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1 Computational Method for Bearing Surface Wear Prediction in

2 Total Hip Replacements

3 Shawn Toh Ming Song^{1,*}, Ariyan Ashkanfar¹, Russell English¹, Glynn Rothwell¹

4 ¹School of Engineering, Liverpool John Moores University, Byrom Street, Liverpool, UK, L3 3AF

5 Abstract

6 Total hip replacement (THR) is a revolutionary treatment when a hip joint becomes severely 7 damaged. Wear is known as one of the main reasons for THR failure. Current experimental 8 techniques to investigate the wear at the bearing surfaces of THRs are time-consuming, complicated 9 and expensive. In this study, an in-house fretting wear algorithm has been further developed to 10 investigate the wear damage that occurs on bearing surfaces of THRs and its consequence on the 11 longevity of the implants. A 3D finite element model has been created with a 36mm diameter 12 Cobalt-Chromium femoral head and a 4mm thick cross-linked polyethylene bearing liner. A gait 13 loading cycle was used to simulate walking for up to 5 million cycles (Mc). The wear algorithm 14 extracts relative displacements and contact shear stresses from the finite element package to 15 predict the linear and volumetric wear rates. This method is shown to have modelled the evolution 16 of wear effectively and found it to be similar to those from experimental analyses. The linear and 17 volumetric wear per million cycles predicted in this study were 0.0375mm/Mc and 33.6mm³/Mc 18 which are comparable to those measured in-vivo THRs. The wear patterns obtained from this study 19 are also comparable to the wear patterns shown on available conventional polyethylene liners. This

- 20 method can be used to further aid in the design and clinical technique to reduce wear rate in THRs.
- Keywords: Wear modelling, Total Hip Replacement, Hip joint prosthesis, Finite Element Modelling,polyethylene wear.

23 1. Introduction

24 A hip joint is one of the most important joints in our body. It bears our body weight in static and 25 dynamic postures and plays an important role in retaining body balance; however, it may lose its 26 functionality due to diseases such as osteoarthritis which causes pain and also in extreme cases, loss 27 of mobility (Holcomb, Miller et al. 2012, Kumar, Bloch et al. 2017). When the joint has been severely 28 damaged and physiotherapy, steroid injections or other treatments have not helped to improve 29 mobility, the damaged joint may be removed and replaced with a prosthesis. According to the NJR's 30 report in 2019, 82.6% of patients who received a total hip replacement (THR) had been suffering 31 from osteoarthritis (NJR 2019). THR has become a revolutionary treatment (Nambiar, Jagani et al. 32 2017) over the last decades (Towheed and Hochberg 1996, Learmonth, Young et al. 2007, Ashman, 33 Cruikshank et al. 2016). A THR usually consists of four parts, an acetabular cup, a bearing liner, a 34 femoral head and a femoral stem (Figure 1). (Ali, Al-Hajjar et al. 2016, Varnum 2017) .

^{*} Corresponding Author

E-mail addresses: s.m.toh@2016.ljmu.ac.uk , shawntoh15@gmail.com



Figure 1: The four main parts of a total hip replacement (THR)

37 Data from the National Joint Registry (NJR) shows there were approximately 92,000 THR procedures 38 performed in the United Kingdom using arthroplasty in 2018 with over a million THR's performed 39 since 2003 (NJR 2019). Further statistics from the NJR in 2019, also shows that there is an average of 40 11.5% increase every year in the number of patients under 55 years old undergoing THR which 41 suggests that more young active patients will undergo THR in the coming years. The longevity of 42 these implants will need to be increased, as the current average lifespan of a THR implant is at 15 43 years (Evans, Evans et al. 2019). Furthermore, nearly 8% of cases had failed prematurely, less than 44 15 years in service, and needed a revision surgery (NJR 2019). Wear is one of the main reasons for 45 premature failure in THRs (Karachalios, Komnos et al. 2018) and can cause a multitude of failure 46 such as aseptic loosening, dislocation, infection or metallosis (Karachalios, Komnos et al. 2018, Neil 47 G. Burke 2018, Sipek, Lyvers et al. 2018). Aseptic loosening accounts for approximately 45% of hip 48 revisions (Buly, Huo et al. 1992, Neil G. Burke 2018, Sipek, Lyvers et al. 2018, NJR 2019). 49 Current experimental techniques to investigate the wear damage in THRs, such as radiography,

50 tribo-testing, and hip joint simulators, are time-consuming, complicated and expensive (Hallan, Lie et

51 al. 2006, Hua, Dou et al. 2019, Ramesh, van Kuilenburg et al. 2019). Computational analysis has

52 several benefits when compared to experimental testing such as lower cost, lower run time, and

53 having detailed solutions which can be an alternative to experimental techniques. With these added

54 benefits, current computational analysis has led to the understanding of different design and

55 material variations, (Shen, Lu et al. 2011, Ashkanfar, Langton et al. 2017, Gao, Hua et al. 2018,

56 Ruggiero, Merola et al. 2018), manufacturing tolerances (Kluess, Martin et al. 2007, Ashkanfar,

57 Langton et al. 2017, Affatato, Merola et al. 2018), and surgical techniques (English, Ashkanfar et al.

58 2016).

59 Recently, studies by Ruggiero, Sicilia et al. (2020) have used an in-silico approach to link

60 experimental investigations to computational investigation to predict wear in the implant over

61 millions of cycles. The main purpose of their study was to propose a wear prediction approach which

62 would reproduce the classical in-vitro wear testing of total hip replacements accounting for

63 unsteady synovial lubrication effects between the femoral head and the acetabular liner (Ruggiero

and Sicilia 2020, Ruggiero, Sicilia et al. 2020). Understanding the wear pattern, damage and the wear

- 65 rates are crucial to identify the different key factors in prosthesis design, materials, tolerances and
- 66 surgical methods which would minimise the wear rates and increase overall longevity.
- 67 Previously, an in-house fretting wear algorithm (English, Ashkanfar et al. 2015) was developed using
- 68 a 3D finite element model and a Python script within the Abaqus environment. The algorithm has led
- to the further understanding of different design and material variations (Ashkanfar, Langton et al. 69
- 70 2017), manufacturing tolerances (Ashkanfar, Langton et al. 2017) and surgical techniques (English,
- 71 Ashkanfar et al. 2016). The fretting wear algorithm was only able to predict wear due to
- 72 micromotion at the taper junction of the THRs. In this study, a new wear algorithm has been
- 73 developed to predict wear at the bearing surfaces for the larger movement of the femoral head.

74 2. Methodology

2.1. Finite element model 75

76 A model of the acetabular cup and femoral head with a liner insert was created in the finite element

- 77 package (ABAQUS 2019) (Figure 2). In this model, the acetabular cup has a 4mm thick liner with a
- 78 3mm thick metal backing (Figure 2b) (Shen, Lu et al. 2011). The materials used in this analysis are
- 79 Cobalt-Chromium (CoCr) for both the femoral head and acetabular cup and cross-linked
- 80 polyethylene (XLPE) for the liner. XLPE has been widely used since the 2000s for its low wear by
- 81 improving wear resistance and oxidative degradation while maintaining its' mechanical properties
- 82 (Affatato, Ruggiero et al. 2018, Hu and Yoon 2018, Carli, Patel et al. 2020). The material properties
- 83 are listed in Table 1 (Innocenti, Labey et al. 2014). The cup and head were meshed in preparation for
- 84 analysis using the eight-node bilinear hexahedral reduced integration elements (C3D8R).



Table 1: Material Properties for THR

87

85

88

Figure 2: FE Model (a) Mesh of the FE model, (b) Partitions showing material assignments

89 To replicate a walking cycle, the rotations and loadings occurring on a typical hip joint were applied 90 onto the model (Figure 3a). The acetabular cup was fixed on its outer surface whereas the femoral 91

head was free to rotate based on the rotation and loading cycles specified. The walking loads and

- 92 rotations (following their amplitude (Figure 4)) are both applied to the centre of the femoral head 93 (Figure 3b, Figure 3c). These conditions simulate the acetabular cup as being cemented into the hip
- 94 while the femoral head transfers the walking and rotation loads onto the inner surface of the
- 95 acetabular cup. A friction coefficient of 0.11 (Wang, Ge et al. 2010) has been applied between the
- 96 contacting surfaces using the penalty method in Abaqus.









99



101 **2.2. Computational wear analysis**

102 There are two main types of wear law, 'Archard's' and the 'Dissipated Energy' wear law (Zmitrowicz 103 2006, Abdo 2015). The Dissipated Energy wear law is used throughout this study as it predicts wear 104 across a wider range of motion with a greater range of application than Archard's wear law (Fouvry, 105 Liskiewicz et al. 2003, Abdo 2015). As elaborated previously by English, Ashkanfar et al. (2015), the 106 wear depth (W_d) can be calculated using Eq. (1), where α is the energy wear coefficient, τ is the 107 contact shear stress and s is the relative displacement between bearing surfaces.

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

108 As the wear analysis would need to be performed for over millions of cycles, a scaling factor (β) 109 needs to be introduced to make the execution of the analysis achievable in acceptable time. The

scaling factor is used to multiply the wear calculated after a single analysis (one walking step) so as

to create a wear value that can be used to modify the surface geometry by a suitable amount to

- 112 facilitate acceptable run times. The scaling factor used can vary across a large range (25,000 to 2
- 113 million). A large scaling factor would result in a faster computational run time but may affect the
- accuracy of the results. A small scaling factor would increase the computational run time but should
- provide a greater accuracy of results. Hence, the scaling factor needs to be optimised to ensure the
- accuracy of the results within an acceptable time frame. The wear for a single cycle of loading of a node can be calculated using Eq. (2), where τ_i and s_i are the surface contact shear stress and
- 118 relative displacement respectively, at each time interval.

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

- 119 The calculation of wear at the contact surfaces requires creating sets of "node pairs". The pairing is 120 achieved by taking a node at the surface with the coarser mesh (Surface A) and determining which nodes are closest on the opposing surface (Surface B). In the previously developed fretting wear 121 122 algorithm (English, Ashkanfar et al. 2015), as fretting wear does not involve any large displacements, 123 a single node-to-node pairing method was sufficient to ensure that all the nodes would have wear 124 depth applied. For the larger relative displacement, in this study, a node from 'Surface A' needs to 125 be paired to a cloud of nodes on 'Surface B' due to different mesh densities on the surfaces. This will 126 avoid any nodes on 'Surface B' to be left unpaired which may cause wear to not be applied at the 127 node and subsequently cause sharp points in the geometry of the model. This has been optimised 128 for each node from 'Surface A' to be paired to three to nine nodes on 'Surface B' (Figure 5). This 129 depends on the difference in the mesh density on the coupling surfaces. The pairing procedure needs to be undertaken at each time interval of the walking cycle. The contact stress and relative 130
- 131 displacement are extracted for all paired nodes at each time interval as illustrated in Figure 6.



Figure 5: Node pairs diagram

- 134 Using Eq.(2), the wear depth for each set of paired nodes is calculated using an energy wear
- 135 coefficient of 5.32(10⁻¹⁰)mm³/Nmm (Matsoukas, Willing et al. 2009). A fraction of the wear depth
- 136 calculated for each paired node is used to update the nodal coordinates. This fraction depends on
- 137 the contact surface interaction properties of the materials in contact. The algorithm applies a
- 138 fraction of the wear depth calculated on each contacting surface to each paired node. The wear
- 139 fraction introduced is 0.99:0.01 for the interaction of XLPE with CoCr respectively (Anissian, Stark et
- al. 1999). Although the wear present in the CoCr is relatively small compared to XLPE, small amounts

- of metal present in the body can lead to a metallosis. The wear fraction is used to highlight theamount of metal particles that would be released into the body.
- 143 To be able to translate wear depth into normal coordinates to update the geometry, the normal
- direction vectors of the nodes are obtained from the initial position of the model. The geometry is
- then updated based on the defined coordinates and a new input file is generated. The analysis is
- 146 then continued until the number of cycles has been reached.
- 147 The scaling factor (β) used in the analysis has a great impact on computational time and wear
- accuracy. A larger scaling factor would result in a quicker analysis but may greatly impact the
- accuracy of the results. A smaller scaling factor would increase the computational effort. An
- optimum scaling factor of $\beta = 10^5$ was used in this study as previously investigated by (English,
- 151 Ashkanfar et al. 2015).
- 152 The method to calculate the wear depth for hundreds of thousands of paired nodes needs to be
- automated. As such a Python script has been written within the Python Development Environment
- 154 (PDE) in Abaqus to automate the procedure. An outline of the python script is shown in Figure 6. The
- 155 python script is then converted into an Abaqus plug-in. Although the methodology here presented is
- using the 'Dissipated Energy' wear law, the algorithm can utilise both 'Archard' and 'Dissipated
- 157 Energy' wear laws for calculations.



159

Figure 6: Flowchart outlining python script

160

161 The graphical user interface of the current wear algorithm is shown in Figure 7. All the necessary

162 variable inputs are taken from the user such as the wear coefficient (α), wear fraction, wear

163 equation to be used, the total number of updates and scaling factor. In addition to calculating the

164 wear depth, the volumetric wear can also be determined with the algorithm by extracting the

165 reduction of element volume for all elements throughout the entire part and calculated at each

166 defined time interval.

💠 Wear Algorithr	n			×		
Work Directory Work Directory Current Directory	Computer Spec	Recovery ent Directory				
	Copy and	Paste the Wor	k Direct	tory:		
	Other Wo	ork Direc:				
Input Data						
Materials Wear	Properties					
Preset Values	Other Values					
Preset Values:	UHMWPE on CoCr	Vear Eq	uation:	Energy 🗠		
Insert Other values in next tab						
CoCr on CoCr: (1.51e-10) (0.5)						
XLPE on CoCr:	(4.84e-9)(0.99)					
Number of Updat	es:					
Scaling Factor:	100000					
Pair Nodes Every -	updates: 100					
Post Algorithm						
Total Walking this Wasser C. L. L. L. W. D. H.						
	ear	o wear Depth				
Use Volumetric Wear After Job Completions						
\bigcirc On \bigcirc Off						
From Job 1 to Job : 0						
0	К		Cancel			

Figure 7: Graphical user interface of the wear algorithm

169 All analyses were executed on a 64-bit Windows 10 professional operating system with a four-core 170 processor Intel central processing unit platform at 3.8 GHz which had a total run time of 850 hours.

171 **3. Results**

172 **3.1.** Variation of contact shear and relative displacement during a gait cycle.

Figure 8 shows the contact shear stress (CSHEAR), distributed on the femoral head, and relative
displacement (CSLIP) on the bearing liner. It is noticeable that at each time interval, the CSHEAR and

175 CSLIP at each point of the contact bearing surfaces are similar. The maximum CSHEAR is 0.352MPa
176 which occurs at 0.60s while the maximum relative displacement of 10.9mm occurs at 0.24s over the

177 walking cycle.

178 As explained earlier, the nodes in contact are paired at each time interval of the analysis. For each

set of paired nodes, the CSLIP (Figure 8a) and CSHEAR (Figure 8b) were extracted. These values are

180 then used to calculate the wear depth using Eq. (2). The wear depth distribution after using a scaling

181 factor of 100,000 is shown in Figure 8c. As expected, due to the wear fraction, the highest wear

depth occurs on the bearing liner with a wear depth of $4.25\mu m$ and the maximum wear depth on the

183 femoral head is 0.0460µm which is around 99 times lower.



Figure 8: a) Variation of shear stresses, b) relative displacement during a walking cycle and the wear from the first 10,000 cycles, c) Wear depth values at the end of 100,000 cycles

188 **3.2. Predicted wear damage over 5 million cycles**

189 The same procedure as explained in 3.1 has been carried out to complete up to 5 million cycles and

the evolution of wear is shown in Figure 9 at every million cycles. The maximum wear depth value

reaches 192.5µm and 2.20µm after 5 million cycles for the bearing liner and femoral head

- respectively (Figure 9a, Figure 9b). It can be seen from Figure 9 that most of the wear occurs at a
- 193 relatively small area.



- 194
- 195

Figure 9: Variation in wear depth over 5 million walking cycles

3.3. Volumetric wear and linear wear of XLPE liner

197 The volumetric wear was determined at each 1 million cycles as the solution progressed based on 198 the reduction of element volume for all the elements of the different parts. As can be expected, the 199 material loss from the surfaces increases over the 5 million load cycles as shown in Figure 10a. The 200 cumulative volumetric loss at the end of 5 million cycles is 169.2mm³ and 1.75mm³ for the XLPE 201 bearing liner and CoCr femoral head due to the material interaction properties. The total material loss from both bearing surfaces after 5 million load cycles is 170.96mm³. The volumetric wear rate at 202 each million load cycle remains similar throughout the analysis between 33.6mm³/Mc to 203 34.1mm³/Mc and 0.337mm³/Mc to 0.362mm³/Mc for the bearing liner and femoral head 204 205 respectively (Figure 10b). This shows that the volumetric wear is increasing linearly throughout the 206 analysis.





The maximum linear wear was determined from the largest wear depth at the XLPE liner at each 0.5 million cycles (Figure 11). The maximum linear wear is shown to have a linear increase with a maximum of 0.192mm at 5 million cycles. The linear wear rate was initially higher for the first million load cycles at 0.0418mm/Mc and then decreases to about 0.0375 mm/Mc subsequently. The higher initial linear wear rate of 0.0418mm/Mc in the first million cycle (Figure 11b) may be due to an initial period of material deformation (bedding-in) and then steady-state wear which would continue after the first million cycle (A., E. et al. 2017).







217 4. Discussion

The scaling factor used in the analysis has a major impact on the solution time, wear evolution, and solution accuracy. Figure 12 shows the total cumulative wear and the wear that is applied at 2 million cycles using different scaling factors of 25,000, 50,000 and 100,000. Although the total cumulative wear at 2 million cycles remains similar, the wear that is being applied to the geometry is not smoothly distributed (Figure 12). As the analysis progresses, this will cause a sharp increase in

223 wear depth at a certain contact area on the surfaces which would then lead to inconsistencies on the

- 224 wear pattern. To mitigate this effect and to reduce the computational time, a node wear smoothing
- 225 feature has been developed in the wear algorithm. In this node smoothing feature, the wear applied
- to each node is checked with a cloud of surrounding nodes to ensure that the wear distribution is
- applied smoothly throughout the analysis.



229

Figure 12: Effect of scaling factor on the wear occurring in the analysis

- 231 The maximum contact pressure variation over the first gait cycle is shown to be 3.21MPa (Figure
- 13a). At the end of 5 million cycles, the variation in contact pressure remains similar to the variation
- at the first gait cycle. These results are comparable to studies performed by Yoshida, Faust et al.
- 234 (2006) and Saikko (2020). For a peak load of 2.5kN, Yoshida reported a maximum contact pressure of
- 235 3.2MPa while Saikko reported a maximum contact pressure of 3MPa.



- 237 The linear and volumetric wear rates shown in this study are comparable to several studies with
- 238 XLPE in the literature (see Table 2). A., E. et al. (2017) and Haw, Battenberg et al. (2017) analysed a
- total of 32 and 48 primary total hip arthroplasties respectively with a 36mm CoCr femoral head size
- 240 coupled with XLPE liners on serial radiographs. A., E. et al. (2017) showed a mean linear and
- volumetric wear rate of 0.07mm/yr and 29.29mm³/yr while Haw, Battenberg et al. (2017) showed a
- 242 mean linear and volumetric wear rate of 0.052mm/yr and 33.09mm³/yr. Khoshbin, Wu et al. (2020)
- analysed a total of 40 primary THR of XLPE liners with CoCr femoral heads using radiography. The
- results obtained showed a mean linear wear rate of 0.0387mm/yr and 31.51mm³/yr.

245 The range of linear and volumetric wear rate for the XLPE liners coupled with a 36mm CoCr femoral 246 head reported in the above studies (A., E. et al. 2017, Haw, Battenberg et al. 2017, Khoshbin, Wu et 247 al. 2020) was between 0.039 - 0.07 mm/yr and 29.29 - 33.09 mm³/yr. The number of steps walked by a patient per year, undoubtedly influences the wear rate per year however by considering an 248 249 average of 1 million walking steps per year (Schmalzried, Szuszczewicz et al. 1998), the linear and volumetric wear rate shown in our study (0.0375mm/yr and 33.8mm³/yr) are comparable to those 250 251 found in the above literature (see Table 2Figure 2). It is noticeable that if a patient walks more than 252 the assumed 1 million cycles per year, it will only hasten the wear and not affect the wear rate per 253 million cycles. There are many factors which can contribute to the wear damage, such as variable 254 wear and friction coefficients, surface roughness, manufacturing tolerances, and the patient's 255 activity level, weight, and implant design.

256

Table 2: Linear and volumetric wear rates of XLPE and UHMWPE in literature.

Material	Literature	Method of wear retrieval	Linear Wear rate (mm/yr)	Volumetric Wear rate (mm³/yr)
XLPE	A., E. et al. (2017)	Radiography	0.07	29.29
	Haw, Battenberg et al. (2017)	Radiography	0.052	33.09
	Khoshbin, Wu et al. (2020)	Retrieved THR	0.0387	31.51
	Range	-	0.039 – 0.07	29.3 - 33.1
	Current study	FEA	0.0375	33.8
UHMWPE	Ali, Al-Hajjar et al. (2016)	Hip Simulator	0.24	12.2
	Trommer, Maru et al. (2015)	Hip Simulator	0.8	56
	Callaghan, Pedersen et al. (2003)	Clinical database	0.08 - 0.12	32.71 - 89.27
	Fialho, Fernandes et al. (2007)	Computational Method	0.09	18
	Literature range	-	0.08 - 0.8	12.2 - 89.3

257

As XLPE liners are a relatively new material (around 15 years) compared to conventional ultra-highmolecular-weight polyethylene (UHMWPE) (around 50 years), many of the primary THR conducted are still currently in service and the investigation on the wear rate is mainly based on radiography as shown in the above literature. Radiography is unable to show the wear pattern on the bearing surface which is paramount to understanding the evolution of wear. The wear algorithm presented in this study can show the wear pattern and highlight areas of concern.

264 To further understand and compare the wear evolution, the wear patterns of conventional

265 UHMWPE were compared with the results shown in this study (see Table 2). A study by Ali, Al-Hajjar

et al. (2016) and Trommer, Maru et al. (2015) which both used a commercial hip simulator to

- 267 evaluate the wear at 5 million load cycles showed a linear and volumetric wear rate of 0.24mm/yr
- and 12.2mm³/yr for a 36mm CoCr femoral head and 0.8mm/yr and 56mm³/yr for a 28mm CoCr
- 269 femoral head. Callaghan, Pedersen et al. (2003) used a clinical database of more than 4000 primary
- 270 THRs with 22mm and 28mm femoral head sizes implanted by a surgeon to evaluate the wear
- 271 mechanism between 5 and 22 years. The range of linear and volumetric wear presented was 0.08 -

- 272 0.12mm/yr and 32.71 89.27mm³/yr respectively. Fialho, Fernandes et al. (2007) used a
- computational method to predict the extent of wear damage for a 28mm CoCr head size at 1 million
 load cycles. The study showed a linear and volumetric wear rate of 0.09mm/Mc and 18mm³/Mc.
- 275 The range of linear and volumetric wear presented for conventional UHMWPE liners in the above
- 276 studies (Callaghan, Pedersen et al. 2003, Fialho, Fernandes et al. 2007, Trommer, Maru et al. 2015,
- Ali, Al-Hajjar et al. 2016) was between 0.08 0.24mm/Mc and 12.2 89.27mm³/yr respectively.
- 278 Although the wear patterns in our study are comparable to the wear pattern shown in conventional
- 279 UHMWPE, the linear and volumetric wear rates of conventional UHMWPE are higher than the values
- shown in XLPE as the overall amount of wear of XLPE may be up to 40% less (Ali, Al-Hajjar et al.
- 281 2016) than conventional UHMWPE (see Table 2).
- Although in this study we have used zero tolerances between the femoral head and bearing liner,
- 283 defining tolerances for manufacturing is crucial. The tolerances may also translate into bearing
- surface clearances which will affect the outcome of wear and implant survivability. Surface
- roughness may also influence wear. There have been studies which incorporate surface roughness
- into the wear coefficient to simulate the actual wear (Pietrabissa, Raimondi et al. 1998, Raimondi,
- 287 Santambrogio et al. 2001). The algorithm developed in this study can be used to perform parametric
- 288 studies to propose the optimum tolerances for manufacturing and surface roughness.
- A fixed friction coefficient and wear coefficient has been used in this study; however, they can be
- 290 continuously changed over the implant's lifetime due to the changes in surface roughness,
- 291 lubrication and wear debris. The algorithm developed in this study can investigate the effect of
- 292 different friction and wear coefficients to improve the design and material characteristics of the
- 293 implant.

294 **5.** Conclusion

- 295 The combination of using a wear algorithm written in the PDE and a 3D FE model presented in this
- study can be used to predict the extent of bearing surface wear damage for millions of load cycles.
- 297 The algorithm developed can be applied to clinical practice such as determining appropriate bearing
- 298 size, bearing liner thickness, implantation angle, and to improve the design of the prosthesis to
- 299 increase its longevity.
- 300 The methodology demonstrates that a dynamic implicit analysis can model the gait cycle effectively.
- The total dissipated energy wear law and the FE model described can predict wear patterns, linear
- and volumetric wear rates when compared to typically observed wear patterns from UHMWPE
- 303 retrievals and XLPE in-vivo wear rates. These results have been validated with literature and show
- 304 promise in predicting the evolution of wear and can be used to investigate different parameters such 305 as body weight, material properties, different implant size and design, manufacturing tolerances and
- 306 different surgical techniques.
- The accurate and smooth evolution of wear across the bearing surface are influenced by the scalingfactor and mesh size used. Using a courser mesh density and a large scaling factor would reduce the
- 309 computational time but will affect the accuracy of the results. A smaller scaling factor (Figure 12)
- 310 would ensure that the wear is evenly distributed and will avoid cyclic wear 'hotspots' being overly
- 311 exaggerated. A fine mesh and a small scaling factor can facilitate an accurate and smooth
- development of wear but with the cost of a much-increased computational time. To help reduce the
- computational time, a node smoothing feature was developed to be used so there is no sudden
- exaggeration in the node wear. As such, a balance of mesh density and the scaling factor is needed
- to ensure accurate results within a reasonable time. For example, the model presented in this study

- has utilised a scaling factor of 100,000 coupled with the node smoothing feature was found to
- 317 provide a smooth wear evolution.
- 318 The wear methodology can be utilised generically in the analysis of other prosthetic devices such as
- knee and shoulder implants. Also, the method can be generalised to involve parts in contact subject
- 320 to cyclic loadings.

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