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The impact of femoral head size on the wear evolution at contacting surfaces of total hip prostheses: A finite element analysis

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ABSTRACT

Total Hip Arthroplasty has been a revolutionary technique in restoring mobility to patients with damaged hip joints. The introduction of modular components of the hip prosthesis allowed for bespoke solutions based on the requirements of the patient. The femoral stem is designed with a conical trunnion to allow for assembly of different femoral head sizes based on surgical requirements. The femoral head diameters for a metal-on-polyethylene hip prosthesis have typically ranged between 22 mm and 36 mm and are typically manufactured using Cobalt–Chromium alloy. A smaller femoral head diameter is associated with lower wear of the polyethylene, however, there is a higher risk of dislocation. In this study, a finite element model of a standard commercial hip arthroplasty prosthesis was modelled with femoral head diameters ranging from 22 mm to 36 mm to investigate the wear evolution and material loss at both contacting surfaces (acetabular cup and femoral stem trunnion). The finite element model, coupled with a validated in-house wear algorithm modelled a human walking for 10 million steps. The results have shown that as the femoral head size increased, the amount of wear on all contacting surfaces increased. As the femoral head diameter increased from 22 mm to 36 mm, the highly cross-linked polyethylene (XLPE) volumetric wear increased by 61% from 98.6 mm^3 to 159.5 mm^3 while the femoral head taper surface volumetric wear increased by 21% from 4.18 mm^3 to 4.95 mm^3. This study has provided an insight into the amount of increased wear as the femoral head size increased which can highlight the life span of these prostheses in the human body.

1. Introduction

Total Hip Arthroplasty (THA) is an effective treatment choice to restore mobility for patients with damaged hip joints due to injuries or disease such as osteoarthritis. Since the first modern THA performed in 1962 (Courpied et al., 2011), there have been great technological advances in the design and materials of the hip prothesis which have allowed for better longevity and have provided better mobility for patients.

Patients undergoing THA have unique skeletal structures and as such, the introduction of modular components allow for the customization of the prosthesis for each individual patient. The femoral stem is manufactured to accommodate the patient's bone size and to ensure adequate fixation; however, the sizes of the individual components can be changed based on the requirements which can lead to providing different ranges of motion (Burroughs et al., 2005; Matsushita et al., 2009). The natural size of a femoral head usually ranges between 40 mm and 54 mm in diameter with slightly smaller sizes in females (Milner et al., 2012). Due to the thickness required for the polyethylene liner in the acetabular cup, the diameter of the femoral head component usually does not exceed 36 mm for a metal-on-polyethylene hip prosthesis. According to the National Joint Registry for England, Wales, Northern Ireland and the Isle of Man (NJR), the size of metal-on-polyethylene THA femoral head sizes used today range from 22 mm to 36 mm (NJR and National Joint Registry, 2022).

Since 2003, the NJR (NJR and National Joint Registry, 2022) has reported a progressive shift away from smaller femoral heads (<28 mm). Currently the three most common femoral head sizes are 32 mm, 36 mm and 28 mm. It was also reported by NJR that 22.25 mm femoral heads had the worst revision rates overall, but 36 mm femoral heads had the

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worst revision rates in the first nine years of follow-up. The increase in femoral head diameters has led to increasing mechanical advantages such as stability and impingement free movements (Cross et al., 2012; Hammerberg et al., 2010; NJR and National Joint Registry, 2021). However, larger femoral heads were found to have increased wear which could lead to implant loosening, taper corrosion, and a higher risk for groin pain (J et al., 2014; Tsikandylakis et al., 2018a; Tsikandylakis et al., 2018b). While having increased wear is not ideal, a balance between stability and wear has to be achieved to reduce complications (Kung et al., 2007).

Wear debris have been known to be deposited within the periprosthetic tissues which elicits a chain reaction resulting in osteolysis and is one of the leading causes alongside dislocation, which is the leading cause of artificial joint failure (Kandahari et al., 2016). Therefore, wear reduction has been a key driver in improving hip prosthesis designs. Previous research into metal-on-metal hip prosthesis found that there was an increased risk for metallosis which subsequently led to them not being used widely today (NJR and National Joint Registry, 2022). However, some metal-on-polyethylene hip prostheses were found to also have failures due to metallosis (Cipriano et al., 2008; Hunter et al., 2019; Chang et al., 2005). Further research into the phenomenon found that the taper-trunnion junction contributed to high amounts of metallic wear within the body and hence this study will incorporate both bearing surface and taper junction wear.

This study aims to investigate the effects of different femoral head sizes on the wear rates and the longevity of the hip prosthesis. Using an advanced computational wear algorithm, an investigation is performed to study the effect of femoral head diameters between 22 mm and 36 mm on the wear in the hip prosthesis for 10 years of walking activity. This study will help to further quantify the amount of wear generated for different femoral head sizes.

2. Methodology

In this study, a computational wear algorithm was used to study the effects of varying femoral head diameters 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 walking 10 million cycles, equivalent to approximately 10 years of walking (Schmalzried et al., 1998).

The FE hip prosthesis was modelled in ABAQUS 2022 and features a 3 mm thick Titanium (Ti) backing (shell), varying thickness of highly cross-linked polyethylene (XLPE) bearing liner, a Cobalt–Chromium alloy (CoCr) femoral head and Titanium (Ti) 12/14 femoral stem as shown in Fig. 1. The material properties assigned on the parts are shown in Table 1. In this study, varying sizes of femoral heads were modelled from 22 mm to 36 mm in diameter. The XLPE bearing liner varied in thickness between 6 mm and 13 mm, depending on the femoral head diameter, i.e. 36 mm diameter femoral head is paired with a 6 mm XLPE bearing liner, while a 22 mm diameter femoral head is paired with a 13 mm XLPE bearing liner. This computational model also considered an initial assembly impaction of 4 kN to simulate the assembly of the femoral head onto the stem (English et al., 2016).

To replicate a walking cycle, the walking loadings, and rotations (following their amplitude for a gait cycle) are applied to the femoral head and are shown in Fig. 1b and c. The models were meshed using eight-node bilinear hexahedral reduced integration elements (C3D8R). The model was submitted as a dynamic implicit analysis and the analysis time discretised into 10 equal time intervals over a 1.2 s period. A mesh convergence study was previously performed with an approximate element size of 0.3 mm for both acetabular liner and femoral head, and 0.4 mm for the femoral stem.

The computational wear algorithm used in this study has been comprehensively explained previously by Toh, Ashkanfar (Toh et al., 2021) for bearing surface wear and English, Ashkanfar (English et al., 2015a) for fretting wear at the taper-trunnion junction. Briefly, this study has used the "Dissipated Energy" wear law to calculate the wear occurring between the surfaces. 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

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

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

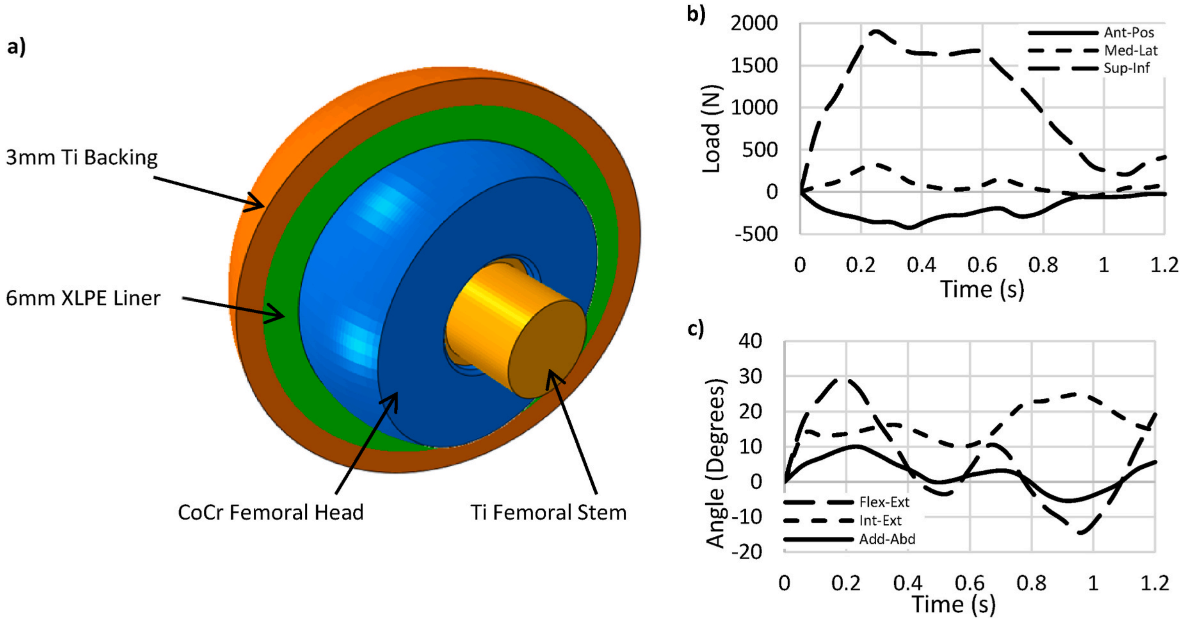

Fig. 1. a) FE model of THA prosthesis, b) Loading cycle applied onto FE model, c) Rotation cycle applied onto FE model.

specified time interval ***i***.

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

This wear algorithm has been previously validated against over fifty clinical retrievals and has been used to investigate various factors contributing to hip prosthesis wear such as manufacturing tolerances (Ashkanfar et al., 2017a), surgical techniques (English et al., 2016), different surface roughness (Ashkanfar et al., 2017b), patient weight (Toh et al., 2022a), and additional patient activity (Toh et al., 2022b).

As the wear depth calculated using Equation (1) is the total wear occurring on both interacting surfaces, a wear fraction is then introduced as different amount of material would be removed from the individual parts due to the material interaction properties to calculate the wear depth at each point of the surface interaction. Between the femoral head and femoral stem (CoCr–Ti interaction), a friction coefficient of 0.21 (Fessler et al., 1989) has been employed, alongside a wear coefficient of 1.06×10^{-7} MPa^{-1} (Zhang et al., 2013), and a wear fraction of 0.9:0.1 for CoCr: Ti as explained previously by English, Ashkanfar (English et al., 2015a). Between the bearing liner, and femoral head (XLPE-CoCr interaction), a friction coefficient of 0.11 (Wang et al., 2010) has been employed alongside a wear coefficient of 5.32×10^{-10} MPa^{-1} (Matsoukas et al., 2009). As there is currently limited research into the wear fractions between XLPE and CoCr, a study by Anissian, Stark (Anissian et al., 1999a) which investigated the wear from both polyethylene liner and CoCr femoral head, has been used to assume the wear rate of 0.99 PE:0.01 CoCr. A previous study on the effect of β on the calculation of wear demonstrated that $\beta = 10^5$ modelled the evolution of wear accurately and smoothly within an acceptable amount of time (Toh et al., 2021). A summary of the material interaction properties used in this study are shown in Table 2.

The FE model is then updated to reflect the amount of wear and the analysis is then allowed to continue until 10 million cycles of walking is achieved.

3. Results

The wear evolution and volumetric wear rates at the bearing surfaces and the taper junction of the hip prosthesis are shown in this section at each 2 million cycles as the solution progressed. The study has modelled walking up to 10 million cycles (1 million steps per year). The wear pattern evolution of the XLPE bearing liner and CoCr femoral head taper surface is shown in Figs. 2 and 3 respectively.

It can be seen in Fig. 2, the XLPE bearing liner maximum wear depth decreases as the femoral head diameter increase. The XLPE bearing liner of the 22 mm femoral head is shown to have a maximum linear wear of 0.37 mm while the 36 mm femoral head only showed a maximum linear wear of 0.22 mm. The overall observed wear pattern remains similar throughout the analysis.

Fig. 3 shows the wear pattern evolution over 10 years at the femoral head taper surface. As the femoral head size increased, the maximum wear depths were observed to be similar, approximately between 0.027 and 0.032 mm. The 36 mm femoral head taper surface was observed to have more wear towards the centre of the taper when compared to the 22 mm femoral head taper surface.

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

Surface Combination	Interaction properties	
Head-Stem	FC: 0.21	Fessler et al. (1989)
	WC: 1.06×10^{-7} MPa^{-1}	Zhang et al. (2013)
	WF: 0.9 CoCr: 0.1 Ti	English et al. (2015a)
Liner - Head	FC: 0.11	Wang et al. (2010)
	WC: 5.32×10^{-10} MPa^{-1}	Matsoukas et al. (2009)
	WF: 0.99 PE: 0.01 CoCr	This study WF (Anissian et al., 1999b)

Fig. 4 shows the cumulative volumetric wear and volumetric wear rates of the XLPE bearing liner, femoral head, and femoral stem.

In Fig. 4a, it is shown that the cumulative volumetric wear for the XLPE bearing liner increases as the femoral head diameter increases. It can be seen that the maximum XLPE volumetric wear for a 22 mm femoral head increases to 98.6 mm^3 while a 36 mm femoral head increases to 159.5 mm^3 at the end of 10 years. The XLPE volumetric wear rate was found to be constant for each of the femoral head sizes. For a 22 mm femoral head, the volumetric wear rate was 10.4 mm^3/yr while the 36 mm femoral head showed a volumetric wear rate of 15.9 mm^3/yr.

Fig. 4b shows the cumulative volumetric wear and volumetric wear rate for the femoral head bearing surface. It can be seen that the maximum volumetric wear for a 22 mm femoral head increases to 1.01 mm^3 while a 36 mm femoral head increases to 1.64 mm^3 at the end of 10 years. The cumulative volumetric wear follows the same general trend as the XLPE bearing liner, and the wear corresponds to the wear fraction applied to the model. For the 22 mm femoral head, the volumetric wear rate was 0.11 mm^3/yr and the 36 mm femoral head showed a volumetric wear rate of 0.16 mm^3/yr throughout the study.

Fig. 4c shows the cumulative volumetric wear and volumetric wear rate for the femoral head taper surface. For a 22 mm femoral head, the maximum volumetric wear increases to 4.18 mm^3 while the 36 mm femoral head increases to 4.95 mm^3. It can be seen that there is a similar trend for different femoral head sizes, where it increases at a lower volumetric wear rate and around 7 million cycles, it increases to a higher stable wear rate. For the 22 mm femoral head, the initial volumetric wear rate of the taper surface was 0.34 mm^3/yr which increases to a stable wear rate of 0.92 mm^3/yr after 7 years. For the 36 mm femoral head, the initial volumetric wear rate for the taper surface was 0.35 mm^3/yr and increases to the stable wear rate of 1.08 mm^3/yr after approximately 7 years. The increase in volumetric wear rate can be attributed to the initial taper locking reducing as explained previously (English et al., 2015a).

Fig. 4d shows the cumulative volumetric wear and volumetric wear rate for the femoral stem. For a 22 mm femoral head, the femoral stem showed a cumulative volumetric wear of 0.36 mm^3 while for the 36 mm femoral head, the femoral stem shows a cumulative volumetric wear of 0.44 mm^3. The different femoral heads showed similar trends of the femoral stem wear with the wear increasing to a stable wear rate after 7 years. For the 22 mm femoral head, the initial volumetric wear rate for the femoral stem was 0.028 mm^3/yr which increases to 0.080 mm^3/yr after 7 years. For a 36 mm femoral head, the femoral stem showed an initial volumetric wear rate of 0.035 mm^3/yr which increases to 0.097 mm^3/yr after 7 years.

Fig. 5 shows the evolution of maximum liner wear and linear wear rate at the XLPE bearing liner for the various femoral head sizes. As the femoral head size increases, the maximum linear wear decreases; a 22 mm femoral head has a maximum linear wear of 0.37 mm while the 36 mm femoral head has a maximum linear wear of 0.22 mm. There is a steady linear wear rate as the simulation progresses for the different femoral head sizes. For the 22 mm femoral head, the maximum linear wear rate was approximately 0.04 mm/yr while the 36 mm was approximately 0.02 mm/yr. Although there are varying XLPE maximum linear wear rates, the average linear wear was found to be approximately 0.1 mm for all femoral head sizes at the end of 10 years.

4. Discussion

Table 3 compares the volumetric wear rates obtained in this study with those available in the current literature. Khoshbin, Wu (Khoshbin et al., 2020), Devane, Horne (Devane et al., 2017), Haw, Battenberg (Haw et al., 2017) and Atrey, Ward (Atrey et al., 2017) investigated

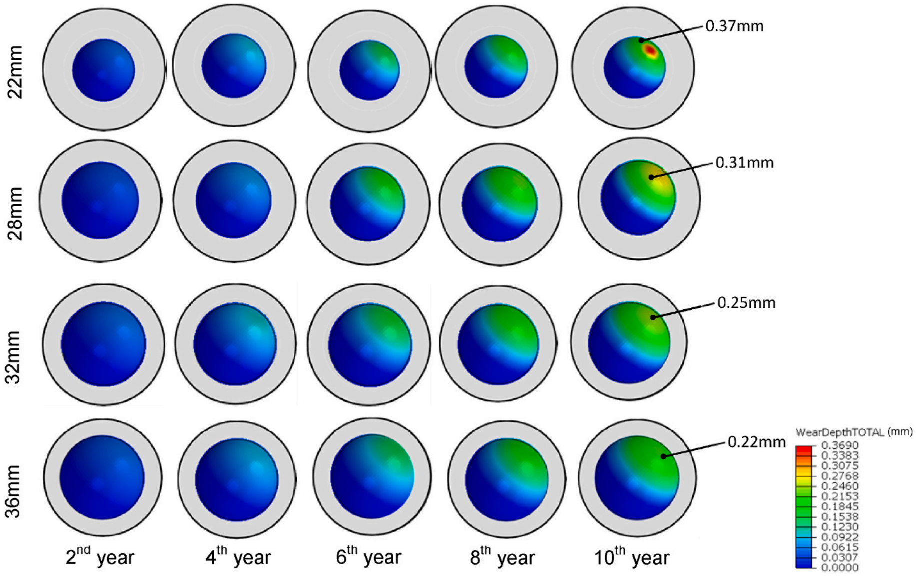

Fig. 2. Evolution of wear pattern over 10 years at XLPE bearing liner for different head sizes.

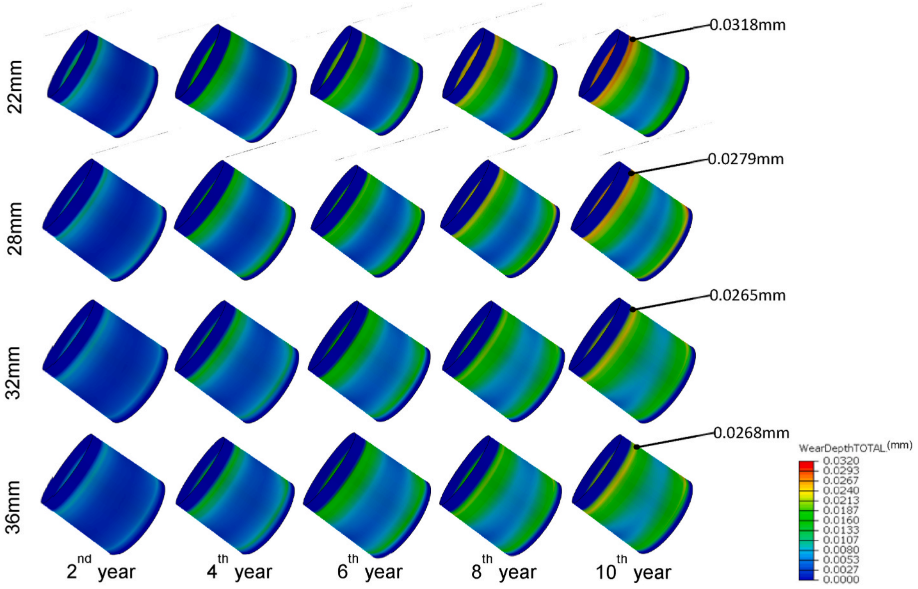

Fig. 3. Evolution of wear pattern over 10 years at femoral head taper surface.

XLPE volumetric wear rates for a total of 247 primary THA prosthesis through radiograph analysis. The studies have observed a range of wear between 1.5 and 33.09 mm^3/yr. The large range of XLPE volumetric wear is attributed to the many factors which affect wear rates such as patient-specific factors, different prosthesis designs and surgical factors. The XLPE wear rates in this study ranged between 9.4 and 15.9 mm^3/yr which are within the range seen in current literature.

Although there is a range of XLPE volumetric wear rate for different femoral head sizes, the average linear wear of the XLPE bearing liner for different femoral head sizes remained at approximately 0.1 mm after 10 years of activity. A study by Lachiewicz, Soileau (Lachiewicz et al., 2016) investigating the effect of femoral head sizes on the XLPE bearing liner wear between 10 and 14 years through radiography also found that femoral head sizes did not have an impact on the linear wear; however, larger femoral heads were associated with higher volumetric wear.

For the femoral head taper surface, the volumetric wear rate of 0.15–1.09 mm^3/yr from this study is comparable to current literature which shows a range between 0.05 and 1.04 mm^3/yr. From current literature, Ashkanfar, Langton (Ashkanfar et al., 2017a), Langton, Sidaginamale (Langton et al., 2012), Langton, Wells (Langton et al., 2018), and Gascoyne, Turgeon (Gascoyne et al., 2018) measured the amount of wear using a coordinate-measuring-machine (CMM) from a total of 308 retrieved prostheses. Bhalekar, Smith (Bhalekar et al., 2020) investigated the femoral head taper volumetric wear through a 6-station hip simulator. Although the results from this study are within the range seen in current literature, there are other factors which can influence the amount of wear seen at the taper junction such as taper mismatch (Ashkanfar et al., 2017a), surgical positioning (English et al., 2016) or the patients' activity (Toh et al., 2022b).

It was observed that the volumetric wear at the taper junction increased as the femoral head size increased. The increase in femoral head size from 22 mm to 36 mm showed an increase in cumulative volumetric wear by 21%. This is comparable to a previous study conducted by Langton, Sidaginamale (Langton et al., 2012) which showed

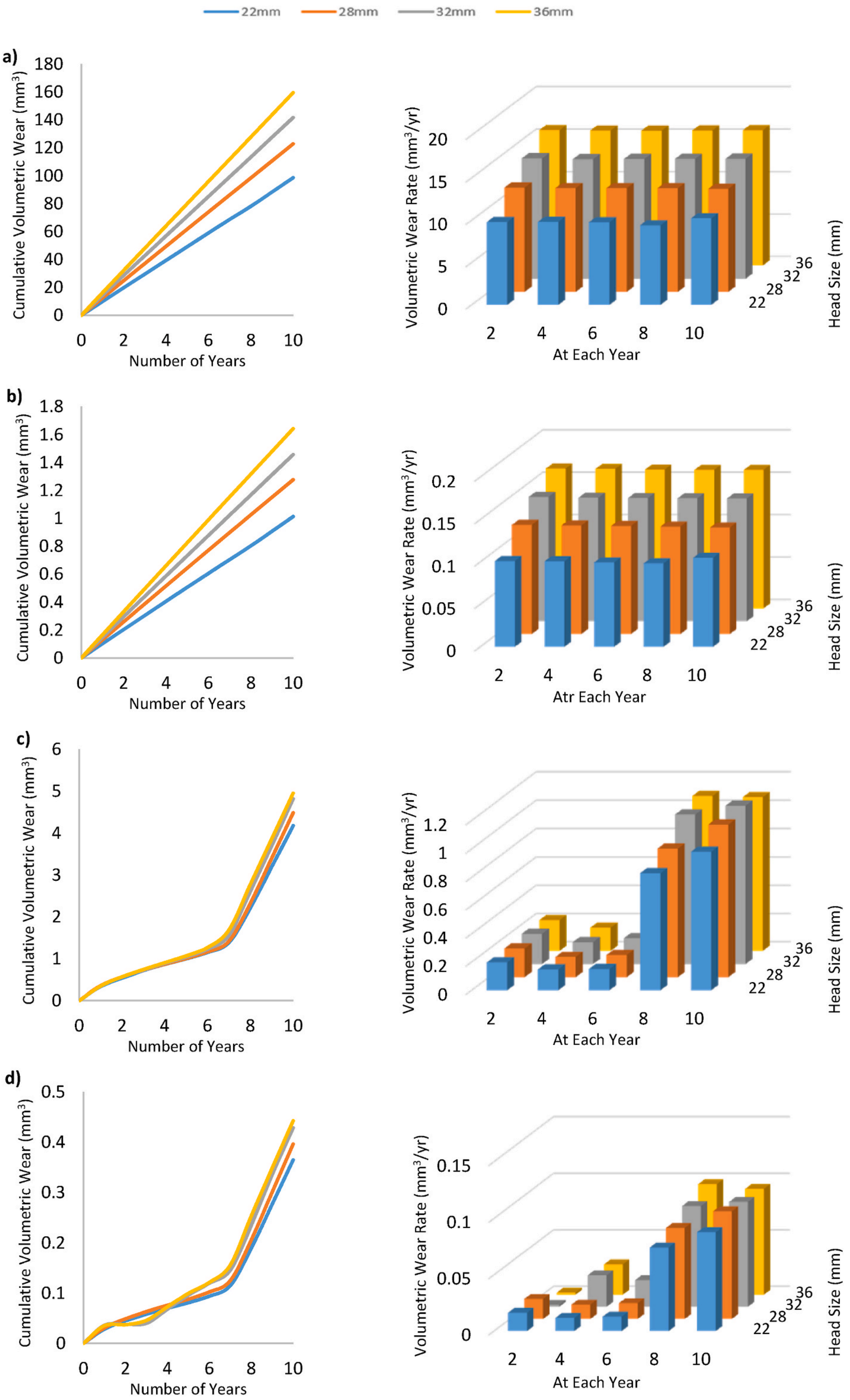

Fig. 4. Cumulative Volumetric Wear and Volumetric Wear Rate of a) XLPE bearing liner, b) Femoral head bearing surface, c) Femoral head taper surface, d) Femoral stem trunnion.

that there was increased taper wear for larger femoral head sizes.

A study conducted by Valente, Lanting (Valente et al., 2019) investigated a total of 79 retrieved femoral head taper junctions between 28 mm and 32 mm femoral head diameters with the same taper design. The study also accounted for similar age, gender, BMI, and implantation time. The study concluded that there was no statistical difference in the mean linear wear at the femoral head taper surface against femoral head size. Another study by Langton, Wells (Langton et al., 2018) investigated the material loss at the femoral head taper from a retrieval database of Exeter V40 and Universal MoP THAs through use of a coordinate-measuring machine (CMM). The results showed a 4-fold increase in median volumetric wear rate between femoral head sizes of 28 mm and 32 mm. Upon inspection of the tapers, it was found that the V40 system was designed with a larger taper than trunnion angle, resulting in a preferential engagement at the trunnion tip. The reverse is true with the Universal system, which engages at the base of the trunnion. A study

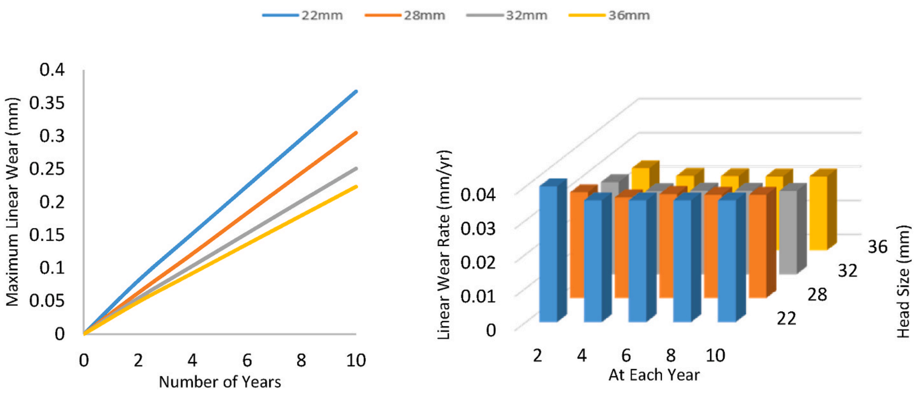

Fig. 5. Evolution of maximum linear wear and linear wear rate at the XLPE bearing liner.

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

Part	Volumetric wear rate (mm^3/yr)		
	Current Study	Literature	Reference
XLPE liner	9.4–15.9	1.5–33.09	(Khoshbin et al., 2020; Devane et al., 2017; Haw et al., 2017; Atrey et al., 2017)
Femoral Head Taper Surface	0.15–1.09	0.05–1.04	(English et al., 2016; Ashkanfar et al., 2017a; Langton et al., 2012, 2018; Gascoyne et al., 2018)

by Ashkanfar, Langton (Ashkanfar et al., 2017a) showed that a taper mismatch of 9.12’ increased the wear by up to 4 times. The study has also found that a slight reduction in the taper mismatch would significantly reduce the magnitude of the wear rates. The findings from these studies and this study can suggest that taper and trunnion design and their tolerances are more likely to play an important role in taper wear rather than femoral head size. This is mainly due to the horizontal lever arm distance which does not change significantly by increasing the femoral head size (Langton et al., 2012, 2017, 2018; Norman et al., 2019).

Wear is an important factor to consider due to the potential release of wear particles into the body (Gascoyne et al., 2018; Varnum, 2017). The ideal hip prosthesis would have low wear, low revision risk, and have no adverse reactions with the body. The stability and range of motion of the hip prosthesis can be changed by the femoral head diameter. Burroughs, Hallstrom (Burroughs et al., 2005) evaluated the effect of different femoral heads between 28 mm and 44 mm diameter on the range of motion of the joint. The study found a significant increase in both flexion before dislocation and displacement between the femoral head and acetabulum for femoral heads greater than 32 mm diameter. Matsushita, Nakashima (Matsushita et al., 2009) found that the range of motion improved as the femoral head size increased primarily due to the increased distance required for impingement of the femur and pelvis to occur.

Data from both the Australian Orthopaedic Association National Joint Replacement Registry and Danish Hip Arthroplasty Register analysed the risk factors for dislocations of different femoral head diameters between 28 mm and 36 mm (Hoskins et al., 2022; Hermansen et al., 2021). Both studies found the 36 mm femoral head to have lower dislocation rates than 28 mm and 32 mm femoral heads. Further data from the Finnish Arthroplasty Register, found that femoral heads greater than 32 mm were associated with lower risk of dislocation when compared to 28 mm femoral heads (Kostensalo et al., 2013). These studies highlighted that the use of large femoral heads due to the high stability and lower dislocation rates however the Swedish Hip Arthroplasty Registry have reported no statistically significant difference between 28 mm, 32 mm and 36 mm femoral heads using 28 mm as a reference (Hailer et al., 2012). A study by de Steiger (de Steiger, 2017) from the Australian Orthopaedic Association National Joint Replacement Registry, investigated late dislocations after primary THR performed with 28 mm, 32 mm and 36 mm of MoP, CoP and CoC bearings. The authors concluded that the 36 mm MoP THR had a higher risk of revision due to late dislocation when compared to 36 mm CoP and CoC. Moreover, they suggested that this difference was due to the effect of the 36 mm metal head on taper corrosion rather than the effect of the 36 mm head on XLPE wear. The results suggest caution when 36 mm MoXLPE hips are used as their long-term survival could be compromised by late dislocation despite the initial short to medium-term stabilizing benefits of 36 mm femoral heads.

Hall, Unsworth (Hall et al., 1996) previously suggested a cumulative volumetric wear of 500 mm^3, on average, was necessary for a polyethylene wear related failure of a THR. Based on this assumption, it can be concluded that the 22 mm femoral head and the 36 mm femoral head in this study would have a lifespan of 53 years and 31 years respectively based on polyethylene wear failures. Other failures such as infection, metallosis, or adverse reaction to particulate debris may drastically reduce the lifespan.

The results from this study are largely dependent on the wear coefficient and amount of activity by the patient. Currently, the simulation only accounts for up to 1 million walking cycles per year and no other activities to be performed by a patient. If a patient is to walk more than 1 million cycles a year, the wear would clearly increase. Increasing the amount of activity and including other activities such as cycling would also further increase the amount of wear observed in the hip prosthesis (Toh et al., 2022b). It is also noted that a fixed wear coefficient was employed throughout the analysis which does not account for surface roughness changes, but it can show the effect of the head size on the wear evolution parametrically. In this study, we have used a previously validated FE based wear algorithm (English et al., 2015b; Song et al., 2021). Although the original validation of the algorithm was not a direct comparison with retrievals for different head sizes, previously, the wear algorithm has been validated against a group of retrievals (n:54) (Ashkanfar et al., 2017a) and the results from this study are in the range of wear published in the literature, as illustrated above. These results provide an insight into the impact of femoral head sizes on the wear evolutions. The analysis within this paper has only considered wear, other methods of material loss would be out of scope of this study.

5. Conclusion

In this study, an FE model coupled with an advanced wear algorithm has been used to investigate the effect of different femoral head diameters on the wear rates on the contacting surfaces of the THR. At the bearing contacting surface, the results show that as the femoral head size increased from 22 mm to 36 mm, the volumetric wear increased from

98.6 mm^3 to 159.5 mm^3 and increased from 1.01 mm^3 to 1.64 mm^3 for the XLPE bearing liner and femoral head bearing surface respectively at the end of 10 million cycles. At the taper junction, the results show that as the femoral head size increased from 22 mm to 36 mm, the volumetric wear increased from 4.18 mm^3 to 4.95 mm^3 and 0.36 mm^3–0.44 mm^3 for the femoral head taper surface and femoral stem trunnion respectively at the end of 10 million cycles. Wear is an important factor to consider due to the potential release of wear particles into the body. If wear was the only factor in prosthesis design, the 22 mm femoral head would be best suited, however, there are other factors to consider, such as dislocation risk arising from using a smaller femoral head. Although a previously developed in-house wear algorithm has been used for this study, it has provided an insight into the amount of increased wear by increasing the femoral head diameter.

CRediT authorship contribution statement

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

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

No data was used for the research described in the article.

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