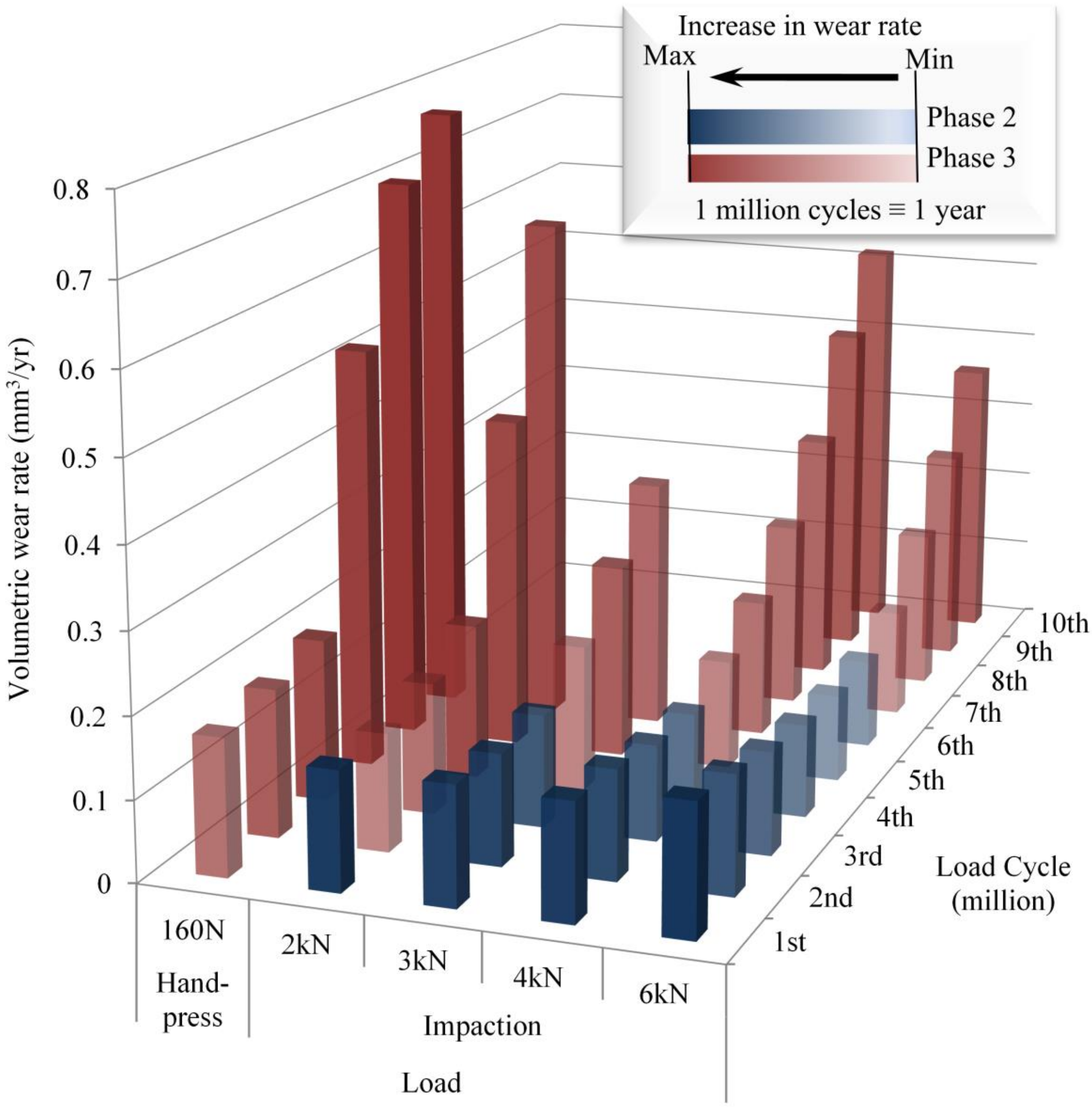

Fig. 13. Volumetric wear rate with respect to assembly load s

Table 2: Average of total volumetric wear rate over analysis period

Average wear rate (mm^3/yr)	Hand press	2 kN	3 kN	4 kN	6 kN
Over 6 year period	0.423	0.284	0.179	0.136	0.128
Over 10 year period	N/A	N/A	N/A	0.236	0.173

Fig. 14 details the total volume loss from the cobalt chrome taper, titanium trunnion surface and in total after completion of the various analyses for the different assembly models. Over the period of 6 million loading cycles the highest total material loss occurs for the "hand press" model at 2.54 mm^3. As the impaction force increases the total material loss is seen to reduce to a minimum value of

0.768mm^3 for the 6 kN impaction analysis. Considering the 4 kN and 6 kN models over the 10 year time period it can be seen that the total material loss is 2.36 mm^3 and 1.73 mm^3 respectively. The volume loss on the head and stem is based on the wear fractions assigned to the parts and the total material loss of the assembly.

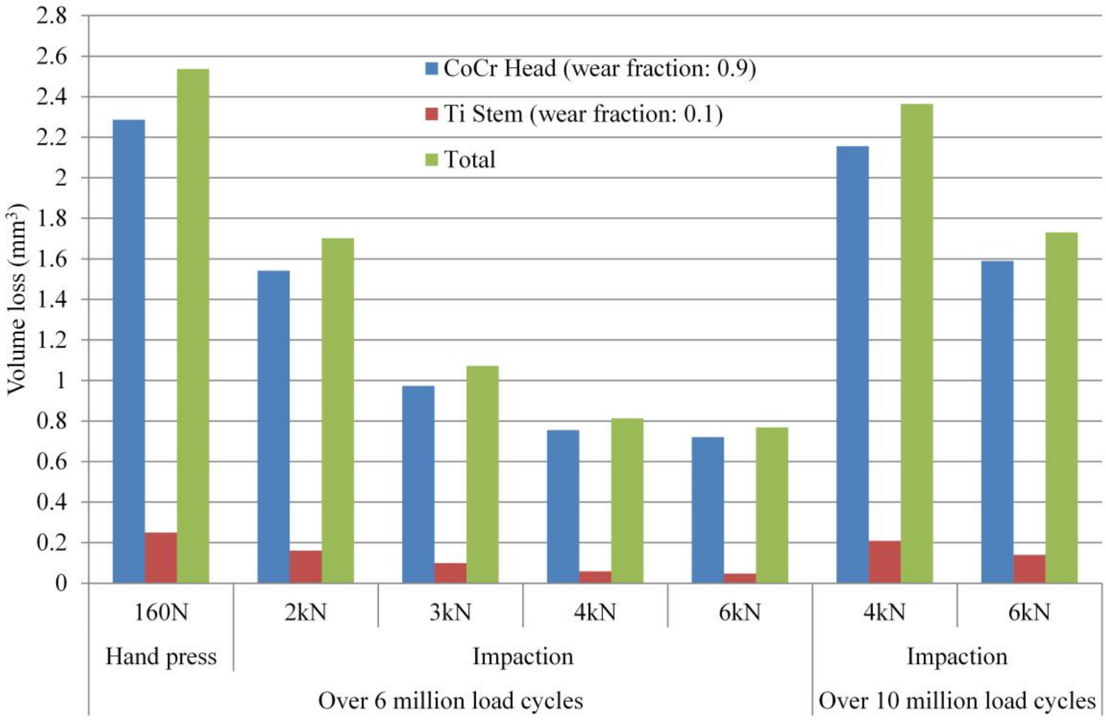

Fig. 14. Volume loss for different assembly forces

5.5 Comparison of computational wear analysis with retrieved prostheses

The results from the numerical wear model have been compared with observation and measurements of retrieved prostheses. Sixteen retrieved prostheses have been scrutinised to assess the fretting wear damage that may typically occur on a THR taper surface. It was not possible to prove how the retrieved prostheses were assembled or their loading history. As such, the retrieved prostheses have been assumed to have been assembled using a “hand press, medium (4 kN) and high (6 kN)” impaction force based on their wear patterns and the comparison with the wear patterns from the FE wear models.

A 4 kN impaction is representative of manufactures guidelines of a ‘firm’ strike and as such is the most likely assembly force used on the retrievals considered here. Figure 15(b) presents a comparison of wear damage seen on 12 of the 16 retrievals observed, with the wear depth distribution obtained from the 4kN impaction model after 10 million loading cycles. The comparison demonstrates close agreement for both the superior and inferior taper surfaces. The greatest damage on the retrieved prostheses is seen on both the distal and proximal edges of the inferior surface with the extent of damage then reducing towards the centre of the taper, this is reciprocated on the FE model with the edge wear showing maximum wear depths of ~13.5μm.

One of the retrieved prosthesis (Fig. 15 (a)) shows relatively uniform wear over the majority of the taper surface with slightly greater wear on the superior side. In comparison it can be observed that the wear damage distribution obtained from the 'hand press' FE model (after 5 million cycles) is also relatively uniform with greater damage showing on the superior side too with wear depths mainly in the region of 8.0μm (superior) compared to 5.5μm (inferior). The proximal edge of the inferior surface of the model shows the greatest wear damage at 16.3μm which is not seen on the retrieval.

The wear damage demonstrated on the superior surface of tapers from 3 retrievals show very good agreement with the 6 kN impaction FE model (after 5 million load cycles). Figure 15(c) shows that for both the retrievals and the FE model almost no wear occurs in a region in the proximity of the distal edge of the taper surface but intermediate wear occurs towards the distal edge. The greatest wear damage (6.8μm) occurs on the FE model on the inferior side of the taper at both the distal and proximal edges, whereas the retrieval only shows edge wearing on the distal edge.

In addition to the observation of the retrieved prostheses, the average volumetric wear rates calculated here, as shown in Table 2, for different assembly forces, are closely comparable to the values obtained by Langton, et al. [5] for measurements obtained at the head taper from retrieved MOM THRs (0.127 mm^3/yr for Articuleze and 0.44 mm^3/yr for DePuy ASR XL at around 1 to 5 years *in vivo*). Table 2 indicates a 'total' average volumetric wear rate of 0.136mm^3/yr for the 4kN impaction model after 6 years, which equates to 0.122mm^3/yr for the prosthetic head alone, this provides a favourable comparison with the wear rate for the Articuleze in Langtons' study.

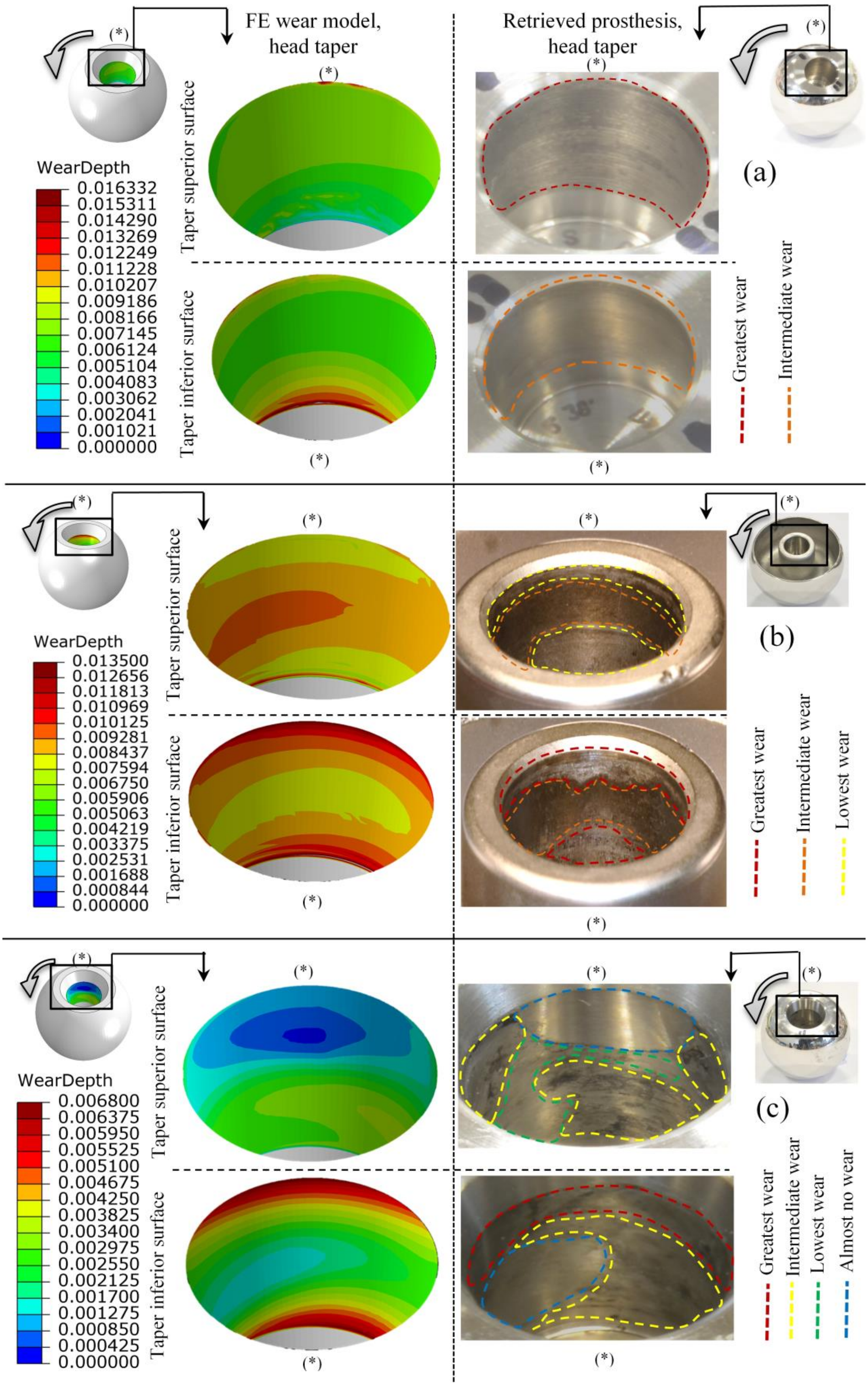

Fig. 15. Comparison of fretting wear damage between FE wear models ((a) hand press at 5th million load cycle, (b) 4 kN impaction at 10th million load cycle and (c) 6 kN impaction at 5th million load cycle) and retrieved prostheses; figures are rotated 180° based on label shown as (*)

6. Discussion

The wear algorithm used in this study is able to model fretting wear at the taper junction of THRs whilst simultaneously modelling the fixation of the femoral head and stem following surgery and the subsequent weakening of this fixation due to progressive wear. It has been utilised to investigate what effect different assembly forces have on the generation of fretting wear debris from the head-stem taper interface over a period of 10 years.

6.1 Definition of assembly forces

There is significant variability in the magnitude of force and techniques used by surgeons to assemble a head to a stem intra-operatively, further, manufacturers guidelines are vague. As such, in order to accurately simulate the impaction forces applied during arthroplasty, using FEA, a series of experimental tests were undertaken to determine a range of typical load-time histories. From observation of surgical technique, impactions described as low, medium and high were investigated resulting in their load-time histories being defined as 2 kN, (3 and 4kN) and 6kN respectively, all with an impulse time of 0.7 ms. It has been suggested in the literature [9-11] that impaction forces of between 4 kN to 5 kN will maximize taper strength whilst mitigating against damage to the femur. Pull-off tests were performed on all the test assemblies to assess taper strength with the disassembly force found to be around 45% of the impaction force, which corresponds closely with [9-12]. It is seen therefore that the use of increased impaction forces require greater pull-off forces which indicates better stability and fixation between the head and stem.

6.2 Effect of impaction force on volumetric wear and wear evolution

The computational model used in this investigation clearly indicates that increasing the assembly force used in surgery results in a reduction in the amount of fretting wear debris produced at the head-stem taper interface over the analysis periods studied. For example, increasing the assembly force from 2 kN to 4 kN results in a reduction in volumetric wear of 52% over the 6 year period studied. The ‘optimum’ assembly force (in terms of minimising wear) was found to be 6 kN. As expected, the extent and depth of wear damage on the taper surfaces increase with ‘time’ irrespective of the assembly force used. It is noticeable too that similar wear patterns evolve over the taper surfaces for all models with maximum wear damage (depth) occurring at both the distal and proximal edges of the inferior surface at the end of the analyses.

6.3 *Effect of impaction force on wear rate and 'transition' point*

The impaction force used in surgery in conjunction with the taper method of assembly fixes the head and stem together by virtue of a taper 'lock'. As 'time' passes, the wear methodology reduces the strength of the taper fixation based on progressive fretting wear at the interface. Eventually, the taper locking 'strength' created by the impaction is removed fully at the 'transition' point which separates phase 2 and 3 of the wear analysis methodology. It is noticeable that the wear rate determined in phase 2 is fairly constant at around 0.12 mm^3/yr irrespective of the assembly force used (although there is a small reduction over time). However, as the analysis continues further into phase 3, a significant increase in wear rate is seen to occur for all models ; for example, the 4kN impaction model has a wear rate of 0.112 mm^3/yr at 4 years (at the end of phase 2), but increases during phase 3 to a value of 0.514 mm^3/yr at 10 years. It follows that maintaining the 'locking effect' due to impaction for as long as possible (i.e. maintaining the model in phase 2) is key to minimise wear rates and debris generation, this can be facilitated by applying an assembly force in surgery of no less than 4 kN. The transition point is therefore important as far as the production of wear debris is concerned and its implications to ASTR following arthroplasty. For assembly forces of "hand press" and impactions of 2, 3, 4 and 6 kN, the transition points occur after approximately 0.8, 1.4, 3.1, 4.1 and 6.9 million load cycles respectively.

6.4 *Variation in contact pressure and relative micromotion*

The variation in wear rate over the time period studied is seen to be dependent on simultaneous changes in contact pressure (and shear stress) and relative micromotion at the taper interface (as the wear coefficient used throughout the analysis is assumed constant).

In general, it has been shown that increased assembly forces in surgery result in increased overall contact pressure at the taper which in turn leads to a reduction in the magnitude of the relative micromotion (see Fig. 10 and 11). The proportional change in taper pressure and relative micromotion between the different impaction cases are similar (immiediately after assembly), and result in a fairly uniform initial wear rate for all models.

In terms of variation of contact pressure and relative micromotion with respect to time, it is necessary to consider changes occurring discretely in phase 2 and phase 3 of the methodology. In phase 2 there is a gradual reduction in contact pressure caused by the reduction in mesh overlap (taper lock) due to progressive fretting wear as the analyses progress. In addition, in phase 2, the magnitude of relative micromotion is very small (due to the taper lock effect), and although it increases slightly as the taper strength (contact pressure) diminishes, the relative reduction in contact pressure is greater. This leads to a continuous (small) reduction in the volumetric wear rate in phase 2 of the analysis (see Fig. 13) which helps maintain the model in phase 2 for a longer period of time. In phase 3 the contact pressure remains relatively constant but significant increases in relative micromotion can be observed as the analyses continue (Fig. 10 and 11). As such, the large increases in relative micromotion that occur in phase 3 are mainly responsible for the increased wear rates observed.

6.5 Comparison with retrieved prostheses considerations

The computational results obtained here (wear pattern and depth) were seen to be in good agreement with observation of the wear occurring on retrieved prostheses and also measurements taken from literature. However, this comparison needs to be considered with caution as the computational results were 'back-fitted' to wear patterns on retrievals which were found to be similar to the results obtained from the specific FEA wear analysis. Observed differences in wear damage distribution and wear depths, could possibly be attributed to THR design, material combination differences, head-stem taper mismatch angle, corrosion and the wear coefficient used in the numerical study. In addition, the assembly process and load history of the retrieved prosthesis is unclear and could be one of the reasons for the slight differences in wear damage distribution too.

7. Conclusion

From this computational study it is seen that the magnitude of the impaction force applied during assembly of the prosthetic femoral head to the stem intra-operatively does have an effect on subsequent fretting wear at the taper junction of THRs. From study of the range of forces used here to simulate the assembly event (160 N to 6 kN), and over a modelling period of 10 years, an assembly impact force of 6 kN has been shown to minimise the generation of wear debris at the taper interface.

As such, to minimize the fretting wear rate, the authors suggest that surgeons should apply an impaction force of at least 4 kN (firm strike) to seat the femoral head on to the stem trunnion whilst simultaneously ensuring the integrity of the patient femur and prosthetic device.

Assembly of the head and stem by a 'hand press' will generate the most wear debris at the taper junction over a specific period of time; however, increasing the magnitude of the impaction force to at least 4kN will result in a significant reduction in the amount of wear debris produced.

The wear algorithm and FE model used in this study indicate that the taper interface contact pressure and relative micromotion are in general seen to increase and decrease respectively with increased impaction force. During the wearing process, it is seen that initially the contact pressure reduces gradually whereas the relative micromotion remains relatively constant. This continues up to the point where the 'taper locking' effect (or fixation) generated by the impaction force used at assembly of the head and stem has been removed due to wear. Following this 'transition point' the contact pressure settles to a relatively constant value whereas a significant increase in relative micromotion (and therefore wear rate) is seen to occur as the analysis continues further into phase 3. As such maintaining the 'locking effect' due to impaction for as long as possible (by application of a suitable assembly force in surgery) is key to reduced wear rates. Removal of this 'locking effect' subjects the prostheses to much increased wear rates early in its life and could explain the premature failure of some devices.

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