A 2D Model Analysis of Artificial Knee Joint during Deep Squatting*

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Abstract

The objective of this study is to analyze kinetics and kinematics of artificial knee joint at deep flexion, using a 2D geometric model. Our knee model was composed of the tibio-femoral and patello-femoral joints, including the patella tendon and the quadriceps muscles. Since the model was 2D, it neglected the rotation and the varus/valgus motion. In the model, such assumption was made that articulation surfaces were rigid and a point contact was made. Also it was assumed that the force and moment equilibrium conditions were always satisfied. The motion to be studied was decided as the motion from standing to deep squatting with heel-rising. From the simulation we found such results that the femur did not make a rollback and contact force at post-cam became pretty large in high and deep flexion, indicating the post-cam mechanism did not function well. Also patello-femoral contact forces reached larger than tibio-femoral contact forces. Our results demonstrated that how to design the post-cam and patello-femoral joint should be critical issues for developing a new prosthesis which can make deep flexion.

Key words: Artificial Knee Joint, Deep Knee Flexion, 2D Model Analysis

1. Introduction

The objective of this study is to analyze kinetics and kinematics of artificial knee joint at deep flexion.

Total Knee Arthroplasty (TKA) has been widely applied for the knee osteoarthritis and the joint rheumatism. 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.

Among conventional prostheses, most widely used are the posterior stabilized type (PS type), which have a post on tibia insert and a cam on femoral component. And the post and cam make contact with each other when flexion angle reaches to certain angle. The post-cam mechanism helps for the femur to make a roll back on the tibial plateau to assure its stability in the posterior direction. As for a normal knee, the posterior cruciate ligament has a role of posterior stabilizer, which is cut off in the case of TKA knee. Although the

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conventional prostheses of PS type have good clinical results with wide range of motion, they do not yet secure deep flexion. Thus in order to investigate what kind of problems would occur in deep flexion for PS type, we performed simulation analysis.

2. The 2D knee model

We constructed a 2D model of total knee joint arthroplasty. It was composed of tibio-femoral joint and patello-femoral joint.

The model was composed of the tibio-femoral and patello-femoral joints, including the patella tendon and the quadriceps muscle. Since the model was 2D, internal/external rotation, varus/valgus motion and medial/lateral translation were not considered. The tibia was set as a fixed coordinate system, and the femur and the patella as moving systems. The positions of the tendon and muscle insertions were determined basing on the anatomical map. The length of patella tendon was determined from the literature⁽¹⁾⁽²⁾, and it was assumed to be constant. The shapes of articulating surfaces were determined so that a 3D knee joint was sagittally sectioned along the medial/lateral contact point trajectory⁽³⁾. Then the above shapes were described with circles and lines (Fig.1).

Since it was difficult to introduce both the tibio-femoral and the patello-femoral articulating conditions at the same time, we first introduced the tibio-femoral articulating condition, and then introduced the patello-femoral articulating condition.

Fig.1 The modeling of contact surfaces.

2.1 Tibio-femoral joint

In the tibio-femoral joint (Fig.2), the soft tissues were not included. As the input data, knee flexion angle and knee joint force were chosen. The relative orientation of each component was introduced as a function of knee flexion angle.

In our model, it was assumed that the contact surfaces were rigid and made point contact. And the model was assumed to be in the state of force equilibrium. Then we could introduce the relative position of each component and contact forces at each contact point.

While the post and cam did not make a contact, only the articulating surfaces made a contact. Then the contact force of articulation surface F_1 might be the counteracting force of knee joint force, and we could introduce the position of contact point and the relative position of each component.

After the post and cam made a contact, the relative position of each component was introduced under the condition that both the articulation surfaces and the post-cam made point contact. Then the orientations of contact forces were introduced. From the force equilibrium condition, the contact forces of articulation surface F_1 and post-cam F_2 were introduced. The contact force values on the condylars were equally divided into the medial and lateral sides basing on the 3D geometry of knee joint.

Fig.2 The 2D model of tibio-femoral joint.

2.2 Patello-femoral joint

The patello-femoral joint model included the patella tendon and the quadriceps muscles (Fig.3). The position/orientation of the femur relative to the tibia were already known and consequently the insertion of patella tendon on the tibia (relative to the femur groove for patella) was also known. We chose the quadriceps force as input data. In the model, such phenomenon could be represented that turning around of the quadriceps on the femur groove. Same as the model of tibio-femoral joint, it was assumed that the articulation surfaces were rigid and made a point contact. And the model was assumed to be in the state to satisfy the force and moment equilibrium conditions. Then we could introduce the relative position/orientation of each component, patello-femoral joint force and the tensile force of patella tendon.

The position/orientation of each component was introduced by the condition of point contact, moment equilibrium and the length of patella tendon. Since the tensile force of patella tendon and joint force were unknown, the moment equilibrium condition cannot be introduced in a usual way. Thus we introduced the moment equilibrium condition through the other way; that is, the vector of quadriceps force F_q , tensile force of patella tendon F_{pt} and joint force F_p intersect at one point. Then the orientation of each force was introduced. Furthermore the joint force and the tensile force of patella tendon were introduced by the force equilibrium condition (Fig.4). Same as the tibio-femoral joint, the patello-femoral joint force was divided into the medial and lateral ones.

Fig.3 The 2D model of patello-femoral joint.

Fig.4 The force equilibrium condition of patello-femoral joint.

3. Materials and Methods

The prosthesis used in the simulation was Scorpio NRG PS (Striker Co., USA). The condylar and the cam were modeled as combinations of circles. The tibia plateau was modeled as circles and the post was as a line.

Although some patients with NRG can make deep flexion, the average range of motion of this prosthesis is about 120° ⁽⁴⁾.

The simulation was performed for the motion from standing to deep squatting with heel-rising. Knee flexion angle was set from 0° to 150° . It should be noted that the prosthetic patients are not allowed to make such motion practically. The reason why we did simulate this motion was to find out the possible problems for the PS prosthesis in case of deep flexion. The input data for our simulation, such as knee joint force and quadriceps force (Fig.5) were introduced from the musculo-skeletal model of lower limb ⁽⁵⁾.

Fig.5 The input data for squatting.

4. Results

Figure 6 shows the position/orientation of each component. In the figure, hollow circles on the tibial insert indicate contact points. The post and the cam contacted when the flexion angle was over 50° . When the flexion angle was over 80° , the quadriceps turned around the femur groove. Figure 7 shows the variation of contact force at each contact point. Figure 8 shows the variation of tensile force of patella tendon.

Fig.6 The position/orientation of each component and soft tissue.

Fig.7 The contact forces on each contact point.

Fig.8 The tension of patella tendon.

5. Discussion

5.1 Validity of the model

Figure 9 shows the joint force of patello-femoral joint and tensile force of patella tendon relative to quadriceps force. The results are analogous to the result of simulation of normal knee based on in-vivo measurement⁽¹⁾. This indicates the validity of our results.

Fig.9 Tension of patella tendon and joint force relative to quadriceps force.

We set hamstrings muscles by deciding the insertions and connect them by a line, and calculated the moment arm length about the contact point on articulation surface (Fig.10). The moment arm was zero when the flexion angle was about 130°. The knee cannot flex over 130° without external force⁽⁶⁾. This result suggests that the range of motion of knee without external forces is limited by the moment arm of hamstrings. And the knee angle when the moment arm was zero was analogous with the maximum knee angle without external forces. Again this fact shows the validity of our results.

Fig.10 The moment arm length of hamstrings about contact point on tibial plateau..

5.2 The function of patella

Without patella, the tensile force of patella tendon should be equal to the quadriceps force. Actually, however, the tensile force of patella tendon was smaller than quadriceps force. Thus we may say that the patello-femoral joint reduces the tension of patella tendon.

5.3 The problem of post-cam mechanism

The maximum contact force on the post was 1.07[kN]. It is said that the post might be broken by over 0.5[kN] of contact force⁽⁷⁾. Thus we have to say that the contact force exerted on the post/cam during squatting is extremely large.

Figure 11 shows the contact location on the tibial plateau in the posterior-anterior direction. Although the femur made a roll back after the post cam made a contact, it did not

after flexion angle was over 90° . The femur made a standstill and did not make a rollback due to the change of rotation center. Thus the post-cam mechanism may not work reasonably at high and deep flexion. And we also found that the contact forces on the articulation surfaces were large during squatting. Therefore a serious friction may be caused in case of squatting.

For new prosthesis which can make deep flexion, the post-cam mechanism must be developed to reduce the stress on the post as well as to make femur rollback in deep flexion. Otherwise it should be considered for developing a new mechanism which could secure the posterior stability as well as the femoral rollback.

Fig.11 The anterior-posterior contact location on tibia.

5.4 The problem of patello-femoral joint

The contact forces on the patello-femoral joint were larger than that of tibio-femoral when the flexion angle was over 110° . Currently various types of prostheses are available however, kinds of patella components are quite few. As for prosthesis capable to make deep flexion, the design of patello-femoral joint should be a key factor in order to reduce contact stress on the patella surface.

6. Conclusion

We performed a 2D model simulation of knee prostheses during deep squatting. Then we introduced the following results. The femur did not make a rollback after flexion angle was over 90° . The maximum contact force on the post/cam exceeded the material strength of the post: over 1[kN]. The contact forces on the patello-femoral joint became larger than those of the tibio-femoral joint in high and deep flexion. To develop a new prosthesis capable to make deep flexion, the design of the post-cam mechanism as well as the patello-femoral joint would be crucial.

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