iMEDiTEC 2017

ORIGINAL PAPER

Polyethylene Wear in Total Ankle Replacement is influenced by its radial curvature: A Computational Wear Simulation study

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ABSTRACT

The longevity of total ankle replacement is limited by its polyethylene wear and osteolysis. It has been suggested that a change in implant dimensions may result in better implant lifespan. Using finite element method, wear analyses for 5 million cycles were conducted on an ankle implant prosthetic designed from polyethylene with varying parameters including thickness (4,6,8,12mm) and radial curvature (16,22,30,36mm). Varying the thickness, the linear and volumetric wear were consistent at 80 µm – 85.9 µm and 30.6 mm^3, respectively. Varying the radial curvature resulted in up to 116% in linear wear (80 µm – 173 µm) with a volumetric wear of up to 88% (19 µm – 36 µm). Conclusion: Polyethylene wear is not influenced by the implant thickness but rather of the radial curvature of the implant.

INTRODUCTION

Polyethylene wear of total ankle replacement (TAR) is a major concern. Although polyethylene wear is insufficient to cause loss of TAR integrity within a short period of time, long term exposure to debris and other pressure can shorten the lifespan of this implant. Polyethylene wear debris has the potential to stimulate local macrophage response leading to bone resorption, thus inducing osteolysis which can later lead to implant loosening (Ingham and Fisher 2005).

Generation of polyethylene wear on TAR is strongly to be related with implant design. The effect of design parameters on total hip replacement (THR) such as head size, radial clearance, and liner thickness were simulated and the volumetric wear and linear wear were then analysed (Bouchard *et al*. 2006; Uddin and Zhang 2013). Meanwhile there were three aspects of design parameter considered in polyethylene wear of the prosthetic shoulder, which are conformity, polyethylene thickness, and fixation type (Hopkins *et al.* 2007). In TAR, the design parameter such as radius of curvature of talar dome on a natural talus and thickness of polyethylene should be considered. Several studies have demonstrated that importance in determining the radius of curvature of the talar component. The radius of curvature followed the anatomical curvature in the sagittal plane (Hintermann *et al*. 2004), but others was longer than a natural talus (Leardini *et al*. 2004; Giannini et al. 2011). The radius of curvature is needed to be properly determined as well as to be compatible with the isometric rotation of the guiding ligaments (Leardini and Rapagna 2002). Besides that, the thickness of meniscal bearing was varied in 1mm increment from 5 mm to 8 mm. The most applicable thickness was chosen to allow ligament variable tension for implantation purposes (Giannini *et al.* 2011).

It becomes viable option to predict polyethylene wear in a real environment. Studies have been carried out on wear mechanism of polyethylene of TAR by means of experimental test (Bell and Fisher 2006; Affatato *et al.* 2007)The objective of present study was therefore to determine the effect of polyethylene thickness and radial curvature on wear for TAR using computational simulation

MATERIALS AND METHOD

Finite Element Modelling

Three dimensional model of the BOX® (Bologna Oxford) TAR was constructed using SOLID WORKS as shown in Figure 1 (a). The tibial and talar components were assumed to be Cobalt-Chromium (CoCr) with the Young's modulus of 210 GPa and Poisson's ratio of 0.3 (Wang *et al.* 2003). The tibial component with a spherical surface of 130 mm radius has contact with bearing component which allows rotations (Ianuzzi and Mkandawire 2006). The talar and bearing had a concave sulcus of 35 mm radius. The bearing was on the inferior surface intact with talar which fully conforms to the bi-concave surface (Leardini *et al.* 2004). The thickness of the bearing was varied with 1-mm increment from 5 to 8 mm (Leardini *et al*. 2004). Figure 1 (b) shows the location of radius and thickness for bearing which was being sectioned in A-A plane from Figure 1 (a). The bearing was made of ultra-high molecular weight polyethylene (UHMWPE) manufactured from compression moulded with Young's modulus of 500 MPa and Poisson's ratio of 0.3 (Leardini *et al*. 2004).

A finite element (FE) model was meshed in ABAQUS/CAE from CAD models of the BOX® (Bologna Oxford) TAR. The tibial and talar components were meshed using three-dimensional four noded tetrahedral elements represented as a rigid body, while the UHMWPE

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eISBN 978-967-0194-93-6 FBME

bearing component was meshed hexahedral elements. The convergence study was conducted and the number of elements chosen was 58441. The interaction between CoCr and UHMWPE surfaces was created using surface-to-surface contact with friction coefficient of 0.4 (Godest et al. 2002). The FE BOX® (Bologna Oxford) TAR was modelled with the mechanical environment as being setup priory (Affatato *et al*. 2007).

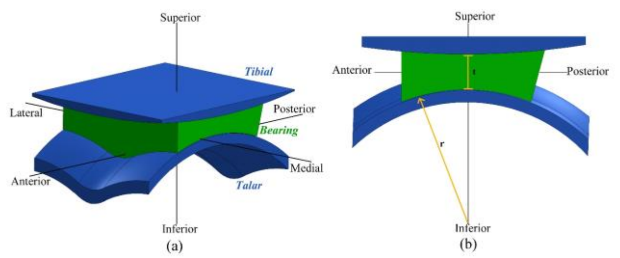

Fig. 1 (a) Three dimensional model and (b) Section A-A for paramter of the BOX® (Bologna Oxford) TAR.

The concentrated loading curve with maximum load of 1600N was applied vertically downward on the tibial as shown in Figure 2(a) (Reggiani et al. 2006; Affatato et al. 2007). The tibial and talar component has been fixed in the distal tibia bone and at the articulating surfaces of talar bone, respectively. The talar was constrained by anterior/posterior force and plantar/dorsiflexion at arc centre, O_c. The physiological activity of normal ankle gait cycle was considered to mimic walking. It is the most common activity of a human body. Figure 2 (b) shows the axial load and kinematic motions in an ankle gait cycle found from experimental analysis (Seireg and Arvikar 1975; Procter P and Paul JP 1982)Basically, there are two phases on ankle gait cycle which are stance and swing phases. The stance phases was only considered in this study. It was divided into 25 discrete instances on the stance phase of ankle gait cycle (the first 62.5% of the cycle).

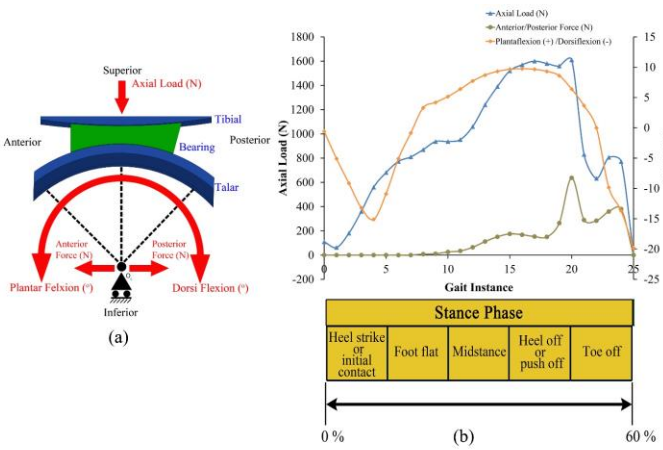

Fig. 2 (a) Boundary Conditions Applied and (b) Load and kinematic motions in an ankle gait cycle.

Computational wear simulation

The computational wear simulation on the bearing surface (UHMWPE) was computed using the Archard's wear model (Archard 1953) that can be described as

$$V = k_w\, F\, s \quad (1)$$

where V was the volumetric wear of the bearing surface, k_w the wear factor, F is the resultant normal load and s the sliding distance between contacting surfaces. Often the Archard's wear model was modified to calculate linear wear, H by dividing Eq. (1) both sides by an area as

$$H = k_w\, p\, s \quad (2)$$

where p denotes the contact pressure. In this study, the wear factor, k_w used was 2.64E-07mm^3/Nm (Knight et al. 2007).

An adaptive remeshing was implemented to update changes of the geometry on the worn surface. The nodes on the worn surface was updated by moving inward in the radial direction by an amount equal to linear wear, H, and hence re-meshed. Since that ankle joint implant in a patient under normal routine activities experiences 1x 10^6 cycles each year in average, therefore this study was carried out up to 5 x 10^6 cycles (equivalent to 5 years). An adaptive remeshing was done at every 0.5 x 10^6 cycles.

RESULTS

Effect of Polyethylene Thickness

Figure 3 (a) shows that there was 6.3% maximum difference in linear wear (80 µm – 85.9 µm). The 4 mm thickness was the least linear wear and the 12 mm thickness was the highest. However, the 6 mm and 8 mm had only 2% difference. The contact area of all model remained the same at 705 mm^2. Figure 3 (b) shows the volumetric wear at variation of the thickness in which total volumetric wear after 5 million cycles were same for all thickness, about 30.6 mm^3. Contact pressure distribution on meniscal bearing surface at 20th instant with different thickness were shown in Figure 3(c). The surface contact for 4 mm thickness insert had a contact pressure of 3% difference (10.2 MPa -10.6 MPa) whilst no difference of contact pressure were observed between the thickness of 6,8,12 mm, but for 4mm, the difference was 3% (10.2 – 10.6 MPa).

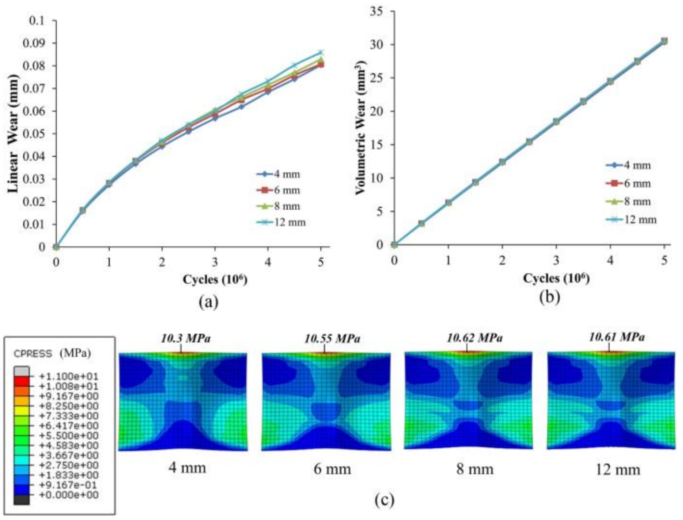

Fig. 3 The different thickness of polyethylene of (a) Linear wear, (b) Volumetric wear depth, and (c) Contact Pressure distribution after 5 million cycles at 20th instance of the stance phase of the gait cycle.

Effect of Radia Curvature of Polyethylene

Figure 4 (a) demonstrate that varying the radial curvature resulted in up to 116% in linear wear (80 µm – 173 µm). The linear wear of different radius of curvature of meniscal bearing shows that the radius of 30 mm and 36 mm are identical and has the lowest linear wear. The radius of 16 mm shows highest value of linear wear. There was 57% difference of linear wear after 5 million cycles of radius between 16 mm and 22 mm whereas there was 33% difference of radius between of 22 mm and 30 mm or 36 mm. Meanwhile, the difference of linear wear between the 16 mm toward 30 mm and 36 mm was relatively 100%.

For the contact area, there were 750, 720, 705, 701 mm^2 for the radius of 16, 22, 30, 36 mm, respectively. Figure 4 (b) shows a volumetric wear different was up to 88% (19 µm – 36 µm). The patterns of volumetric wear curve has reversed from patterns of linear wear and contact pressure curve. The difference of the volumetric wear between the 30 mm bearing radius to the16 mm and 22 mm bearing radius was higher of 37% and 23% respectively. Meanwhile,

eISBN 978-967-0194-93-6 FBME

the difference of the volumetric wear between the 30 mm has lower 18% to the 36 mm bearing radius.

Figure 4 (c) demonstrated the contact pressure of radial curvature was extremely high in implants with 16 mm radii (43.38MPa) while the lowest were in implants with 36 mm radii (8.29 MPa), thus demonstrating differences of up to 423%. The areas of higher stress located were relatively small as compared to the area of surface contact that have seen on the 16 mm and 22 mm bearing radius.

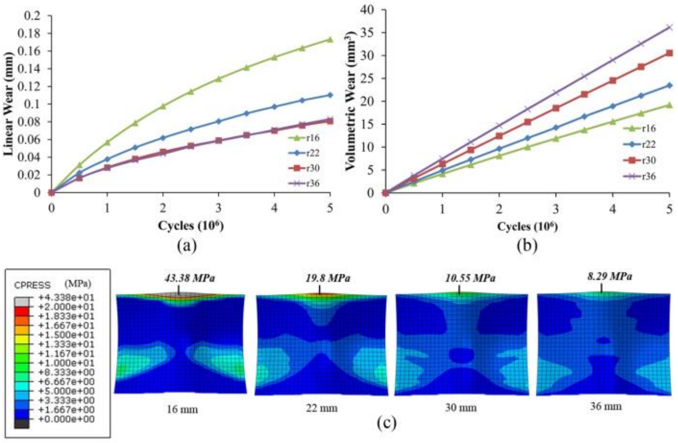

Fig. 4 The radius of curvature of polyethylene of (a) Linear wear, (b) Volumetric wear, and (c) Contact Pressure distribution after 5 million cycles at 20th instance of the stance phase of the gait cycle.

DISCUSSION

The present study demonstrates that radial curvature influence polyethylene wear in TAR, thickness not. Varying the thickness of polyethylene shows that as the polyethylene became thicker, the contact pressures developed were seen to be converged. In facts, there is only little difference of linear wear while the volumetric wear was similar at varying thickness of polyethylene. Therefore, varying thickness of polyethylene did not show significant differences towards wear prediction as it purposely uses to adjust the ligament tension.

The present studies demonstrate that at varying radial curvature, the large differences of linear wear clarify that the contact pressures play a major role in determining wear. As the contact pressure increases, the linear wear will increase. It was found that the smaller radius of curvature shows higher contact pressure and linear wear. It is because one of the motions of the ankle joint is the anterior/posterior motion whereby this motion allows the talar component to displace anterior or posterior while the bearing remains at it position. The meniscal bearing has constraints which are loads applied at top surface of tibial component pressing it inferiorly. Therefore, the concentration stress was greater on the tip of the anterior bearing contact surface for the smaller radius of curvature of meniscal bearing. When the size of meniscal bearing radius of curvature is reduce, it cause larger displacement and vice versa. The volumetric wears has produced by multiplication of contact area and wear depth. Thus, even the radius of 16 mm has a large surface contact area as compared to others; however, it has small contacted area of contact pressure distribution and produce less volumetric wear. Besides that, the 36 mm radius has a smaller contact area showing the lower contact pressure and linear wear but higher in volumetric wear. These indicate that the level of contact pressure distribution and contacted area determine the wear prediction.

CONCLUSION

This study developed the computational wear simulation using finite element analysis in order to predict polyethylene wear on total ankle replacement (TAR). The Bologna-Oxford (BOX) TAR was analysed with loading and boundary condition applied for the stance phase of ankle gait cycle. Polyethylene wear of TAR is not influence by the implant thickness but rather of the radial curvature of the implant.

ACKNOWLEDGEMENT

This project was sponsored by Ministry of Higher Education (MOHE) through Fundamental Research Grant Scheme (FRGS) R.J130000.7824.4F137, Research Management Centre (RMC), UniversitiTeknologi Malaysia (UTM).

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