

Efficient Machining of Artificial Hip Joint Components

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Abstract. This paper investigates the effect of tool and workpiece motions on the machining efficiency in the fabrication of hip joint prosthesis. The finite element method was used to characterize the three-dimensional motion of the system, using the uniformity or even distribution of a cutting tool tip trajectory as an efficiency indicator. It was found that a proper combination of the rotational speeds of a cutting tool and a workpiece can improve significantly the efficiency of the machining operation.

Introduction

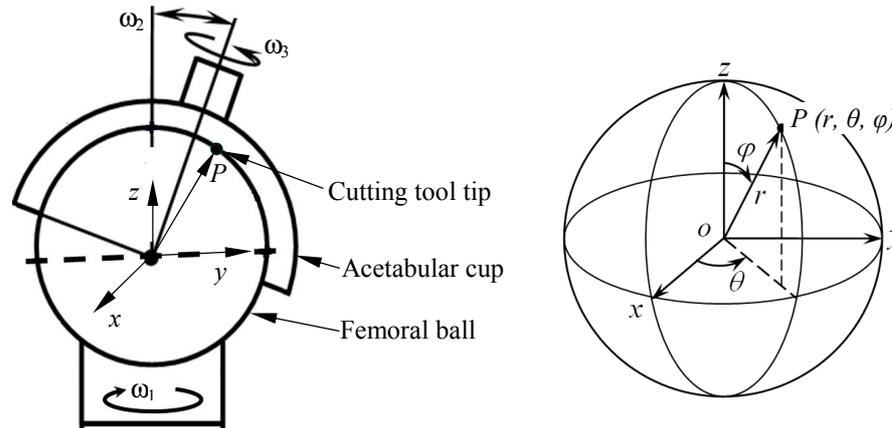
With the increasing percentage of elderly people, healthcare demands in the field of arthritis have had a significant rise [1]. In Australia and in the United States, there are about 21 and 16.7 percentages of adults, respectively, who have suffered from arthritis. While in Europe, more than 100 million people have arthritis [2, 3, 4]. A solution to arthritis is to replace the arthritic hip joint with an artificial one [5] but sufficient care must be taken in its fabrication. One of the major issues is the dimensional accuracy and surface finish of an artificial hip joint component, because it influences the performance and in-vivo life of the prosthesis. In the fabrication process by machining, the speeds of a cutting tool and a workpiece play an important role in determining the surface finish and machining efficiency [6, 7]. If the machining speed combination is not properly selected, part of the component surfaces can be machined repeatedly while the rest can be left untouched, due to an uneven distribution of the cutting tool trajectory on the surface. This situation should be avoided since it leads to inaccurate mating, reduced lifespan and higher machining cost. However, in the current practice, the machining of spherical surfaces is mostly carried out by machinists using trial and error methods. Missing zones and dimensional errors occur [6].

This study focuses on the motion analysis during the machining of an artificial acetabular cup or femoral ball to improve the distribution of cutting tool trajectories. The investigation aims to find a proper combination of tool/workpiece motion speeds to generate a uniform trajectory distribution at a given machining duration. The finite element method will be used to analyse the three-dimensional motion of the machining process.

Finite Element Modeling

The surface machining process of an acetabular cup or a femoral ball of an artificial hip joint is illustrated in Fig. 1, with three independent rotational motions, namely the spinning of the femoral ball, ω_1 , the oscillation of the acetabular cup, ω_2 , and the spinning of the acetabular cup, ω_3 . A commercially available finite element code, ANSYS Workbench version 11.0, was used in this investigation. The cup component was treated as workpiece and a point on the ball component was regarded as a cutting tool tip (or vice versa) while analysing the trajectories on the cup (or ball) component. All simulations were performed for a machining time of five seconds.

Parameter Setting. The ranges of the femoral ball and acetabular cup rotation speeds considered in this investigation were based on the commonly used values [6], i.e., $\omega_1 = 1200 \sim 2000$ rpm, $\omega_2 = 10 \sim 90$ rpm and $\omega_3 = 600 \sim 1000$ rpm.



(a) Cartesian coordinate systems (b) Spherical coordinate systems
Fig. 1 Motions of the artificial hip components and location of the cutting tool tip [8].

Geometry and Meshing. The diameter and height of the ball were 22 and 26 mm, respectively, while the external diameter and height of the cup were 32 (its inner diameter is the same as that of the ball) and 36 mm respectively. For simplicity, the ball and cup were considered rigid. Mass elements were used for finite element meshing of rigid bodies.

Connection. Three different types of joints, ‘revolute’, ‘general’ and ‘spherical’ programmed by the ANSYS code, were applied in this analysis. The revolute joint allows one degree of freedom, and was applied to the femoral ball. The general joint, on the other hand, allows three degrees of freedom, and hence was applied to the rotation of the acetabular cup. The spherical joint, which allows three degrees of freedom, was used to model the contact between the ball and cup.

Results and Discussion

Trajectory Pattern on the Cup. In order to generate the trajectory pattern on the cup, a joint probe was used to measure the relative rotation of the spherical joint. The reference coordinate system was fixed to the cup while the mobile coordinate system was fixed to the ball. To study the effects of ω_1 , ω_2 and ω_3 , only one of them was varied at a time keeping the others unchanged. The initial position of the cutting tool tip was assumed to be at P (11mm, 90° , 45°) on the femoral ball, as shown in Fig. 1, which, during the machining motion, would produce a trajectory on the cup surface. The relative rotation of the cutting tool tip (on ball) with respect to the cup was obtained in X, Y and Z coordinates and the relative rotations were then transformed to positions using a rotation matrix for every machining condition.

Spinning of Acetabular Cup (ω_3). ω_3 was varied from 600 to 1000 rpm to investigate its effect on machining efficiency. The spinning speed (ω_1) of the femoral ball and oscillation speed (ω_2) of acetabular cup were fixed at 1200 and 10 rpm respectively. The best trajectory pattern was obtained at $\omega_3 = 700$ rpm as shown in Fig. 2(a). The cutting tool trajectory was distributed almost evenly throughout the entire acetabular cup surface, ranging from the radius approximately 5 to 10 mm in XY plane, and 4 to 10 mm in both XZ and YZ planes. However, the trajectory distribution was very uneven when $\omega_3 = 600, 800$ or 900 rpm. At these speeds, the cutting tool followed a same trajectory repeatedly. Thus, the surface finish and geometrical tolerance of the prosthesis components can be poor. When the angular velocity ω_3 was 1000 rpm, the machining process produced a distorted trajectory pattern. In brief, 700 rpm gave the best trajectory pattern among the range of angular velocities (ω_3) considered in this investigation.

Oscillation of Acetabular Cup (ω_2). To understand the effect of ω_2 , ω_1 was held at 1200 rpm while ω_3 was fixed at the best operating condition identified above (700 rpm). The oscillation speed ω_2 was varied from 10 to 90 rpm. The best trajectory pattern was obtained at $\omega_2 = 70$ rpm, as shown in Fig. 2(b), which covers the entire acetabular surface from radius 5 mm to 10 mm in XY plane and

height 4.5 mm to 10 mm in XZ and YZ planes. When ω_2 reached 90 rpm, the trajectory pattern was deteriorated and some areas were left un-machined.

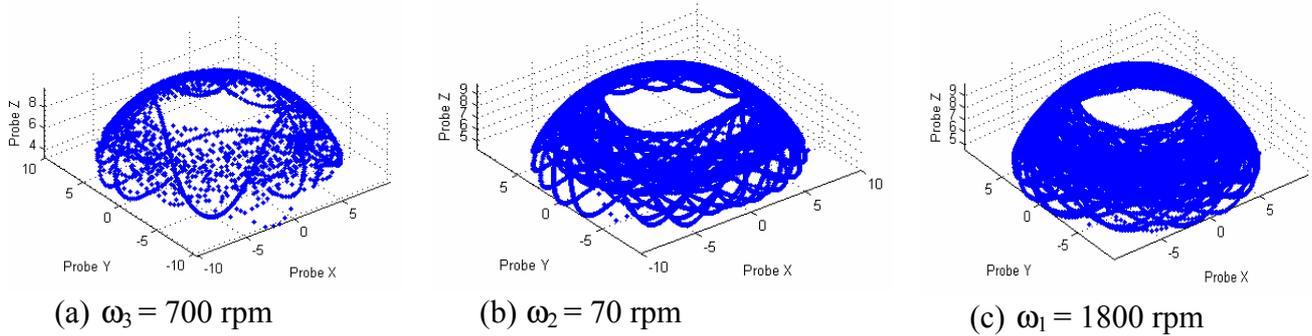


Fig. 2 Trajectory patterns on the cup at different speed combinations.

Spinning of the Femoral Ball (ω_1). The third set of simulations was carried out to study the influence of the ball spinning speed, ω_1 varying from 1200 to 2000 rpm, on the trajectory pattern while ω_3 and ω_2 of the acetabular cup were fixed at their best values, 700 and 70 rpm respectively, as obtained above. It was found that ω_1 from 1600 to 2000 rpm produces similar trajectory patterns on the acetabular cup, but the best patterns were generated by $\omega_1 = 1800$ and 2000 rpm, as shown in Fig. 2(c). It is clear that the influence of ω_1 is less significant compared to ω_3 and ω_2 . At $\omega_1 = 1800$ or 2000 rpm, the tool tip trajectory covers evenly the areas from radius 5 mm to 10 mm in XY plane and from height 4.5 mm to 10 mm in XZ and YZ planes.

Discussion. An even trajectory distribution is important since it reduces the machining time and cost, thus increases the efficiency. By using the obtained machining speeds, the trajectory pattern can cover the largest surface area of both femoral ball and acetabular cup around the cutting tool tip within 5 seconds. The whole surface can be machined efficiently by increasing the number of cutting tool tip. The trajectory patterns after one cycle oscillation of acetabular cup at the obtained speeds are shown in Fig. 3.

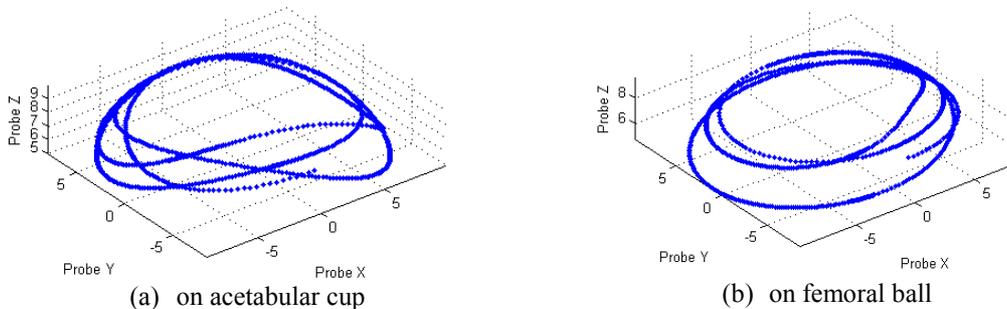


Fig. 3 Trajectory pattern after one cycle oscillation of acetabular cup at obtained speeds

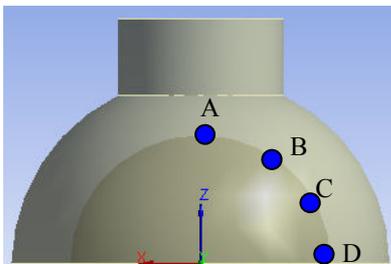


Fig. 4 Locations of four cutting tool tips

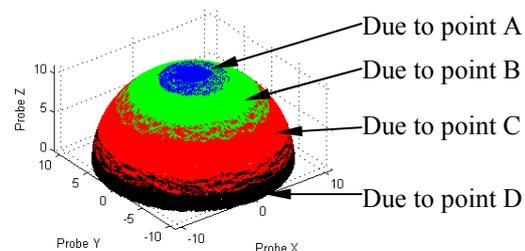


Fig. 5 Trajectory patterns (points A – D) on acetabular cup in 5 seconds

Multiple Cutting Tips

To verify the effectiveness of the speeds obtained above, the number of cutting tool tip was increased to four as shown in Fig. 4. The tip positions used in the simulation were at A: (11 mm, 90°, 0°), B: (11 mm, 90°, 30°), C: (11 mm, 90°, 60°) and D: (11 mm, 90°, 90°). It shows that the above obtained speed combination produces evenly distributed trajectories across the whole spherical surface, as shown in Fig. 5.

Conclusions

This paper has investigated the effect of combinations of tool and workpiece speeds on the efficiency of machining artificial hip joint components. Three key parameters have been considered in the analysis, namely the spinning (ω_1) of the femoral ball and the spinning (ω_3) and oscillation (ω_2) of the acetabular cup. The best trajectory pattern was obtained at $\omega_1 = 1800\text{--}2000$, $\omega_2 = 70$ and $\omega_3 = 700$ rpm for the model considered in five seconds.

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