Influence of Elastic Recovery of Machining Surface Asperities on the Contact Stress and Plastic Strain of Polyethylene Tibial Insert in Virgin Knee Prosthesis

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Ultra-high molecular weight polyethylene (UHMWPE) is the sole polymeric material currently used for weight-bearing surfaces in total joint arthroplasty. However, the wear phenomenon of UHMWPE in knee and hip prostheses after total joint arthroplasty is one of the major restriction factors on the longevity of these implants. The authors focused on the microscopic machining surface asperities of the UHMWPE tibial insert of the virgin knee prosthesis as a factor influencing the wear mechanism of the UHMWPE tibial insert. In a previous study performed by the authors, on static contact analysis between the microscopic machining surfaces and the metallic femoral component, the influence of the microscopic machining surface asperities was noted on the stress and plastic strain of the UHMWPE tibial insert. In this study, repeated elasto-plastic contact analyses using the finite element method (FEM) between the machining surface asperities and the femoral component were performed in order to investigate the influence of elastic recovery of the machining surface asperities on the contact stress and plastic strain of the UHMWPE tibial insert. The analytical findings of this study suggest that the elastic recovery of the machining surface asperities of the UHMWPE tibial insert of the virgin knee prosthesis is another possible factor influencing the microscopic failure and/or microscopic wear behavior of the UHMWPE tibial insert in the knee prosthesis after total knee replacement.

Keywords: ultra-high molecular weight polyethylene (UHMWPE), tibial insert, machining surface asperities, contact analysis, finite element method (FEM), elastic recovery, wear

1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE) has been used as a major polymeric material for weight-bearing surfaces in total joint arthroplasty. However, the wear phenomenon of UHMWPE components in knee and hip prostheses and the polyethylene wear particles generated in the human body after total joint arthroplasty cause serious clinical and biomechanical reactions, such as osteolysis and eventual loosening of knee and hip prostheses [1]. Therefore, the wear phenomenon of UHMWPE components in total joint arthroplasty is one of the major restriction factors on the longevity of these implants. In order to minimize the wear of UHMWPE components and to improve the longevity of artificial joints, it is necessary to clarify the factors influencing the wear

mechanism of UHMWPE.

In a previous study [2], which was performed by the authors, on the microscopic surface observation of the virgin knee prosthesis with anatomical design, a huge number of microscopic machining surface asperities caused by the machining process during manufacture of the component were observed on the surface of the UHMWPE tibial insert as shown in Fig. 1. It is thought that the microscopic machining surface asperities might contribute to increasing and/or accelerating wear of the UHMWPE tibial insert. The authors focused on these machining surface asperities of the UHMWPE tibial insert of the virgin knee prosthesis as a factor influencing the wear mechanism of the UHMWPE tibial insert. In a previous study [3], which was performed by the authors, on the static contact analyses between the UHMWPE microscopic machining surfaces with machining grooves

Fig. 1 Virgin UHMWPE tibial insert (a) and microscopic machining surface with asperities (b)

and the metallic femoral component, the influence of the machining surface asperities was noted on the contact stress and plastic strain of the UHMWPE tibial insert. The primary purpose of this study was to investigate the influence of elastic recovery of the machining surface asperities on the mechanical state (contact stress and plastic strain) and wear behavior of the UHMWPE tibial insert in the virgin knee prosthesis.

2. Material and methods

In a previous study [3], which was performed by the authors, only the static contact analyses between the UHMWPE microscopic surface with machining grooves and the metallic femoral component were performed in order to investigate the mechanical state and wear behavior of the UHMWPE surface zone with the machining grooves. In this study, additional repeated contact analyses between the machining surface with asperities and the metallic femoral component were performed in order to carry out further investigation into the influence of elastic recovery of the machining surface asperities on the mechanical state (contact stress and plastic strain) and wear behavior of the UHMWPE tibial insert.

The three-dimensional microscopic surface profile measurement of a virgin UHMWPE tibial insert for LCS

Knee System (DePuy Synthes Trauma & Joint Reconstruction, Johnson & Johnson K.K.) shown in Fig. 1(a) was performed by using a confocal laser scanning microscope (OLS1100, OLYMPUS Co., Japan). Then, the reproduction of the machining surface of the tibial insert by using the 3D CAD software (Rhino 4.0, Robert McNeel & Associates, Inc., USA) was performed in order to produce the 3D finite element models of the microscopic machining surface asperities of the virgin tibial insert based on actual measurement data. Figure 2(a) shows the reproduced 3D machining surface profile of the tibial insert. Six sliced parts were extracted from this reproduced microscopic machining surface as an example shown in Fig. 2(b) and the finite element model of the machining surface asperity was produced for each individual sliced part, in order to improve the computational efficiency and the convergence rate by decreasing the numbers of nodes and elements.

In this study, repeated elasto-plastic contact analyses using the finite element method (FEM) between the six UHMWPE machining surface models including surface asperity modeled by above-mentioned process and the metallic femoral component were performed in order to investigate the influence of elastic recovery after

Fig. 2 Reproduced microscopic machining surface of the UHMWPE tibial insert with asperities (a) and an example of the sliced CAD model used for contact analyses (b)

unloading and reloading of the machining surface asperities on the mechanical state (contact stress and plastic strain distributions) and microscopic wear behavior of the UHMWPE insert. Figure 3 [3] shows the definitions of amount of elastic recovery and rate of elastic recovery defined in this study. Figure 3(a) shows the initial contact position between the machining surface asperity and the femoral component surface before compressive loading. The symbol h shown in Fig. 3(b) means overall compression depth and the symbol h' shown in Fig. 3(c) means distance from the top of machining surface asperity to the initial contact position after unloading. The amount of elastic recovery (h_{er}) was defined as the difference between h and h' as shown in Eq.

(1). And the rate of elastic recovery (r_{er}) was defined as the ratio of h_{er} to h as shown in Eq. (2).

$$h_{er} = h - h' \quad (1)$$

$$r_{er} = \frac{h_{er}}{h} = \frac{h - h'}{h} \quad (2)$$

Figure 3(a) also shows an example of 3D finite element model for one of the contact analyses performed in this study. The metallic femoral component was assumed to be a rigid flat surface and modeled with an analytical rigid surface. The UHMWPE machining surface with asperities was assumed to be an elasto-plastic body that has the Poisson's ratio equal to 0.45 and meshed using three-dimensional ten-node tetrahedral structural solid elements.

The degrees of freedom of any nodes on the both Y-Z surfaces of the sliced UHMWPE machining surface model shown in Fig. 2 were not constrained. Only the translational degree of freedom of the Y-axis direction of all nodes on the both X-Z surfaces was constrained. And all nodes on the bottom surface of the UHMWPE machining surface model were entirely constrained. The coefficient of friction between the metallic femoral component surface and the UHMWPE machining surface was also assumed to be 0.1 [4]. The contact between the metallic femoral component surface and the UHMWPE machining surface was simulated as a rigid flat surface deforming a soft elasto-plastic body by applying to the femoral component the normal displacement, which represents the compression depth. The repeated elasto-plastic contact analysis of ten times returned to the initial contact position after the femoral component surface had been compressed to the UHMWPE machining surface was performed. The rate (speed) of loading and unloading was not considered in the repeated contact analyses performed in this study.

As for the material model of the UHMWPE used in the FEM contact analyses performed in this study, an elasto-plastic material model of UHMWPE established in a previous study [5] by the present authors was used. The linear elastic modulus, the yield stress and the tensile strength of the UHMWPE were 498, 13.3 and 167.6 MPa respectively. All the finite element analyses in this study were performed using the commercial finite element analysis software ANSYS Release 14.5 (ANSYS, Inc., USA).

3. Results

An example of the results of a series of the 3D FEM contact analyses performed in this study is shown in Figs 4 to 7. This example is the results of the repeated contact analysis of the UHMWPE machining surface model with an asperity shown in Fig. 2(b). The height of the machining surface asperity (projection portion) was about 1.0 μm , and the overall compression depth by the metallic femoral component surface was 0.25 μm . Figures 4(a,b) show the distributions of the contact stress

Fig. 3 An example of finite element model for one of the repeated contact analyses and definitions related to the elastic recovery

Fig. 4 Contour plots of contact stress and plastic strain in the UHMWPE machining surface with an asperity; (a) and (b): after the 10th compression, (c) and (d): after the 10th unloading

and the plastic strain respectively in the UHMWPE machining surface with an asperity after the tenth compression. Figures 4(c,d) show the distributions of the residual stress and the residual plastic strain respectively in the UHMWPE machining surface with an asperity after the tenth unloading. The stress and the plastic strain in this paper mean the von Mises equivalent stress and the equivalent plastic strain respectively.

The graphs shown in Figs 5 to 7 are the summary of results of the repeated contact analysis shown in Fig. 4. The graphs in Figs (5,6) show the changes in the maximum contact stress and the maximum plastic strain respectively in the UHMWPE machining surface with an asperity with the number of compression of the metallic femoral component surface. The graph in Fig. 7 shows the changes in the rate of elastic recovery of the UHMWPE machining surface asperity with the number

Fig. 5 Changes in maximum contact stress in the UHMWPE machining surface with number of compression of the metallic femoral component surface

Fig. 6 Changes in maximum plastic strain in the UHMWPE machining surface with number of compression of the metallic femoral component surface

Fig. 7 Changes in rate of elastic recovery of the machining surface asperity with number of compression of the metallic femoral component surface

of compression of the metallic femoral component surface. The integral numbers of 1 to 10 and the decimal numbers of 1.5 to 10.5 shown in the number of compression of horizontal axis in the graph shown in Fig. 5 mean under compressive loading (upper dashed line; contact state of the femoral component surface) and after unloading (lower dashed line; noncontact state of the femoral component surface) respectively.

The summary of results of the repeated contact analyses for the six UHMWPE machining surface models performed in this study is shown in Table 1.

Table 1 Summary of results of the repeated contact analyses for the six UHMWPE machining surface models

Model No.	Range of maximum contact stress [MPa]	Range of maximum plastic strain [%]	Range of rate of elastic recovery [%]
1	16.71 ~ 28.90	24.96 ~ 25.23	45.12 ~ 46.34
2	10.59 ~ 24.25	14.04 ~ 14.25	60.69 ~ 61.39
3	19.32 ~ 29.66	28.80 ~ 29.29	41.33 ~ 42.72
4	11.90 ~ 23.70	13.84 ~ 14.04	65.39 ~ 65.84
5	15.39 ~ 28.78	25.99 ~ 26.47	40.67 ~ 42.30
6	15.65 ~ 29.81	26.56 ~ 28.33	44.34 ~ 46.06

4. Discussion

As the results of a series of the 3D FEM contact analyses, it was found that repeated high contact stresses which exceed the yield stress of UHMWPE and considerable plastic strains caused by the elastic recovery under repeated loading-unloading occurred in the UHMWPE machining surface asperity for even a very small compression depth of 0.25 μm equivalent to 25% of the height of the machining surface asperity, as shown in Fig. 4. The maximum values of the contact stress and the plastic strain occurred in the top surface region of the machining surface asperity. In addition, considerable residual stresses and residual plastic strains occurred in the UHMWPE surface zone with machining surface asperity after unloading. The magnitudes of the contact stresses and the plastic strains under compressive loading and the magnitudes of the residual stresses and the residual plastic strains after unloading in the UHMWPE surface zone with machining surface asperity increased markedly with increasing compression depth of the metallic femoral component surface. The generation regions of the significant contact stresses and plastic strains and the generation regions of the considerable residual stresses and residual plastic strains spread markedly with increasing compression depth of the metallic femoral component surface.

It was found that repeated contact stresses of approximately constant amplitude caused by the elastic recovery under repeated loading-unloading occurred in the UHMWPE machining surface asperity as shown in Fig. 5. It was also found that the maximum values of the plastic strain generated in the UHMWPE surface asperity with the number of compression of the metallic femoral component surface converged to a specific value after the fifth loading-unloading as shown in Fig. 6. The rates of elastic recovery of the range of 40.67-65.84% occurred in the repeated contact analyses of the six UHMWPE machining surface models including asperities which were performed in this study. It was found that the rate of elastic recovery of the UHMWPE

surface asperity decreased gradually after the maximum value was indicated after the first loading-unloading, and converged to a specific value after the fifth loading-unloading as shown in Fig. 7. The rate of elastic recovery of the UHMWPE surface asperity decreased markedly with increasing compression depth of the metallic femoral component surface. All the results of the repeated contact analyses of the six UHMWPE machining surface asperity models performed in this study had the same tendency as the above-mentioned.

From the results of the repeated contact analyses shown in Figs 4 to 7, it is thought that the elastic recovery and the repeated high contact stresses caused by unloading and reloading of the UHMWPE machining surface asperity contribute to generations of not only adhesive wear in the top surface region of the machining surface asperity but also fatigue wear such as pitting in the surface region of the virgin UHMWPE tibial insert. In addition, it would appear that the elastic recovery and the repeated high contact stresses of the machining surface asperity contribute to structural weakening of the surface region of the virgin UHMWPE tibial insert. Therefore, it is thought that the elastic recovery of the machining surface asperities has potentially harmful influences on the initial wear of the UHMWPE tibial insert in the knee prosthesis after total knee replacement.

There were some limitations in this study. The FEM analyses performed in this study were simple contact analyses under repeated simple compressive loading between the UHMWPE machining surface with asperities and the metallic femoral component. The authors also could not investigate the relationship between the FEM analysis results performed in this study and the wear behavior of the UHMWPE tibial insert in the virgin knee prosthesis. Therefore, further FEM analyses including sliding process are required in order to investigate the influence of the long-term sliding contact. Further experimental studies are also required in order to clarify the relationship between the FEM analysis results and the wear behavior of the UHMWPE tibial insert.

5. Conclusion

The primary purpose of this study was to investigate the influence of the elastic recovery of the machining surface asperities on the contact stress and plastic strain of the UHMWPE tibial insert in the virgin knee prosthesis through the repeated FEM contact analysis. The analytical findings of this study suggest that the elastic recovery of the machining surface asperities of the UHMWPE tibial insert of the virgin knee prosthesis has significant influences on the mechanical state (contact stress and plastic strain distributions) in surface region of UHMWPE under repeated loading-unloading. This is therefore another possible factor influencing the microscopic failure and/or microscopic wear behavior of the UHMWPE tibial insert in the knee prosthesis after total knee replacement.

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