journal of the mechanical behavior of biomedical materials 139 (2023) 105673

Contents lists available at ScienceDirect

Journal of the Mechanical Behavior of Biomedical Materials

journal homepage: www.elsevier.com/locate/jmbbm

How does bicycling affect the longevity of Total Hip Arthroplasty? A finite element wear analysis

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ABSTRACT

As the number of young and active individuals undergoing Total Hip Arthroplasty (THA) are increasing yearly, there is a need for hip prostheses to have increased longevity. Current investigations into the longevity of these prostheses only include walking as the patient's activity as there is limited data on the amount and intensity of other activity performed by the patient. To further understand the evolution of wear and increase the longevity of these implants, the impact of different activities on the hip prosthesis needs to be investigated. In this study, a finite element model and wear algorithm was developed to simulate both walking and bicycling over a 5-year period. The XLPE acetabular cup volumetric wear rate was found to be 33 mm^3/yr while the femoral head taper wear rates were between 0.01 – 0.39 mm^3/yr. The results showed that by adding bicycling of up to 80 km per week with normal walking activity, the XLPE mean volumetric wear rate increased by 67% and the metallic mean volumetric wear rate by 11%. However, the patient may gain further health benefits from this additional activity. Assistive electric bikes may also be used to further reduce the loads on the hip joint, allowing for lower amounts of wear.

1. Introduction

As the number of patients undergoing Total Hip Arthroplasty (THA) increases every year (NJR, 2021), the longevity of the prosthesis is very important for maintaining a healthy active life. As part of the recovery process, the National Health Service (NHS) of the UK recommends patients who have undergone THA to perform regular exercise to restore strength and general mobility. Recreational activities after the recovery period are recommended to have a low to medium impact on the hip joint such as swimming, bicycling and golfing (Buckwalter, 2003). The recommended activities have also evolved throughout the years with further research which saw an increase in the number of sports allowed (Siebert, 2017).

According to a report by STRAVA, Inc. (2021), an exercise tracker, there was a significant increase in the number of people exercising due to the COVID-19 pandemic, with walking and bicycling being the most popular activities recorded. Bicycling saw an 180% increase in participation in 2020 as compared to 2019 (STRAVA, 2021). Although bicycling is becoming increasingly popular for all ages, the effect of sports on the longevity of the prosthesis remains unknown (Ollivier et al., 2012, Meira and Zeni, 2014; Tischer et al., 2019). A study involving 139 surgeons asked their advice regarding participation in fifteen different activities post THA. The results showed that most of the surgeons allowed low impact activities such as swimming, bicycling or golf while high impact sports were commonly discouraged (Swanson et al., 2009; Morgan, 2021). It is important to note that the surgeons did not have strong scientific evidence for these recommendations. Furthermore, other studies have found that most THA patients only participated in recommended activities advised by their surgeon and did not resume higher impact activities, such as jogging, mainly due to fear of damaging the prosthesis (Delasotta et al., 2012; Abe et al., 2014).

Several methods are used to investigate wear damage at the hip prosthesis. These include clinical retrievals investigation (Callaghan et al., 2003; Atrey et al., 2017), hip joint simulator (Trommer et al., 2015; Ali et al., 2016), and computational simulations (Fialho et al., 2007; English et al., 2015; Ashkanfar et al., 2017). Currently, most literature only considers walking as the main activity to investigate wear and longevity of the prostheses as there is limited data on the intensity and duration of other activities while the prosthesis is in service. Computational analysis can aid to understand the effect of different activities (such as bicycling, running and golf) on the wear damage and longevity of the prosthesis. This would help surgeons advise patients on the impact of such activities on the implant.

Sener et al. (2009), Dickinson et al. (2003) and Harms and Kansen

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https://doi.org/10.1016/j.jmbbm.2023.105673
Received 17 June 2022; Received in revised form 12 December 2022; Accepted 7 January 2023
Available online 16 January 2023

(2018) investigated bicycling use in the United States, United Kingdom and Netherlands respectively. Sener et al. (2009) showed an average of 8 km per single trip, Dickinson et al. (2003) showed 7 km per single trip and Harms and Kansen (2018) have shown up to 15 km per single trip. As such in this study 16 km per day has been assumed to simulate an average cycling by a cyclist. The aim was to find out the effect of commuting by bicycle on the longevity of these devices which could show the clinical relevance of this study.

This study aims to investigate the effects of bicycling on the wear rates and longevity of the hip prosthesis. Using an advanced computational wear algorithm, an investigation is performed to study the effect of the inclusion of bicycling (up to 80 km per week) on the wear in the prosthesis alongside the accepted standard of 1 million walking cycles per year (Schmalzried et al., 1998). This study will investigate and compare the wear damage pattern and material loss on a commercial design of hip implant.

2. Methodology

In this study, our previous computational wear algorithm (Toh et al., 2021) has been further developed to include the effect of bicycling on the wear of the hip prosthesis. A finite element (FE) model of the hip prosthesis was created to simulate the loadings and rotations of both walking and bicycling for up to 5 years of activity. In the simulations it has been assumed that a person post THA, walks 15.5 km per week, equivalent to 1 million cycles a year (Schmalzried et al., 1998), and rides a bicycle 80 km a week, equivalent to 400,000 hip rotations per year (Dickinson et al., 2003).

The FE hip prosthesis model features a 3 mm thick Titanium (Ti) shell, a 6 mm thick highly cross-linked polyethylene (XLPE) bearing liner, a 36 mm Cobalt–Chromium (CoCr) femoral head and a Titanium femoral stem with a 12/14 taper as shown in Fig. 1. The material properties assigned on the parts are shown in Table 1.

To replicate a walking and bicycling cycle, the femoral head has been assembled towards the orientation for the respective activities as shown

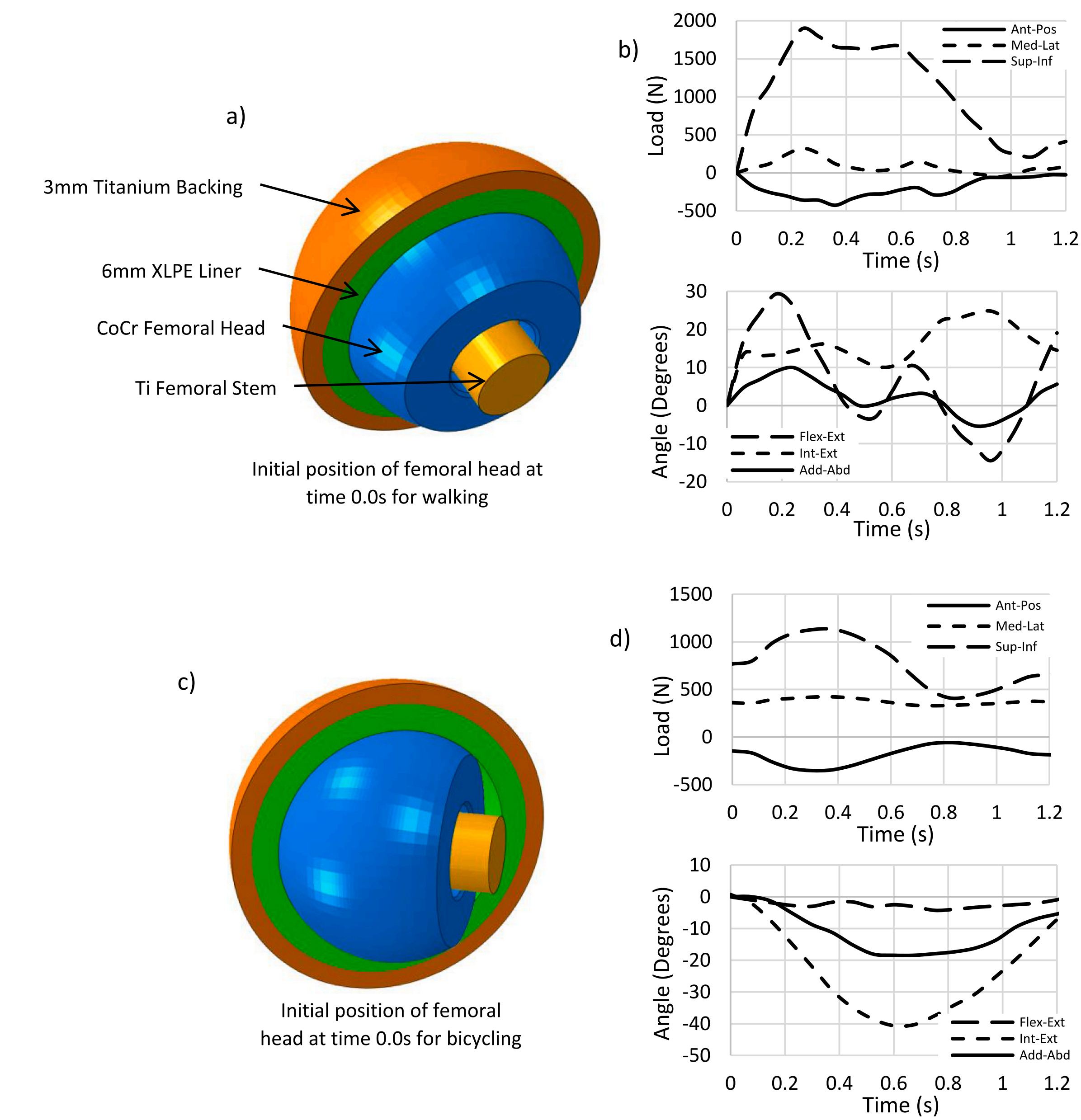

Fig. 1. a) FE model of hip prosthesis assembled for walking, b) Loadings and rotations for walking cycle, c) FE model of hip prosthesis assembled for bicycling cycle, d) Loadings and rotations for bicycling cycle.

Table 1
Material properties for titanium, cobalt–chromium, and XLPE.

Material	Young's Modulus (GPa)	Density (kg/m^3)	Poisson's ration
Ti	114	4430	0.34
CoCr	210	7800	0.3
XLPE	1	963	0.4

in Fig. 1a and c. The respective loadings and rotations for both walking and bicycling are shown in Fig. 1b and d. The material interaction properties for each material combination have been assigned as outlined in Table 2. In order to assemble the femoral head onto the femoral stem, a 4 kN impaction load has been used which provides the optimum initial fixation required for the parts (English et al., 2016).

Our previously developed wear algorithm has been modified to simulate wear for both walking and bicycling within the same analysis. The implementation and in-depth methodology of the wear algorithm has been explained in previous studies, Toh et al. (2021) and English et al. (2015). Briefly, the wear algorithm uses the "Dissipated Energy" wear law (Equation (1)) by considering the material interaction properties shown in Table 2 to calculate the wear depth at each point of the surface interaction:

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

where β is a scaling factor, α is the wear coefficient, and τ_i and s_i is the surface contact shear stress and relative displacement respectively at each time interval of the analysis. This wear algorithm has been validated against over fifty clinical retrievals. The validated algorithm has been used to investigate various factors contributing to wear such as manufacturing tolerances (Ashkanfar et al., 2017), surgical techniques (English et al., 2016), different surface roughness (Ashkanfar et al., 2017), and patient weight (Toh et al., 2022).

In this study, the algorithm has been further developed to simulate the two distinct activities of walking and cycling. As the initial starting position for both walking and bicycling is different, the algorithm repositions prosthesis parts for the initial starting point of the activity, and changes the loadings and rotations applied onto the parts for each activity. The repositioning of the model is achieved through a python script which rotates the femoral head to the initial starting position within the input file. This allows for the analysis to alternate between walking and cycling concurrently. The sequence of loading is the application of 100,000 walking cycles and then 40,000 bicycling cycles, which alternate until 5 million walking cycles and 2 million bicycling cycles have been achieved, equivalent to 5 years of activity (Schmalzried et al., 1998; Dickinson et al., 2003; Sener et al., 2009; Harms and Kansen, 2018). A brief overview of the wear algorithm is shown in Fig. 2.

3. Results

Initially, a study was performed for bicycling only to better understand the wear pattern observed on the XLPE bearing liner due to the difference in range of motion. Fig. 3 compares the wear pattern observed from walking only and bicycling only up to 5 years of activity. The difference in wear area highlights that, different activities may have considerable impact on the evolution of wear rate and the lifespan of the prosthesis. As such, the methodology in this study has been developed to simulate different activities concurrently, 100,000 walking cycles followed by 40,000 bicycling cycles until 5 years of activity is reached.

Table 2
Material interaction properties, Friction Coefficient (FC), Wear Coefficient (WC), and Wear Fractions (WF).

Material Interaction	Interaction properties	
Ti – CoCr	FC: 0.21	Fessler and Fricker, (1989)
	WC: 1.31 x 10^{-8} MPa^{-1}	(Zhang et al., 2013)
	WF: 0.9 CoCr: 0.1 Ti	(English et al., 2015)
CoCr – XLPE	FC: 0.11	(Wang et al., 2010)
	WC: 5.32 x 10^{-10} MPa^{-1}	(Matsoukas et al., 2009)
	WF: 0.99 XLPE: 0.01 CoCr	(Anissian et al., 1999)

Fig. 4 shows the wear pattern of the contacting surfaces of the hip prostheses up to 5 years of concurrent walking and bicycling. At the bearing surfaces, the XLPE liner had a maximum linear wear of 0.28 mm while the femoral head had a maximum linear wear of 0.0018 mm at the end of 5 years. At the taper junction, the femoral head taper surface had a maximum linear wear of 0.0065 mm while the femoral stem had a maximum linear wear of 0.0007 mm. The results are consistent with the wear fraction applied onto the model: 99% wear on the XLPE liner and 1% wear on the femoral head bearing surface, 90% wear on the femoral head taper surface and 10% wear on the femoral stem.

Fig. 5 shows the total volumetric wear and volumetric wear rates over 5 years of walking and bicycling at the XLPE bearing liner, femoral head, and femoral stem. Fig. 5a shows that the XLPE bearing liner has a total volume loss of 166 mm^3 at the end of 5 years, and the volumetric wear rate is maintained at approximately 33 mm^3/yr throughout the analysis.

Fig. 5b shows the total metallic volumetric wear and volumetric wear rate of the femoral head which includes both the wear from the taper junction and the bearing surface. It also shows the proportion of wear distributed between the taper junction and bearing surface. As the analysis progresses, the total volumetric wear increases to approximately 2.06 mm^3, and the volumetric wear rate has an initially high wear rate of 0.63 mm^3/yr and decreases to a stable volumetric wear rate of 0.3 mm^3/yr approximately after 3 years of activity. It can be also seen that the taper junction initially contributes to the higher amounts of wear but decreases as the analysis progresses.

Fig. 5c shows the total volumetric loss and volumetric wear rate at the femoral stem taper. The total volumetric loss increases to approximately 0.088 mm^3 at the end of 5 years of activity. The volumetric wear rate for the femoral stem has an initially high wear rate, approximately 0.053 mm^3/yr' at the end of the first year which quickly decreases to approximately 0.006 mm^3/yr.

4. Discussion

The volumetric wear rates observed in this study are comparable to previous studies in literature as shown in Table 3. As XLPE is a relatively new material (15 years) used in THRs compared to conventional polyethylene (>50 years), many of the prostheses using XLPE bearing liners are still currently in service. Hence, radiography has been used to estimate the volumetric wear loss of the XLPE bearing liner. The use of XLPE has rose quickly as it has better wear characteristics than conventional polyethylene allowing for lower amounts of wear. Khoshbin et al. (2020), Devane et al. (2017), Haw et al. (2017) and Atrey et al. (2017) have used radiography to analyse a total of 247 primary THA with XLPE bearing liners with CoCr femoral heads and found that the volumetric wear rate ranged between 1.5 and 57.6 mm^3/yr. The results in this study of 33 mm^3/yr XLPE volumetric wear rate was within the range obtained from literature.

A co-ordinate measuring machine (CMM) has been previously used to measure the volumetric wear of 54 retrieved femoral stems which reported a mean volumetric wear rate of 0.55 mm^3/yr with a range between 0.02 and 2.241 mm^3/yr (Ashkanfar et al., 2017). Additionally, a study by Langton et al. (2012) 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 0.127 mm^3/yr with a range between 0.01 and 3.15 mm^3/yr. The results in this study of between 0.1 and 0.39 mm^3/yr are within agreement with those in the literature of 0.01–3.15 mm^3/yr.

It is important to note that the results obtained from previous literature do not account for the patients' activity as the amount of activity

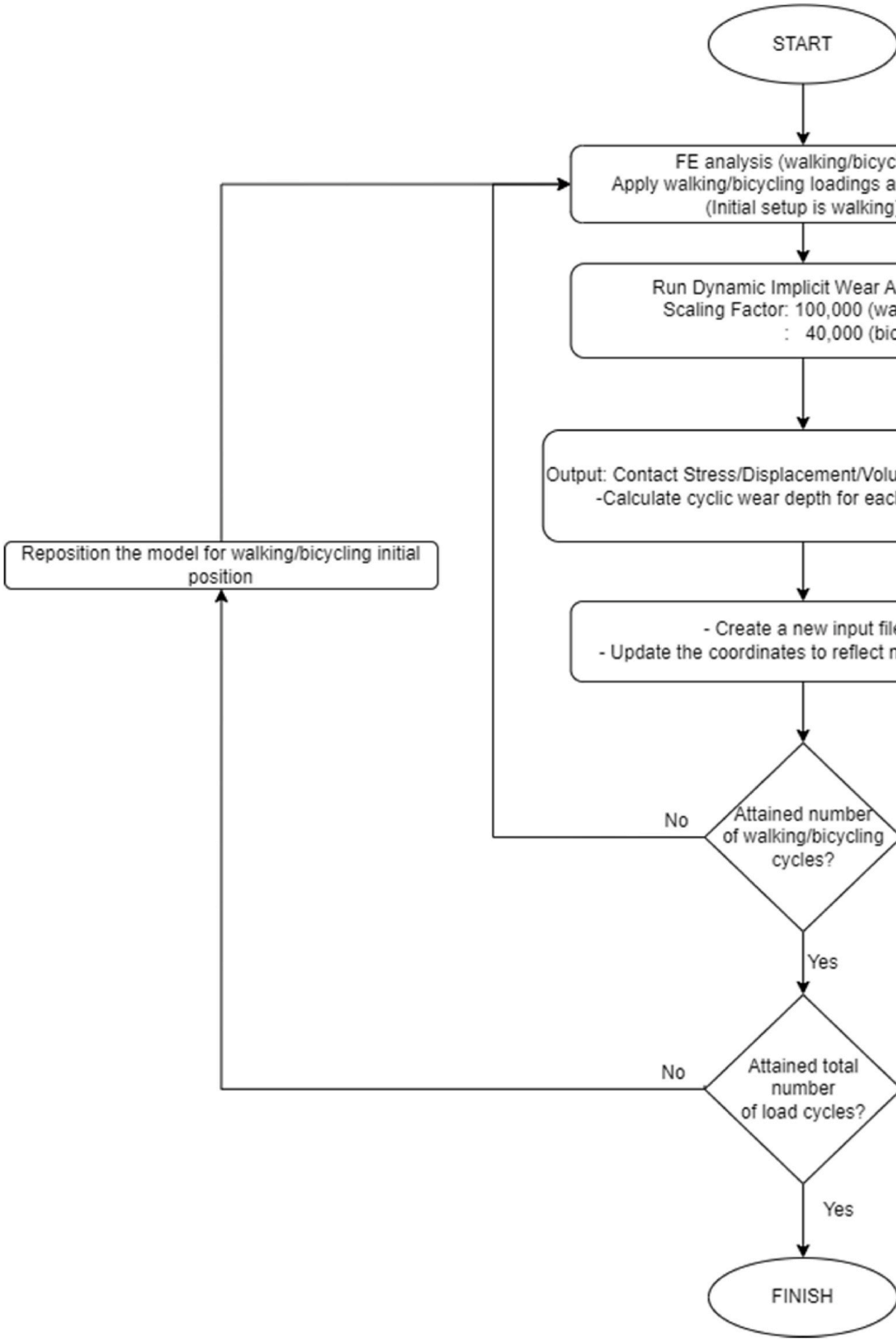

Fig. 2. Brief overview of the developed wear algorithm.

performed by an individual is unknown. Furthermore, a variety of distinct factors can influence prostheses wear such as patient activity, weight, prostheses design, or surgical positioning of components.

Table 4 highlights the increased amount of volumetric wear rate induced by additional bicycling of 80 km per week for 5 years (over walking alone). It can be seen that the mean volumetric wear increases by 67% for XLPE and 11% for metallic wear. Previously, a study by Hall et al. (1996) examined over 100 explanted Charnley UHMWPE sockets and found that the median volume of wear at revision to be 508 mm^3. If UHMWPE and XLPE debris is assumed to have the same effect on the human body, a life span of 25.7 years can be calculated with walking only, compared to 15.4 years with walking and bicycling. Given that the average age of the recipient of an artificial hip joint in the UK is 69 (NJR, 2021), the benefits of exercise such as bicycling over a 15 year period will likely outweigh the drawback of additional polyethylene wear (Oja et al., 2011). It is also important to note that the amount of bicycling simulated in this study was the higher end of activity by the patient. Furthermore, Haw et al. (2017) identified hips with risk of osteolysis to have wear above 80 mm^3/yr. The walking and bicycling wear rate of 33 mm^3/year is less than half of the osteolysis wear rate offered by Haw

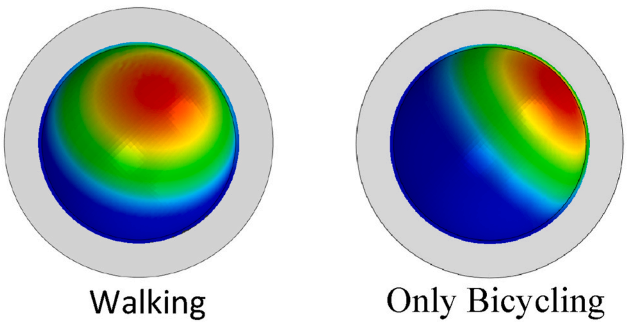

Fig. 3. Comparison of wear patterns between walking and bicycling up to 5 years of XLPE liner.

et al. (2017).

Walking and bicycling are currently two of the most performed activity by a patient. The hip joint forces during a normal walking cycle were found to be between 2.9 and 4.7 times of body weight (Kuster, 2002) while it was found that during bicycling, the hip joint forces are between 0.5 and 1.4 times body weight (Ericson and Nisell, 1986, Damm et al., 2017). To lower the amount of loading the prosthesis experiences during bicycling, THA patients may consider utilising an electric bicycle to reduce the impact on the hip prosthesis especially during uphill bicycling. This will further reduce the wear rates and help patients be active post-surgery.

In this study, the upper limit of 80 km per week for bicycling activity was used to simulate a patient's activity and as such, the findings of this study show the wear of a hip prosthesis higher than what could be seen in patients. This study also has not considered for other activities performed by patients which could be paramount to the wear pattern shown.

5. Conclusion

As the number of THA patients are increasingly active, it is important to investigate the impact of different sports on the wear of the hip prosthesis. In this study, an FE model coupled with an advanced wear algorithm has been used to investigate the impact of bicycling up to 80 km a week on the wear of the contacting surfaces of a hip prosthesis over a period of 5 years. The results have shown that the XLPE bearing liner undergoes steady volumetric wear rate of 33 mm^3/yr, the femoral head undergoes a decreasing volumetric wear rate from 0.54 mm^3/yr to 0.26 mm^3/yr at the end of 5 years, while the femoral stem showed an initial

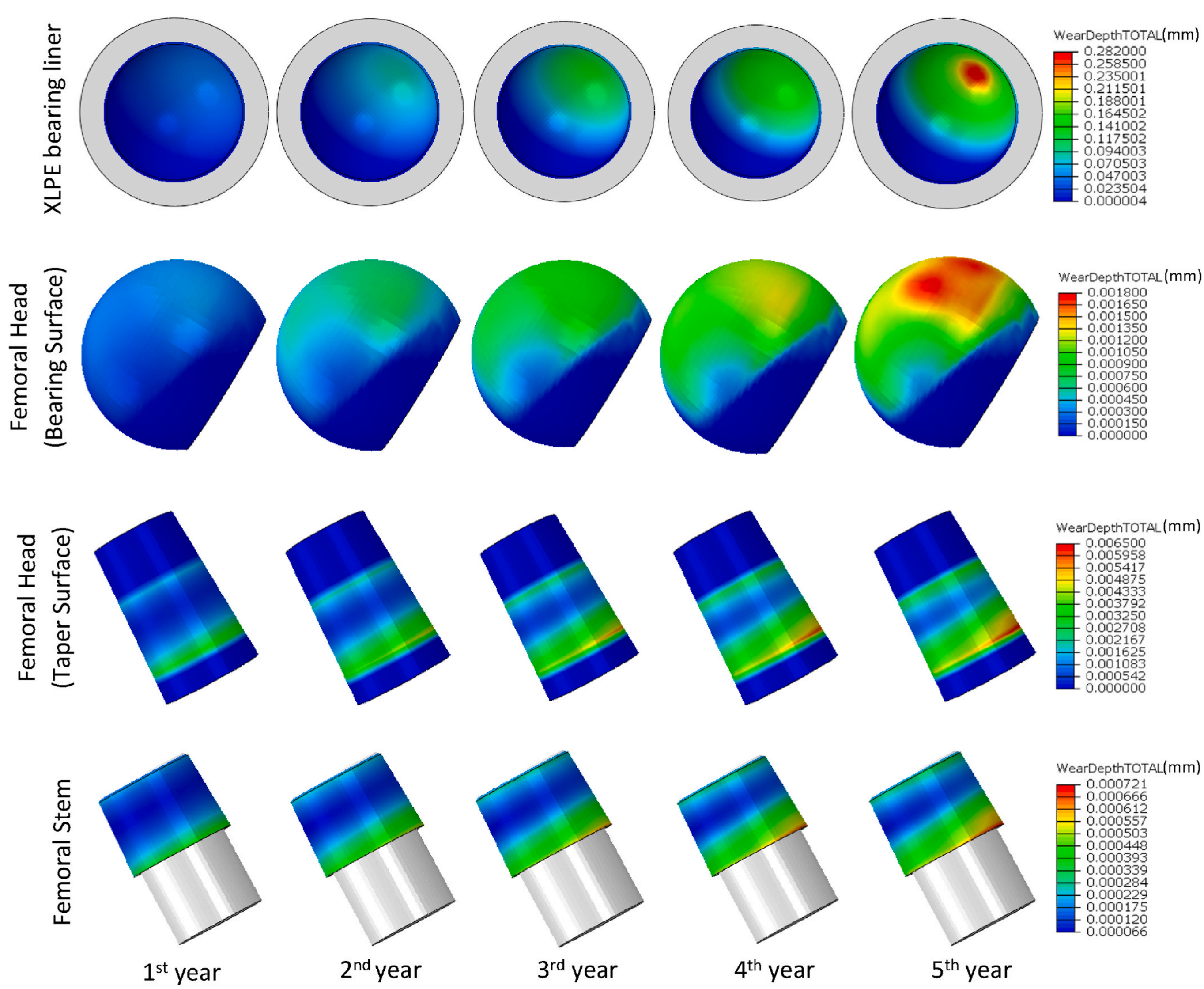

Fig. 4. Evolution of wear patterns of the XLPE bearing liner, femoral head bearing surface, femoral head taper surface, femoral stem surface for walking and bicycling up to 5 years.

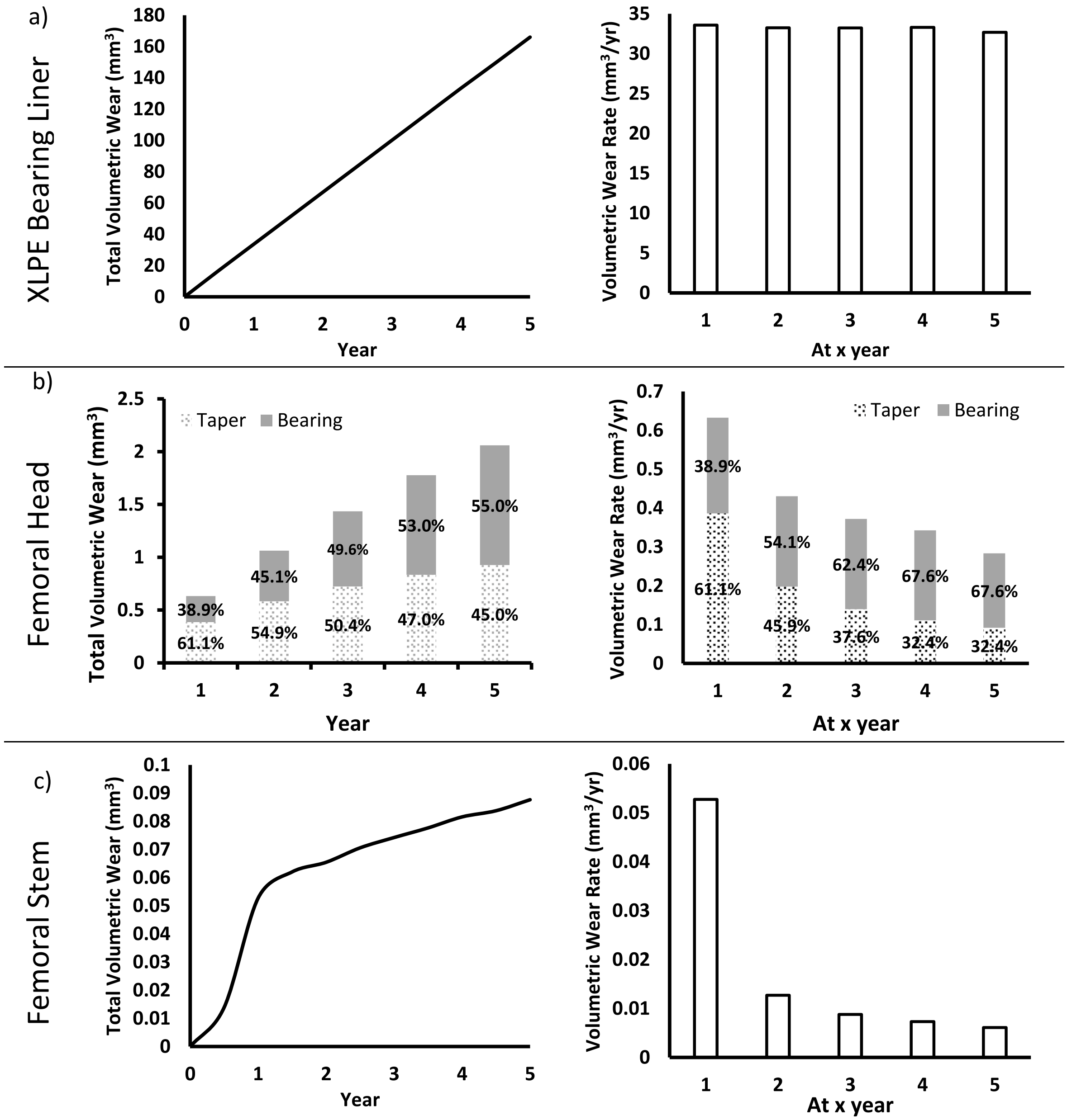

Fig. 5. Total volumetric wear and volumetric wear rates for a) XLPE bearing liner, b) Femoral head, c) Femoral Stem.

Table 3
Volumetric wear rates of XLPE liner in current study vs literature.

Part	Volumetric wear rate (mm³/yr)		
	Current Study	Literature	Reference
XLPE liner	33	1.5–57.6	(Atrey et al., 2017; Devane et al., 2017; Haw et al., 2017; Khoshbin et al., 2020)
Femoral Stem	0.1–0.39	0.01–3.15	(Langton et al., 2012; Ashkanfar et al., 2017)

volumetric wear of 0.073 mm³/yr which reduces to a steady volumetric wear rate of 0.009 mm³/yr. It was found that by adding bicycling up to 80 km per week, the volumetric wear rate increases up to 67% on the XLPE bearing liner, 11% on the femoral head and 12.5% on the femoral stem when compared to just walking up to 5 years. If XLPE and UHMWPE wear debris is assumed to have the same effect on the body, the THA lifespan can be calculated as 25.7 years for walking only compared to 15.4 years with walking and bicycling. The findings of this study have considered the upper limit of a patient's activity and as such, may show higher wear than what could be seen in patients. There are also other health benefits such as improved cardiovascular health, weight loss, and general fitness improvement.

Table 4
Volumetric wear rate between walking and bicycling up to 5 years.

Part	Mean Volumetric Wear Rate (mm³/yr)		
	Walking	Walking and Bicycling	% Increase
XLPE bearing liner	19.8	33.0	67%
Metallic Wear	0.365	0.406	11%

Statement of originality

I, on behalf of my co-authors, declare that the work described in the manuscript “How much wear does bicycling for commute affect the wear of a Total Hip Replacement prosthesis? A finite element wear simulation” has not been published previously in any other journal and neither is under consideration for publication in any other journal.

CRediT authorship contribution statement

Shawn Ming Song Toh: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis. **Ariyan Ashkanfar:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Russell English:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Glynn Rothwell:** Writing – review & editing, Methodology, Conceptualization. **David J. Langton:** Writing – review & editing, Validation, Investigation. **Thomas J. Joyce:** Writing – review & editing, Validation, Supervision, Investigation.

Declaration of competing interest

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.

Data availability

Data will be made available on request.

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