Toh, SMS, Ashkanfar, A, English, R and Rothwell, G

The relation between body weight and wear in Total Hip Prosthesis: A finite element study

Journal Pre-proof

The relation between body weight and wear in Total Hip Prosthesis: A finite element study

Shawn Ming Song Toh , Ariyan Ashkanfar , Russell English , Glynn Rothwell

PII: S2666-9900(22)00011-8
DOI: https://doi.org/10.1016/j.cmpbup.2022.100060
Reference: CMPBUP 100060

To appear in: *Computer Methods and Programs in Biomedicine Update*

Received date: 23 September 2021
Revised date: 25 April 2022
Accepted date: 21 May 2022

Please cite this article as: Shawn Ming Song Toh , Ariyan Ashkanfar , Russell English , Glynn Rothwell , The relation between body weight and wear in Total Hip Prosthesis: A finite element study, *Computer Methods and Programs in Biomedicine Update* (2022), doi: https://doi.org/10.1016/j.cmpbup.2022.100060

The relation between body weight and wear in Total Hip Prosthesis: A finite element study

Shawn Ming Song Toh[1] , Ariyan Ashkanfar[1] , Russell English[1] , Glynn Rothwell[1]

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

Corresponding Author:

Shawn Ming Song Toh
School of Engineering, Liverpool John Moores University,
Byrom Street, Liverpool, L3 3AF, UK
Email: s.m.toh@2016.ljmu.ac.uk , shawntoh15@gmail.com
Mobile Number: +44 7708366645

The relation between body weight and wear in Total Hip Prosthesis: A finite element study

Shawn Ming Song Toh[1], Ariyan Ashkanfar, Russell English, Glynn Rothwell
School of Engineering, Liverpool John Moores University, Byrom Street, Liverpool, L3 3AF, UK

Highlights

- A novel wear algorithm was developed to simulate wear in hip implants.
- Hip implant was modelled to simulate a walking up to 5 million cycles.
- Femoral head accounts for approximately 95% of metallic wear.
- Increased patient weight showed up to 30% extra wear compared to average weight.

Abstract

As the current obesity epidemic grows, an increased number of obese patients undergoing Total Hip Arthroplasty (THA) can be expected in the coming years. The National Health Service of the UK (NHS) recommends that an obese patient should undergo weight loss before THA. It is understood that an increased body weight would increase the wear rates on the prostheses, however, the extent of increased wear and the impact on the longevity of the prosthesis is unclear. The NHS found that 45% of THA failures in 2019 were caused by wear which led to a multitude of failures such as infection, aseptic loosening and dislocation such that a revision surgery is then needed. In this study, a finite element model was created to model a walking cycle and a newly developed wear algorithm was used to perform a series of computational wear analyses to investigate the effect of different patient weights on the evolution of wear in THAs up to 5 million cycles. The wear rates shown in this study are closely comparable to previous literature. The XLPE volumetric wear rates were found to be between 15 – 35mm^3/yr (range: 1.5 – 57.6mm^3/yr) and femoral head taper surface volumetric wear rates were between 0.174 – 0.225mm^3/yr (range: 0.01 – 3.15mm^3/yr). The results also showed that an increased weight of 140kg can increase the metallic wear by 26% and polyethylene wear by 30% when compared to 100kg body weight. As increased wear can lead to a multitude of failure such as aseptic loosening, dislocation and metallosis, from this study, it is recommended that obese patients undergo recommended weight loss and maintain this lesser weight to reduce wear and prolong the life of the THA.

Keywords: Wear Modelling, Total Hip Arthroplasty, Hip Joint Prosthesis, Finite Element Modelling, Fretting Wear, Polyethylene Wear

1. Introduction

In recent years, there have been a rise in obesity in adults and is now being described as reaching epidemic proportions [1]. Generally, obesity is measured based on the body mass index (BMI) which divides the body weight in kilograms by the square of the body height in meters. According to the National Health Service, UK (NHS), the classification for an overweight person is someone with a BMI

[1] Corresponding Author
Email addresses: s.m.toh@2016.ljmu.ac.uk , shawntoh15@gmail.com

over 25, an obese person has a BMI over 30, and a morbidly obese person has a BMI over 40. Between 1993 and 2019, the Health Survey for England (HSE) showed an increase of 11% of adults who are either overweight or obese [2]. It can also be seen that, during the COVID-19 pandemic, approximately 27% of the 7,753 participants in a study have had an increase in their body weight [3].

It is projected that just under 5 million people across the UK will be classed as morbidly obese by the year 2035 which is a 165% increase from 1.9 million in 2015 [4]. With increasing numbers of people being obese, it is also expected that the number of obese patient's receiving total hip arthroplasty (THA) will also increase in the coming years. It was found that the mean age of a THA recipient was 10 years younger for morbidly obese patients when compared to those with a normal BMI [5]. Morbidly obese patients would normally be advised to undergo weight loss before a THA is performed, however, it may depend on the circumstances [6]. Several studies in the literature have examined the impact of obesity on the longevity of THAs, which all found that there was no significant difference in the rates of complication or revision surgery between obese and non-obese patients [7-11]. Although, it has also been shown that obese patients would have a lower satisfaction and range of movement when compared to non-obese patients, arthroplasty would still be advised [11, 12].

Traina, Bordini [13] investigated the revision rates of THAs with the BMI and body weight as the main categories. The BMI category was subdivided into normal, overweight, obese, and morbidly obese while the body weight category was subdivided into less than 80kg and above 80kg. The statistics showed that BMI had no effect on the revision rates, however, the revision rates were higher for patients above 80kg. This showed that weight rather than BMI influences the survival of hip prostheses. Other studies have also suggested that BMI should not be an indicator of hip arthroplasty risk, but rather their weight as the loading applied to an implant depends on the weight of the patients [7, 9-11, 13-19].

A THA normally consists of 4 components, acetabular cup, acetabular bearing liner, femoral head, and femoral stem with 2 contacting surfaces. Wear is known to be the main cause of premature failures in THAs and can cause a multitude of failures such as aseptic loosening, dislocation, infection or metallosis. The sites of wear can be found at the contacting surfaces between the femoral head and bearing liner, and the contacting surfaces at the taper junction between the femoral head and stem. There are many factors which can influence the longevity on the implant. Current literature on the impact of body weight on the wear rates of a THA is unknown. In this study, the effect of body weight in THAs is investigated to provide a clearer understanding on evolution of wear damage and wear patterns up to 5 million cycles at both the bearing surfaces and taper junction. This equates to approximately 5 years as it is estimated that 1 million cycles are walked by a patient in one year [20].

2. **Methodology**

2.1. Finite Element Model

A finite element model of the acetabular cup with an acetabular cup liner insert, femoral head and femoral stem was created in a finite element package (ABAQUS 2019) (Figure 1a). In this study, a THA prosthesis with a 36mm femoral head was considered for this study. The acetabular cup was modelled to include a 4mm thick liner and a 3mm thick metal backing [21]. The materials used in this analysis are Cobalt-Chromium (CoCr) for the femoral head, highly cross-linked polyethylene (XLPE) for the bearing liner and Titanium (Ti) for the femoral stem and acetabular cup metal backing. The material and interaction properties are shown in Table 1 [22]. A body weight of 60kg is then applied to the model and the analysis was completed to 5 million walking cycles. An average of 1 million walking cycles per year has been assumed in this study [20] to compare the results of the study to results from literature. The body weight applied on the model was then changed to 80kg and further increased in increments of 20kg up to 140kg.

The computational model has also modelled the initial impaction to simulate the assembly of the head onto the stem. In a previous study [23], a 4kN initial assembly force was found to be optimal and as such, used for all the models subsequently (see Figure 1a). To replicate a walking cycle, the walking loadings and rotations following their amplitude for a gait cycle is shown in Figure 1b and Figure 1c respectively [24]. The models were then meshed using eight-node bilinear hexahedral reduced integration elements (C3D8R). The model is then submitted as a dynamic implicit analysis and the analysis time is discretised into 10 equal time intervals over 1.2 second period. A mesh convergence analysis has been performed with an approximate element size of 0.8mm for both acetabular liner and femoral head, and 0.4mm for the femoral stem.

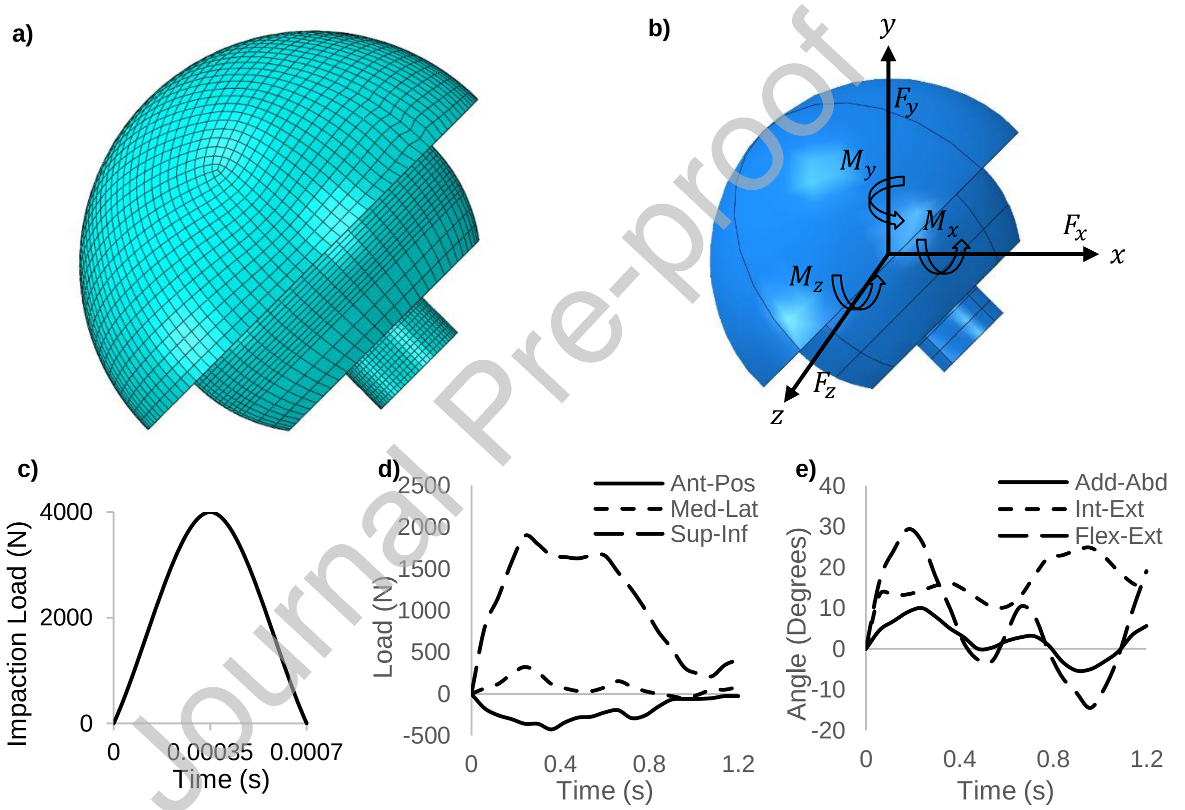

Figure 1: a) FE model with mesh, b) Point of loadings and rotations applied associated with a gait cycle c) Impaction load, d) Loadings of a gait cycle, e) Rotations of a gait cycle

Table 1: Material Properties for THA with interaction properties, Friction Coefficient (FC), Wear coefficient (WC) and Wear Fractions (WF)

Material	Young's Modulus (GPa)	Density (kg/m^3)	Poisson's Ratio	Interaction properties	
Ti	114	4430	0.34	Ti - CoCr: FC: 0.21 [25] WC: 1.31 x 10^{-8} MPa^{-1} [26] WF: 0.9 CoCr : 0.1 Ti [27]	-
CoCr	210	7800	0.3		XLPE - CoCr: FC: 0.11 [28] WC: 4.84 x 10^{-8} MPa^{-1} [29] WF: 0.99 XLPE: 0.01 CoCr [30]
XLPE	1	963	0.4	-	

2.2. Wear Law

The “Dissipated Energy” wear law-predicts wear across a wide range of motion and has been used in this study [31, 32]. This law considers the interfacial shear work and relative motion as predominant parameters to calculate the volumetric wear. Its’ implementation and methodology into the finite element analysis model has been explained previously by Toh, Ashkanfar [33] and English, Ashkanfar [27]. Briefly, according to the “Dissipated Energy” wear law, the total wear depth (W_d) for β walking cycles can be determined using Equation (1), where β is the scaling factor used, α is the energy wear coefficient, τ_i and s_i are the surface contact shear stress, and relative displacement respectively, over the total time interval, *n*, and specified time interval ***i***. As the simulation would be performed for up to 5 million cycles, a scaling factor is introduced to execute the analysis which can vary across a large range. A previous study on the effect of β on the calculation of wear demonstrated that β = 105 modelled the evolution of wear accurately and smoothly within an acceptable amount of time [27].

$$W_d = \beta \sum_{i}^{n} \alpha\, \tau_i s_i \qquad (1)$$

As the wear depth is the total wear on both the interacting surfaces, a wear fraction is introduced as different fractions of wear would be removed from the individual parts. The wear fraction is dependent on the material interaction properties. The wear fractions and wear coefficients used in this study are shown in Table 1.

In previous studies, an in-house Python algorithm was developed to simulate micromotion wear (fretting wear) [27]. Utilising the framework of the fretting wear algorithm, a new algorithm was developed to simulate wear at the bearing surfaces of the prostheses [33]. This algorithm was validated against over 50 clinical retrievals. The algorithm was used to investigate different factors which contribute to fretting wear such as manufacturing tolerances resulting from taper mismatch [34], surgical techniques during assembly of the prostheses [23], and different surface roughness [35]. In this study, we have further developed the wear algorithm to combine both fretting and the bearing surface wear within the same analysis. Further add-ons have also been developed for this wear algorithm in order to calculate the total volumetric material loss and volumetric wear rate for each individual part to investigate and compare the material loss individually at each surface pairs.

3. Results

The linear and volumetric wear rates at the bearing surfaces and taper junction of THA shown in this section were presented at each million cycles as the solution progressed. In order to investigate the effect of body weight on the wear evolution damage, the wear patterns are only shown on the XLPE bearing liner (Figure 2) and head taper surfaces (Figure 3). This is mainly because these surfaces carry 99% and 90% of the wear fraction calculated respectively.

It can be seen in Figure 2 for the XLPE bearing liner, by increasing the body weight the maximum linear wear increases also. For 60kg BW, the maximum linear wear was found to be 0.083mm at the end of 5 million load cycles, while for 140kg BW it had increased by 2.7 times to 0.221mm. However, the maximum linear wear at the femoral taper surface for all body weights is almost constant at approximately 0.004mm.

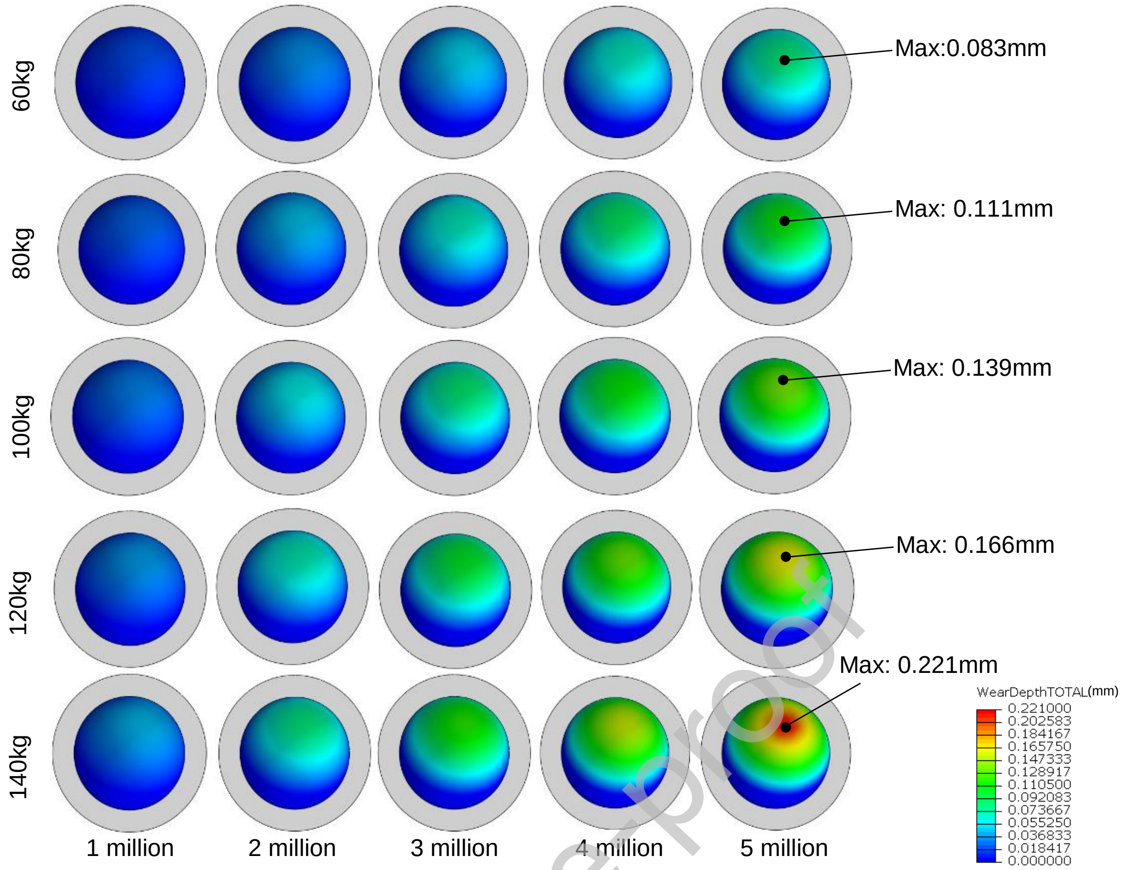

Figure 2: Evolution of wear pattern on the XLPE bearing liner during wear analysis for different patient's weights

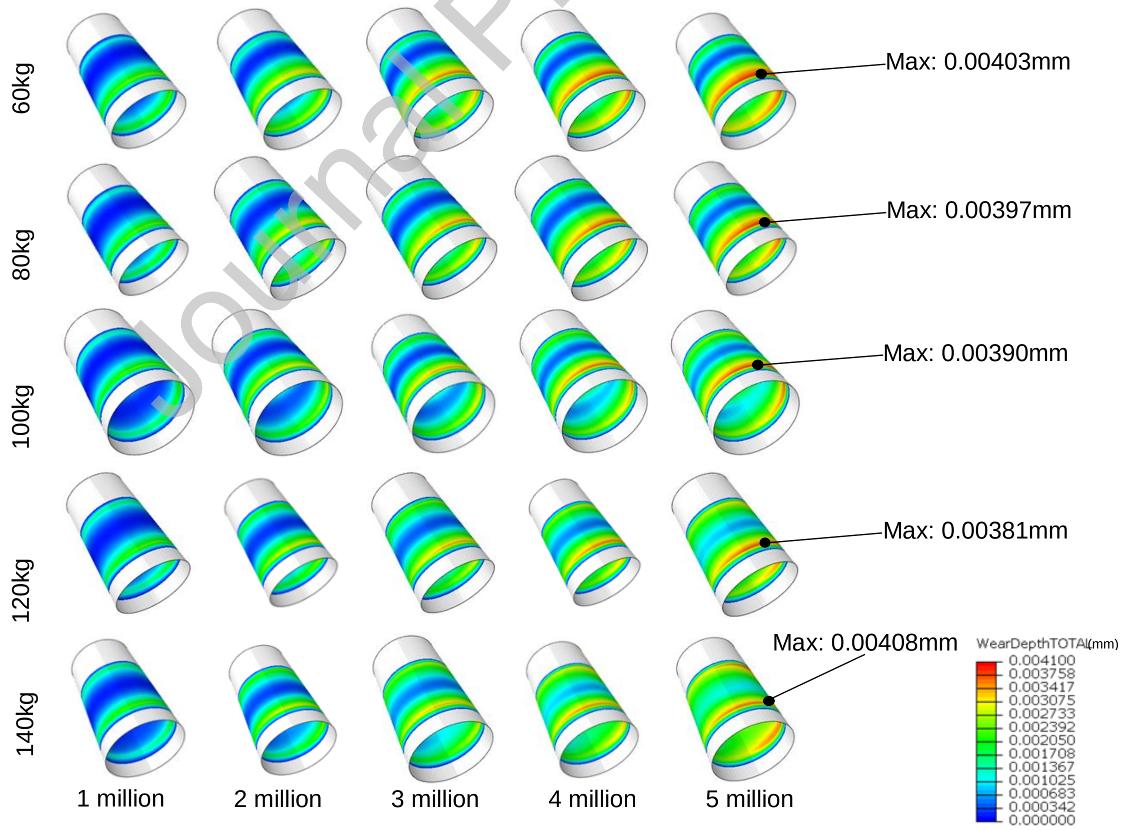

Figure 3: Evolution of wear pattern on the femoral head taper surface during wear analysis for different patient's weight

Figure 4 shows the volumetric wear and volumetric wear rates over 5 million cycles at the XLPE bearing liner. It can be seen in Figure 4a that the volumetric wear in all cases increases linearly. The total volume loss for 60kg BW is 75mm^3 while for a 140kg BW, it increases to 175mm^3. This linear behaviour is further highlighted in Figure 4b which shows a constant volumetric wear rate of 15mm^3/Mc for 60kg BW and increases to 35mm^3/Mc for 140kg BW.

As shown in Figure 2, although the wear damage for all BWs has a similar pattern, the linear wear for 140kg BW is 2.7 times higher than 60kg BW. It can be seen in Figure 4a, increasing the BW from 60kg to 140kg in 20kg intervals, the volumetric wear of the XLPE bearing liner increases linearly by 25mm^3 at each interval over a 5 million load cycle.

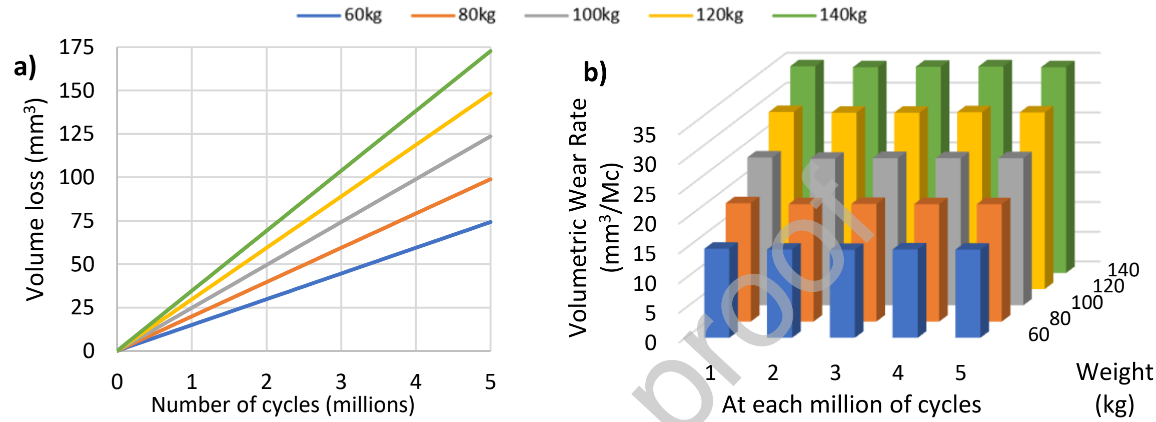

Figure 4:XLPE liner a) total volumetric wear b) volumetric wear rates over 5 million cycles

Figure 5 shows the volumetric wear and volumetric wear rates over 5 million cycles at the bearing surface of the femoral head. The total volume loss for 60kg BW is 0.7mm^3 while for 140kg BW, it increases to 1.65mm^3. The linear behaviour of the volume loss is further highlighted in Figure 5b which shows a constant volumetric wear rate of 0.14mm^3/Mc for 60kg BW which increases to 0.33mm^3/Mc for 140kg BW.

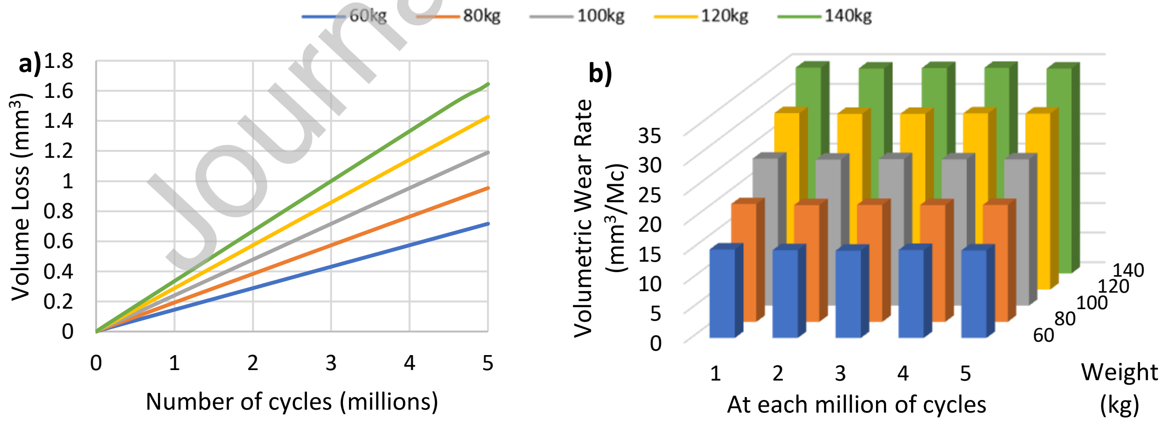

Figure 5: Femoral head bearing surface a) total volumetric wear, b) volumetric wear rates over 5 million cycles

Figure 6 shows the volumetric wear and volumetric wear rates over 5 million cycles at the femoral head taper surface. The total volume loss over 5 million load cycles is similar for body weights from 60kg to 100kg at 0.85mm^3. While this total volume loss increases by 1.3 times to 1.12mm^3 for a body weight of 140kg. It can further be seen in Figure 6b that the volumetric wear rate at the 1st million load cycle is equal to 0.34mm^3/Mc for all cases regardless of the body weights. While it decreases to 0.08mm^3/Mc and 0.19mm^3/Mc for 60kg and 140kg BW respectively over the 5 million load cycles.

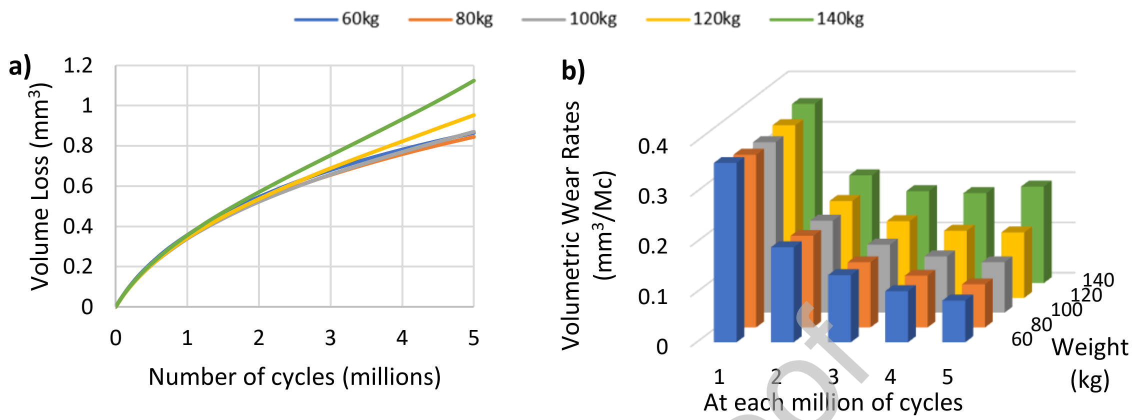

Figure 6: Femoral Head taper junction a) total volumetric wear, b) volumetric wear rates over 5 million cycles

Figure 7 shows the volumetric wear and volumetric wear rates over 5 million cycles for the femoral stem taper surface. The total volume loss evolution over 5 million load cycles follows a similar trend for body weights from 60kg to 100kg at an approximate maximum value of 0.08mm^3 while it increases to approximately 0.11mm^3 and 0.13mm^3 for 120kg and 140kg BW respectively.

It can be further seen in Figure 7b that there is an initial higher volumetric wear rate of 0.046mm^3/Mc on average which decreases to 0.015mm^3/Mc at the end of the 2nd million cycle for a body weight of 60kg and further decreases to approximately 0.005mm^3/Mc between the 3rd and 5th million cycle. The decrease in volumetric wear rates between 1 to 2 million cycle can be attributed to the removal of the initial taper locking effect which is explained further in depth by English, Ashkanfar [27]. The same exponentially decreasing trend is seen as the body weight increases to 100kg, where the initial volumetric wear rate was 0.041mm^3/Mc and decreases to 0.021mm^3/Mc at the end the 2nd million cycle and further decreases to approximately 0.0088mm^3/Mc between the 3rd and 5th million cycle. As the BW increases past 100kg, the volumetric wear loss for 140kg BW retains its initial high volumetric wear rate, however, the volumetric wear rate remains similar at 0.022mm^3/Mc between the 2nd million cycle and 5th million cycle.

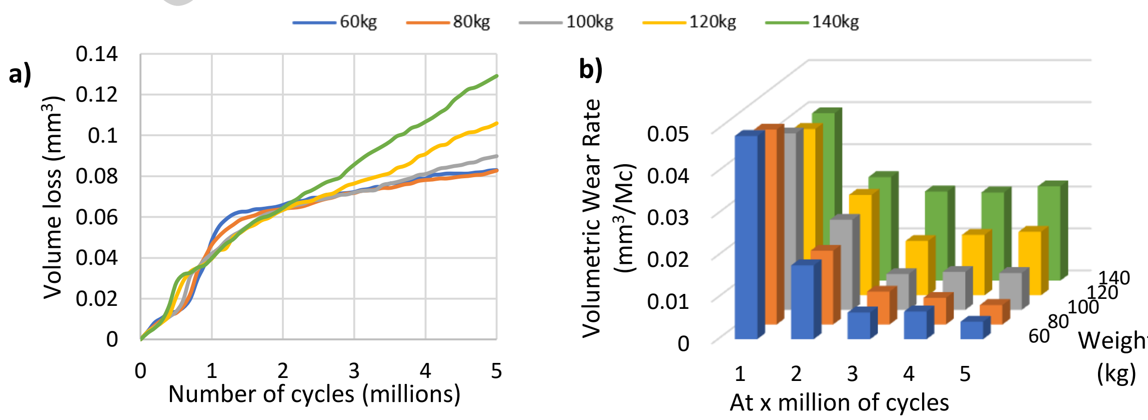

Figure 7:Femoral stem a) total volumetric wear b) volumetric wear rates over 5 million cycles

4. Discussion

The FE wear model and results presented in this study has clearly shown that heavier body weight increases the wear damage at contacting surfaces. Due to the Data Protection Act it is not possible to access any details about patient's weight and prostheses from the studies performed on retrievals [34, 36-40], however, the results obtained in this study are within range of published literature on retrievals as shown in Table 2 and Table 3 and highlights the amount of increased wear based on different body weights.

The results highlight that the body weight is directly proportional to the amount of volumetric wear on the bearing contacting surfaces. The XLPE volumetric wear rates reported in this study are closely comparable to results in the literature [36-39] (see Table 2). As XLPE liners are a relatively new material (around 15 years) compared to conventional polyethylene (around 50 years), many of the primary hip arthroplasty performed are still in service. Hence, the main method for analysing wear is through radiography. Khoshbin, Wu [36] analysed a total of 40 primary THA of XLPE liners with CoCr femoral heads and found the volumetric wear rate was between 7.8 – 31.51mm^3/yr. Devane, Horne [37] analysed a total of 57 primary THA of XLPE liners with CoCr femoral heads and found the volumetric wear rate was between 1.5 – 18.9mm^3/yr. Haw, Battenberg [38] analysed a total of 48 primary THA of XLPE liners with CoCr femoral heads and found the volumetric wear rate was between 19.2 – 46.9 mm^3/yr. A., E. [39] analysed a total of 102 primary THA of XLPE liners with CoCr femoral heads and found the volumetric wear rate was between 5.82 – 52.76mm^3/yr.

Table 2: Volumetric wear rates of XLPE liner in contact with CoCr femoral via radiography

Literature	Volumetric Wear (mm^3/yr)
Khoshbin, Wu [36]	7.8 – 31.51
Devane, Horne [37]	1.5 – 18.9
Haw, Battenberg [38]	19.2 – 46.9
A., E. [39]	5.82 – 52.76
Range	**1.5 – 57.6**
Current Study	**15 – 35**

The volumetric wear rates reported in this study are closely comparable to results in the literature [34, 40] (see Table 3). A co-ordinate measuring machine (CMM) has been previously used to measure the volumetric wear at 54 retrieved femoral head tapers. It showed the mean volumetric wear rate was 0.475mm^3/yr with a range between 0.021 – 1.860 mm^3/yr. Additionally, a study by J., R. [40] also used a CMM to measure the volumetric wear rate at the taper surface of 48 retrieved hip prostheses and found the mean volumetric wear rate to be 0.127mm^3/yr with a range between 0.01 – 3.15mm^3/yr. Considering different BWs in this study, the mean volumetric wear up to 5 million cycles in this study was between 0.174 – 0.225mm^3/Mc for 60 – 140kg BWs which is within the range in literature of 0.01 – 3.15mm^3/yr.

Table 3: Volumetric wear rates of femoral head taper surface in literature

Literature	Mean Volumetric Wear (mm^3/yr) (range)
Ashkanfar, Langton [34]	0.475 (0.021 – 1.860)
J., R. [40]	0.127 (0.01 – 3.15)
Range	0.01 – 3.15
Current Study	0.174 – 0.225

As there are many variables which could influence the wear rates, such as patient's activity level, weight, surgical techniques, and prostheses design variations, there is a large range of volumetric wear rates as shown in the above studies.

Although the femoral head bearing surface accounts for 1% and the femoral head taper surface accounts for 90% of the total wear between their respective surfaces, it can be seen in Figure 8, for a 60kg BW, the taper surface accounts for 56% of the total volumetric wear on the femoral ball and decreases to 40% for a 140kg BW. This highlights the relative high amount of wear at the bearing surface despite having a low wear fraction.

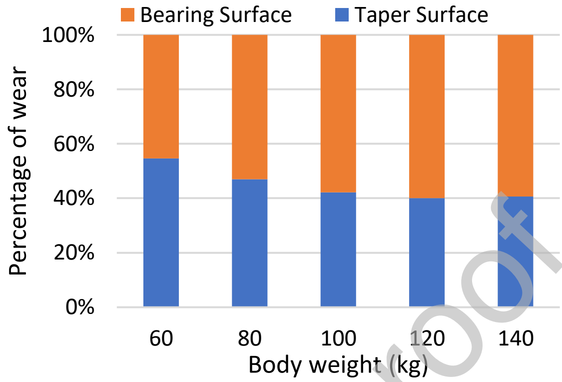

Figure 8: Percentage of wear between the bearing surface and taper surface at the femoral ball at 5 million cycles

Metallosis is the adverse reaction to metallic ions in the body which can lead to a variety of complications such as, infection, dislocation, or even the death of the tissue surrounding the prostheses [41]. Figure 9 shows the total metallic volumetric loss of the components in this study from the femoral head bearing and taper surface, and the femoral stem taper. It can be seen that approximately 95% of metallic wear loss is from the femoral head for all different BWs. At lower BW's, the main metallic wear loss is from the femoral head taper surface at approximately 52%. However, as BW increases, this metallic wear decreases to just 38% and the majority of wear shifts to the femoral head bearing surface.

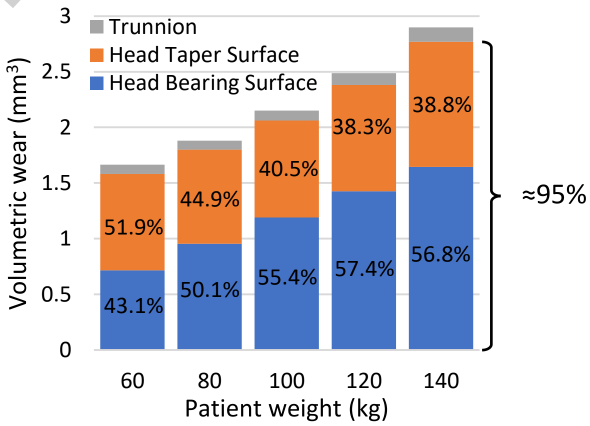

Figure 9: Total metallic volumetric wear at 5 million cycles

There are a variety of manufacturing and surgical factors, such as a taper mismatch or different assembly loads, which may affect the longevity of the prostheses in terms of wear. Although in this study zero taper mismatch was assumed, previous investigations showed an acceptable 6" taper mismatch did not significantly increase the wear rates [34]. Another factor which could affect the wear rates is the effect of assembly loads during impaction of the modular head onto the femoral stem trunnion. It was found that a minimum assembly load of 4kN was needed to minimise wear rates. A lower assembly load below 4kN would severely increase the total volumetric wear loss at the taper junction [23].

5. Conclusion

To further improve the design and ultimately increase the longevity of THAs, it is crucial to understand the evolution of wear throughout the lifespan of these devices. In this study, our previous wear algorithms have been further developed to investigate the effect of different patient weights on the evolution of wear at the contacting surfaces of the implants. The result of this study showed that reducing the initial BW from 140kg to 100kg before THA would decrease the metallic wear by 26% and polyethylene wear by 30%. This can significantly improve the longevity of the prosthesis. As such losing weight down to 100kg before THA can be highly recommended, however, further research is required to investigate the effect of losing weight on the longevity of these devices while in service.

Acknowledgement

This work is funded by the School of Engineering, Liverpool John Moores University, Liverpool, UK.

References

1. Ayton, A. and A. Ibrahim, *Obesity is a public health emergency.* BMJ : British Medical Journal (Online), 2019. **366**.
2. NHS, *Health Survey for England 2019: Overweight and obesity in adults and children.* 2020.
3. Flanagan, E.W., et al., *The Impact of COVID-19 Stay-At-Home Orders on Health Behaviors in Adults.* Obesity, 2021. **29**(2): p. 438-445.
4. Keaver, L., et al., *Morbid obesity in the UK: A modelling projection study to 2035.* Scandinavian Journal of Public Health, 2020. **48**(4): p. 422-427.
5. M., C., et al., *The relationship between obesity and the age at which hip and knee replacement is undertaken.* The Journal of Bone and Joint Surgery. British volume, 2008. **90-B**(3): p. 360-363.
6. NHS, *Hip and knee replacement surgery in obese patients.* 2019.
7. Andrew, J., et al., *Obesity in total hip replacement.* The Journal of bone and joint surgery. British volume, 2008. **90**(4): p. 424-429.
8. Jackson, M., et al., *The effect of obesity on the mid-term survival and clinical outcome of cementless total hip replacement.* The Journal of bone and joint surgery. British volume, 2009. **91**(10): p. 1296-1300.
9. Ibrahim, T., et al., *No influence of body mass index on early outcome following total hip arthroplasty.* International Orthopaedics, 2005. **29**(6): p. 359-361.
10. Michalka, P.K., et al., *The influence of obesity on early outcomes in primary hip arthroplasty.* The Journal of arthroplasty, 2012. **27**(3): p. 391-396.
11. Yeung, E., et al., *The effect of obesity on the outcome of hip and knee arthroplasty.* International orthopaedics, 2011. **35**(6): p. 929-934.
12. Chee, Y., et al., *Total hip replacement in morbidly obese patients with osteoarthritis: results of a prospectively matched study.* The Journal of bone and joint surgery. British volume, 2010. **92**(8): p. 1066-1071.
13. Traina, F., et al., *Patient Weight more than Body Mass Index Influences Total Hip Arthroplasty Long Term Survival.* HIP International, 2011. **21**(6): p. 694-699.
14. Kessler, S. and W. Käfer, *Overweight and Obesity: Two Predictors for Worse Early Outcome in Total Hip Replacement?* Obesity, 2007. **15**(11): p. 2840-2845.
15. McCalden, R., et al., *Does morbid obesity affect the outcome of total hip replacement? An analysis of 3290 THRs.* The Journal of bone and joint surgery. British volume, 2011. **93**(3): p. 321-325.
16. Espehaug, B., et al., *Patient-related risk factors for early revision of total hip replacements: A population register-based case-control study of 674 revised hips.* Acta Orthopaedica Scandinavica, 1997. **68**(3): p. 207-215.
17. McLaughlin, J. and K. Lee, *The outcome of total hip replacement in obese and non-obese patients at 10-to 18-years.* The Journal of bone and joint surgery. British volume, 2006. **88**(10): p. 1286-1292.
18. Moran, M., et al., *Does body mass index affect the early outcome of primary total hip arthroplasty?* The Journal of arthroplasty, 2005. **20**(7): p. 866-869.
19. Haverkamp, D., et al., *Obesity in total hip arthroplasty—does it really matter? A meta-analysis.* Acta orthopaedica, 2011. **82**(4): p. 417-422.
20. Schmalzried, T.P., et al., *Quantitative assessment of walking activity after total hip or knee replacement.* Journal of Bone and Joint Surgery - Series A, 1998. **80**(1): p. 54-59.
21. Shen, F.-W., Z. Lu, and H.A. McKellop, *Wear versus thickness and other features of 5-Mrad crosslinked UHMWPE acetabular liners.* Clinical Orthopaedics and Related Research®, 2011. **469**(2): p. 395-404.
22. Innocenti, B., et al., *Development and validation of a wear model to predict polyethylene wear in a total knee arthroplasty: a finite element analysis.* Lubricants, 2014. **2**(4): p. 193-205.

23. English, R., A. Ashkanfar, and G. Rothwell, *The effect of different assembly loads on taper junction fretting wear in total hip replacements.* Tribology International, 2016. **95**: p. 199-210.
24. Bergmann, G., F. Graichen, and A. Rohlmann, *Hip joint loading during walking and running, measured in two patients.* Journal of Biomechanics, 1993. **26**(8): p. 969-990.
25. Fessler, H. and D.C. Fricker, *Friction in femoral prosthesis and photoelastic model cone taper joints.* Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 1989. **203**(1): p. 1-14.
26. Zhang, T., et al., *A finite element methodology for wear–fatigue analysis for modular hip implants.* Tribology International, 2013. **65**: p. 113-127.
27. English, R., A. Ashkanfar, and G. Rothwell, *A computational approach to fretting wear prediction at the head–stem taper junction of total hip replacements.* Wear, 2015. **338-339**: p. 210-220.
28. Wang, S.B., et al. *Wear behaviour and wear debris characterization of UHMWPE on alumina ceramic, stainless steel, CoCrMo and Ti6Al4V hip prostheses in a hip joint simulator*. in *Journal of Biomimetics, Biomaterials and Tissue Engineering*. 2010. Trans Tech Publ.
29. Matsoukas, G., R. Willing, and I.Y. Kim, *Total Hip Wear Assessment: A Comparison Between Computational and In Vitro Wear Assessment Techniques Using ISO 14242 Loading and Kinematics.* Journal of Biomechanical Engineering, 2009. **131**(4).
30. Anissian, L., et al. *HIP-SIMULATOR WEAR COMPARISONS OF COCR/COCR VERSUS COCR/PE THR AT 10 MILLION CYCLES*. in *Proceedings of the Annual Meeting of the Orthopaedic Research Society, Anaheim, California*. 1999.
31. Fouvry, S., et al., *An energy description of wear mechanisms and its applications to oscillating sliding contacts.* Wear, 2003. **255**(1): p. 287-298.
32. Abdo, J., *Materials Sliding Wear Model Based on Energy Dissipation.* Mechanics of Advanced Materials and Structures, 2015. **22**(4): p. 298-304.
33. Toh, S.M.S., et al., *Computational method for bearing surface wear prediction in total hip replacements.* Journal of the Mechanical Behavior of Biomedical Materials, 2021. **119**: p. 104507.
34. Ashkanfar, A., D.J. Langton, and T.J. Joyce, *A large taper mismatch is one of the key factors behind high wear rates and failure at the taper junction of total hip replacements: A finite element wear analysis.* Journal of the mechanical behavior of biomedical materials, 2017. **69**: p. 257-266.
35. Ashkanfar, A., D.J. Langton, and T.J. Joyce, *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.* Journal of Biomechanics, 2017. **63**: p. 47-54.
36. Khoshbin, A., et al., *Wear Rates of XLPE Nearly 50% Lower Than Previously Thought After Adjusting for Initial Creep: An RCT Comparing 4 Bearing Combinations.* JBJS Open Access, 2020. **5**(2): p. e0066.
37. Devane, P.A., et al., *Highly Cross-Linked Polyethylene Reduces Wear and Revision Rates in Total Hip Arthroplasty: A 10-Year Double-Blinded Randomized Controlled Trial.* JBJS, 2017. **99**(20): p. 1703-1714.
38. Haw, J.G., et al., *Wear Rates of Larger-Diameter Cross-Linked Polyethylene at 5 to 13 Years: Does Liner Thickness or Component Position Matter?* The Journal of Arthroplasty, 2017. **32**(4): p. 1381-1386.
39. A., A., et al., *Ten-year follow-up study of three alternative bearing surfaces used in total hip arthroplasty in young patients.* The Bone & Joint Journal, 2017. **99-B**(12): p. 1590-1595.
40. J., L.D., et al., *Taper junction failure in large-diameter metal-on-metal bearings.* Bone & Joint Research, 2012. **1**(4): p. 56-63.
41. Pritchett, J.W., *Adverse reaction to metal debris: metallosis of the resurfaced hip.* Current Orthopaedic Practice, 2012. **23**(1): p. 50-58.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: