Short Communication

Control of Femoral Rollback of PS Knee Prosthesis through Slip Ratio

Michihiko Fukunaga1)†, Jin Kawanoya1) and Shunji Hirokawa2)

1) Department of Intelligent Machinery and Systems, Kyushu University
744 Moto-oka, Nishi-ku, Fukuoka 819-0395, Japan
2) Department of Mechanical Engineering, Kyushu University
744 Moto-oka, Nishi-ku, Fukuoka 819-0395, Japan
*Corresponding author: fukunaga@gs.mech.kyushu-u.ac.jp

(Manuscript received 25 November 2009; accepted 1 February 2010; published 31 January 2011)
(Presented at the World Tribology Congress 2009, Kyoto, 6-11 September, 2009)

The objective of this study was to set forth guidelines for designing such an artificial knee joint that can make deep flexion. To this respect, we performed 2D model simulation for deep squatting in which the conventional posterior stabilized knee prosthesis was fitted. In the simulation we introduced a newly defined slip ratio in order to describe an over slipping phenomenon; the slipping and the rolling directions were mutually reversing. Then, the results demonstrated that the slip ratio was over 1 at high and deep flexion, indicating that the femoral rollback did not occur even though the post and the cam contacted. The relation also indicated that the conventional post-cam mechanism would not work appropriately at high/deep flexion. To overcome the above, and to promote femoral rollback even at high/deep flexion, we proposed a new design of the post-cam mechanism, which we called as a ball-ditch mechanism.

Keywords: artificial knee joint, femoral rollback, slip ratio, posterior stabilized type, 2D model analysis

1. Introduction

The objective of this study was to introduce the design method of artificial knee joint which can make deep flexion.

Total Knee Arthroplasty (TKA) has been widely applied for the knee osteoarthritis and the joint rheumatism. Replacing the articular surface of the knee joint to artificial objects, it removes the pain and improves the activity of the knee. Although many kinds of prostheses are used, most of them have been designed based on the analysis of level walking. Besides level walking, people need to perform various kinds of lower limb activities in their daily life. Especially for Asian and Arabic people, to attain deep knee flexion is crucial because of their life style or religious reason. New prostheses which can make deep flexion are under developing, however, the analytical data concerning about deep flexion of knee joint are lacking.

Therefore we performed the simulation of deep squatting of conventional artificial knee joint and analyzed the kinematics by slip ratio which we defined newly. And then we suggested the new mechanism of the artificial knee joint, introducing the reason why conventional knee prostheses cannot make deep flexion.

2. Materials and methods

2.1. Objective knee prosthesis

The objective knee prosthesis was Scorpio NRG (Striker Co.), the typical prosthesis of PS (posterior stabilized) type. Prostheses of PS type have the post and the cam; they contacts to make femoral rollback1). Femoral rollback is necessary to avoid dislocation or impingement for deep flexion. Posterior cruciate ligament works for make rollback in normal knee though it is cut to implant the artificial knee joint.

Although some patient with NRG can make deep flexion, the average range of motion of this prosthesis is about 120° or 130°2).

Fig. 1 Objective artificial knee joint

†Corresponding author: fukunaga@gs.mech.kyushu-u.ac.jp

Copyright © 2011 Japanese Society of Tribologists
2.2. Method

The method was the 2D model simulation\(^3\). The model was constructed by femoral component, tibia insert and patella component, including some soft tissues around the knee. It introduced the position/orientation of each component, position of contact point and contact forces form the knee flexion angle, muscle forces and external forces, through the geometrical condition of point contact and the force/moment equilibrium condition. The objective motion was deep squatting, namely the motion from standing position to heel-rise deep squatting. The motion was deep squatting, namely the motion from standing position to heel-rise deep squatting. The flexion angle was from 0° to 150°.

It should be noted that the patients with the objective prosthesis are strictly prohibited to perform such motion. The unfavorable results would not indicate the kink of its design.

![Fig. 2 Deep squatting](image)

2.3. Newly defined slip ratio

We used the slip ratio as a parameter to evaluate the results. However, the conventional slip ratio\(^4\), Eq.(1), cannot describe over-slipping, the motion of slipping reversing rolling, which sometimes occur at tibiofemoral joint. Such motion for the tibiofemoral joint is called paradoxical motion\(^5\). Therefore we defined the slip ratio, Eq.(2), newly to describe such motion. In Eq.(2), the directions were contained, that is, \(lf\) is positive when the knee flexes and is negative when the knee extends, and \(lt\) is positive when the contact point moves to posterior and is negative when the contact point moves to anterior (Fig. 3). Figure 4 shows the range of \(S_1\) and \(S_2\) in case of each motion.

\[
S_1 = \frac{lf - lt}{lf + lt} \quad 0 \leq S_1 \leq 1 \quad (1)
\]

\[
S_2 = \frac{lf - lt}{lf} \quad (2)
\]

In \(S_2\), \(lt\) and \(lf\) are not symmetrical. Its denominator was defined to use the slip ratio as a function of flexion angle. Since a femur is relatively circular and a tibia is flat, \(lf\) is almost proportional to the flexion angle. Therefore the newly defined slip ratio is for estimating the mechanics of artificial knee joint, whereas the conventional slip ratio is usually used for predicting the wear amount of machine elements.

![Fig. 3 Explanation about \(lf\) and \(lt\)](image)

![Fig. 4 Explanation about the newly defined slip ratio](image)

Fig. 4 Explanation about the newly defined slip ratio

3. Results

The results are shown below. Figure 5 shows the position and orientation of each component, patella ligament and quadriceps. The white points indicate the position of contact point. Figure 6 shows the slip ratios \(S_2\) of tibiofemoral joint.

The post and cam contacted when the flexion angle was about 60°. From then the slip ratio was below 1, indicating the femur rolled back on the tibia. However, the slip ratio was over 1 when the flexion angle was over 90°, indicating the femoral over slipping occurred instead of rollback.

And the slip ratio below 0 showed that the rollback was too much and the femur slipped on the tibia.

![Fig. 5 The position and orientation of each component at each knee flexion angle](image)

![Fig. 6 The slip ratio \(S_2\) of tibiofemoral joint](image)

Fig. 5 The position and orientation of each component at each knee flexion angle

4. Discussions

4.1. The reason why femur did not rollback

The mechanical problem for the knee prosthesis to
Michihiko Fukunaga, Jin Kawanoya and Shunji Hirokawa

flex deeply was that the slip ratio was over 1 when the flexion angle was over 90°, though the post and the cam were contacting. The reason of this could be explained by its design of posterior-stabilizing mechanism.

In order to introduce the relation between the femoral rollback and the design of prosthesis, we constructed the simple model. In the model, articular surfaces of tibia were modeled by a plane and the post was perpendicular to the articular surfaces.

The equation (3) shows the rollback speed. And then we introduced the relation between the slip ratio and the design of the femoral component, especially of the cam (4).

\[ v = (\sin \theta \cos \theta) \left( \frac{a}{b} \right) \theta \]

\[ S_2 = 1 - \frac{a \sin \theta + b \cos \theta}{R_f} \]

In these equations, \((a, b)^T\) means the position vector of the center of cam from the center of condylar surface (Fig. 7), \(\theta\) means the knee flexion angle and \(R_f\) means the curvature radius of condylar surface. Although the equation was introduced through the simple model, the results could explain the real phenomena reasonably.

It is important that the slip ratio (or rollback speed) could be estimated by the position of the center of cam, as the function of flexion angle.

Putting (4) to the function of \((a, b)^T\) we introduced (5). It means the straight line on \(a-b\) plane and moves by inputting \(S_2\). By using this, the slip ratio can be controlled by designing the cam.

\[ b = \frac{\sin \theta}{\cos \theta} + \left(1 - S_2\right)R_f \]

Figure 8 shows the area for the center of cam to make the slip ratio below 1 and over 0. The area was large in low and middle knee flexion, however, it was small in high and deep flexion. It is because of the change of curvature of the condylar surfaces; because \(R_f\) became small when the flexion angle was over 90°, the coefficient of \(S_2\) became smaller (Fig. 9).

And Fig. 10 shows the center of cam in case of objective prosthesis, NRG. It was not contained in the area for high and deep flexion to be 0 \(\leq S_2 \leq 1\).

Thus we explained the reason why the PS type of knee prosthesis did not make femoral rollback in high and deep flexion.

4.2. The new mechanism to make femur rollback

It was very difficult to put the center of cam in the area shown in Fig. 8 for the cam became thin. Then the curvature of cam became larger and the contact stress on post might be very large.

However, it was possible when the cam was so large that it protruded from the condylar; then the cam should be shaped as a ball. And then, the post should be shaped as a ditch in order to adapt the ball. Then, we suggested the ball-ditch mechanism (Fig. 11) instead of post-cam mechanism.
We analyzed the newly suggested knee prosthesis by the 2D model (Fig. 12) and introduced the slip ratio (Fig. 13). The slip ratio was always below 1 when the ball and ditch contacted, which indicated that the femoral rollback continued even in high and deep flexion.

Such design that the femur with ball have already suggested as CFK, Complete Flexion Knee, which has ball-socket mechanism to reduce the contact stress6). Therefore the problem about femoral rollback might be overcome. However, the results above are introduced by the 2D model analysis. The detail of the design should be considered carefully by the other analytical methods, especially taking the rotational motion into consideration.

5. Conclusion

We performed the 2D model simulation of deep squatting and analyzed artificial knee joint using newly defined slip ratio and found that the femoral rollback did not occur during high and deep flexion. We introduced the relation between the slip ratio and the design of posterior stabilizing mechanism, and explained the reason why the femur did not rollback in high and deep flexion for PS type of prosthesis. And using the method, we suggested the design method of posterior stabilizing mechanism to control the femoral rollback using the newly defined slip ratio. We suggested the new posterior stabilizing mechanism, ball-ditch bearing, to make femur rollback even in high and deep flexion.

6. Acknowledgement

This work was supported by Japan Society for the Promotion of Science, Grant-in-Aid for Scientific Research, Scientific Research (B) (20300161).

7. References