# BIOMECHANICAL ANALYSIS OF THE ANTERIOR DISPLACEMENT OF TIBIAL TUBEROSITY (MAQUET OPERATION): A COMPUTER MODEL STUDY

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Abstract - *A computer model of the patellofemoral joint was developed and the effects of the anterior displacement of the tibial tuberosity were investigated. The input geometrical and verification data for the model were obtained from an experimental study on a cadaver knee, mounted in an instron machine. The computer program found the configuration of the patellofemoral joint which satisfied both the geometrical and force equilibrium conditions, simultaneously, using a trial graphical approach. Verification of the model was achieved by determining the patellar sagittal plane motion and patellofemoral contact locations and comparing the results with the experimental results of the same specimen and published data. Simulation of the anterior displacement of the tibial tuberosity by the model showed that the location of contact area migrates distally on the femur and proximally on the patella following operation. The contact force of the patellofemoral joint decreased significantly by 70% at full extension, 30% at 30 degrees flexion and around 15% at higher flexion angles for a 1 cm anterior displacement of the tibial tuberosity and nearly doubled for a 2 cm anterior displacement. The change of the effective moment arm of the quadriceps was not considerable. The results suggest that the major effect of the Maquet operation on the contact force appears in extension and mid-flexion rather than deep flexion angles. Further displacement of the tuberosity enhances the reduction of the contact force, however, the total reduction is less than what was predicted by Maquet. The change of the contact location relieves pain in short term but causes hyperpressure in the proximal retropatellar surface which might be detrimental in long term.*

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## INTRODUCION

Application of computer modeling in the study of human joints has been increasingly appreciated in recent years as a result of the significant success of these models in predicting and analyzing the behavior of natural and artificial joints (1-6). Computer models provide a better understanding of the role and significance of each individual relevant factor (i.e., muslce strength, ligament stiffness, tendon insertion, articular surface geometry) in the joint's normal or pathological function and produce simultaneous detailed data of the motion, force and contact characteristics of a specimen in different geometry and load conditions. However, the most attractive feature of computer, modeling for orthopaedic surgeons may be the capability of the models to simulate pathological joints and predict the result of conservative or surgical treatments. This not only helps to evaluate the effectiveness of commonly used treatments and find their right indications, but also encourages the design of new surgical plans.

Although the patellofemoral joint is not apparently interposed into the weight-bearing column of the lower limb, it is subjected to contact forces and stresses that may actually be higher than every other joint in the human body (7). The patellar tendon of a weight lifter was calculated as being loaded by more than 17.5 times his body weight when it ruptured (8). Acting under such enormous forces, it is not surprising that anterior knee pain caused by patellofemoral bone and soft tissue difficulties, is so common. Anterior displacement of the tibial tuberosity for relief of anterior knee pain, resulting from patellofemoral osteoarthritis and chondromalacia of the patella, was first described by Maquet et al. in 1963 (9). It is thought to increase the moment arm of the quadriceps and decrease the joint contact force by opening the angle between quadriceps and patellar tendons. In 1976, Maquet reviewd 39 patients after anterior displacement of the tibial tuberosity, with an average follow-up of 4.7 years, of which 37 had a good or excellent result (10). Later studies, have reported less satisfactory results particularly in long term, varying in a range of 63 to 97 precent (11). The appropriate amount of the anterior displacement, has also been under much debate (10-13).

The purpose of this study was to demonstrate the application of computer modeling in orthopaedic surgery and to investigate the effects of the Maquet operation with different amounts of anterior displacement on the patellofemoral joint contact force, contact area, and the effective moment arm of the quadriceps.

## MATERIALS AND METHODS

### Experimental data basis

An experimental data basis was necessary for providing the input information of the computer model and for verifying its predictions. The input data consisted of the motion data: positions of the tibial tuberosity in various flextion angles, and the geometry data: articular surfaces of the patella and femur, insertions of the tendons, etc. The verification data included the motion data of the patella. A fresh frozen cadaver knee specimen from a male aged 72 was used in this study. All the skin, fat and muscular tissues were removed leaving only the tendons, ligaments, retinaculae and the joint capsule intact. Colorful markers were placed on the patella and tibia and the knee was mounted in an instron machine with the femur fixed vertically and the tibia free to be flexed to any desired flexion angle (Fig. 1). A horizontal rod blocked tibial extension when the quadriceps was pulled. The quadriceps tendon was connected to the load cell of the instron through a freezing clamp. A constant tension of 500 N was applied to the quadriceps tendon parallel to the femoral shaft in the frontal plane and 5 degrees anteriorly in the sagittal plane. The knee was flexed from full extension to 120 degrees flexion by 5 to 10 degrees intervals. At each flexion angle, the position of the markers on the patella, tibia and femur were traced by lateral photographs.

The articular geometry of the joint was obtained by embedding the patella and femur in bone cement and sectioning into thin sagittal slices by a high precision saw (Fig. 2). Eight successive slices were cut in the central zones of the patella and femur with a thickness of 3 mm each. The slices were photographed, projected to × 10 magnification and then digitized. The length of the patellar tendon and the insertion sites of the quadriceps and patellar tendon in the patella were also measured.

### Computer modeling

Computer programs in Auto LISP language were developed for reconstruction of the patellofemoral joint geometry and analysis of the joint's sagittal plane articulation, in Auto CAD environment. The articular surfaces of the patella and femur were expressed by B-spline profiles in parallel sagittal planes with different elevations (Figure 3). The quadriceps muscle was modeled as a string with variable length and the patellar tendon as a stiff spring with constant lenght.

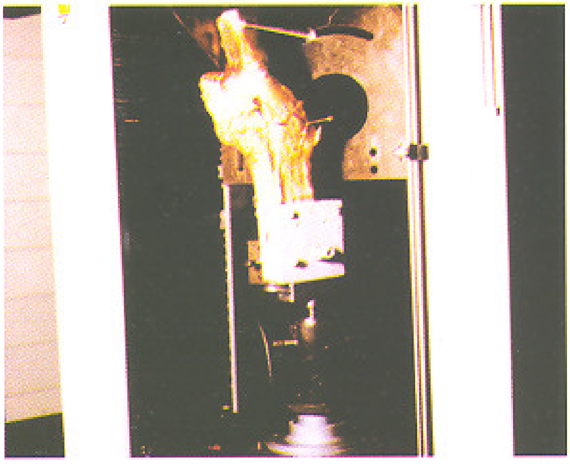

Fig. 1. The specimen mounted in the instron machine with the femur fixed, the quadriceps tendon pulled by the cross head, and the tibial extension blocked by the rod.

Using the positions of the tibial tuberosity as the input data, trial positions for the insertion point of the patellar tendon into the patella were assumed in an arc with the tuberosity as the center and the length of the tendon as the radius. Then the computer program swung the patellar profiles around its tendon insertion to make contact with the femoral profiles, resulting in a configuration which satisfied the geometrical conditions of the joint. However, to satisfy the force equilibrium conditions of the joint, the contact force, the quadriceps force and the patellar tendon force should intersect in a single point in this configuration (7). Otherwise, another point in the arc was assumed as the trial position of the patellar tendon insertion and the procedure was repeated. This continued until a configuration was found that satisfied both of the geometrical and force conditions simultaneously.

## RESULTS

The computer model predictions for the patellofemoral joint configuration in the sagittal plane are represented in Fig. 3. At full extension, the patellofemoral contact occurred on the origin of the femoral groove and the distal part of the patellar ridge. With knee flexion the contact area moved proximally on the patellar surface, and distally on the femoral groove towards intercondylar notch. Fig. 4 includes the motion data of the patella calculated by the model along with the experimental measurements. The correlation between the results was remarkable: the maximum error was less than 4 degrees for the patellar flexion and 3.5 degrees for the angulation between patellar tendon and tibial shaft.

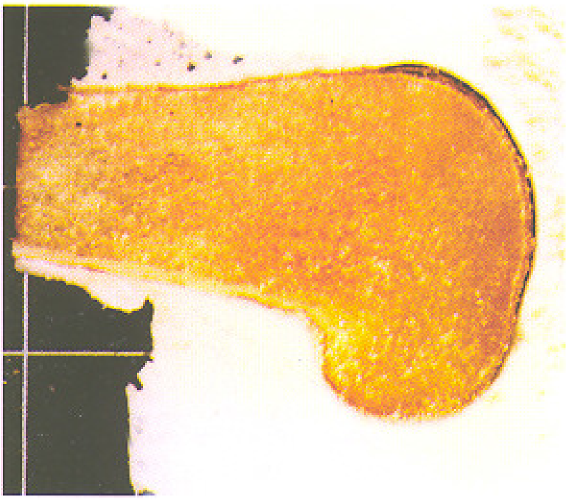

Fig. 2. Sagittal slices of the femur and patella obtained to assess the articular geometry of the joint. The insertion sites of the quadriceps and patellar tendon in the patella can be recognized in the patellar slice.

To simulate the Maquet operation, at each flexion angle, the position of the tibial tuberosity was displaced anteriorly by 10 and 20 mm in a direction perpendicular to the long axis of the tibia and the model was analyzed again (Fig. 5). Displacement of the tibial tuberosity rotated the patella in the sagittal plane, moving the apex distally and anteriorly, and causing the contact area to migrate distally on the femur and proximally on the patella. The contact forces and effective moment arms of the quadriceps calculated by the model before and after Maquet operation are compared in Figure 6. The contact force decreased significantly in the entire range of flexion following Maquet operation. With 10 mm displacement, the reduction was 70% at full extension, 30% at 30 degrees flexion and around 15% at higher flexion angles. When the 20 mm displacement was applied, the reduction was doubled to

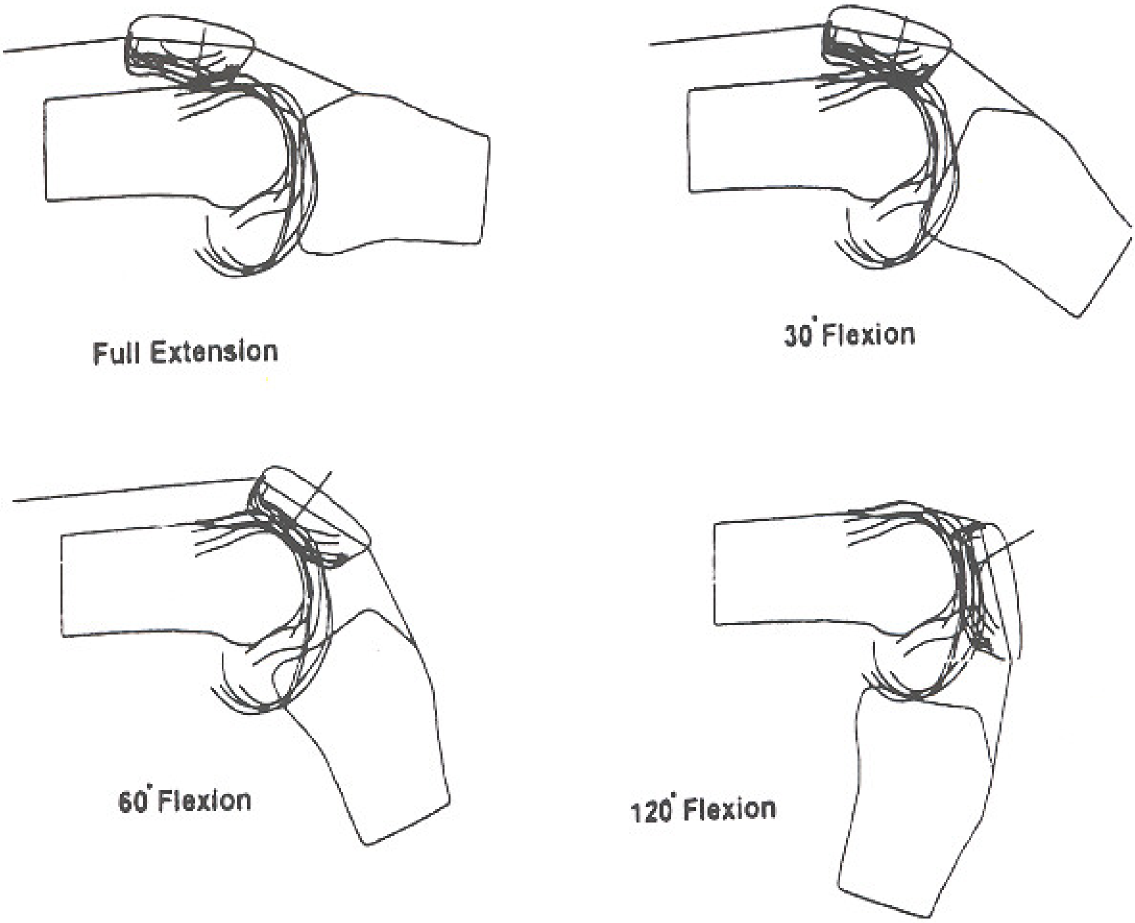


Fig. 3. The patellofemoral articular surfaces were reconstructed using profiles of sagittal slices and the geometrical configuration of the joint at different flexion angles was calculated by the model.

60% at 30 degrees and around 30% at higher flexion angles; there was no contact between the patella and femur before 20 degrees flexion. The change of the quadriceps effective moment arm was not considerable. The largest increase was only 4 mm in extension and mid-flexion angles, following 20 mm displacement of the tibial tuberosity.

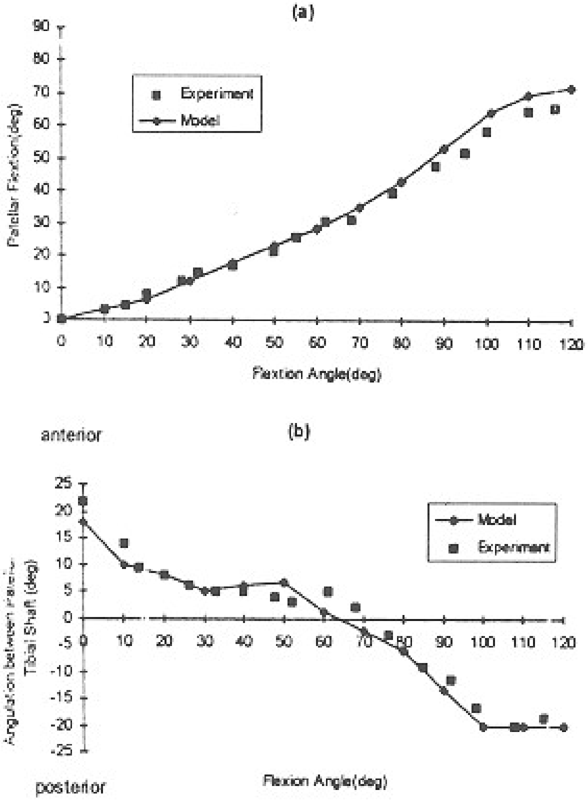


Fig. 4. Patellar motion data as predicted by the model and measured experimentally. (a) patellar flexion, (b) angulation between patellar tendon and tibial shaft.

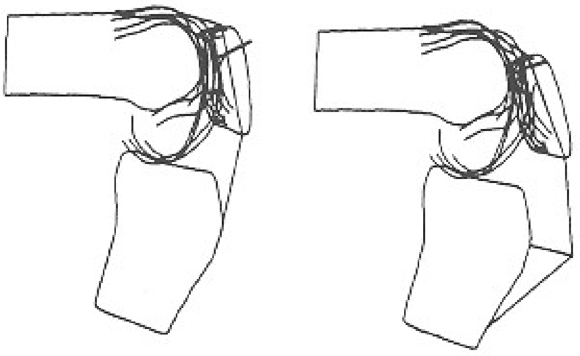

Fig. 5. The change of the sagittal plane configuration of the patellofemoral joint following 20 mm anterior displacement of the tibial tuberosity.

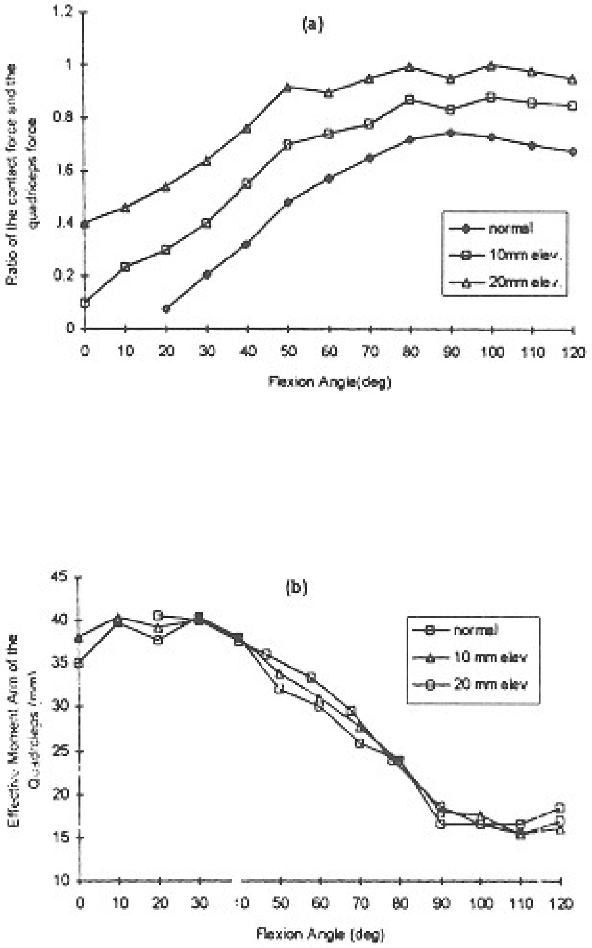


Fig. 6. The effect of the Maquet operation on (a) the contact force and (b) the effective moment arm of the quadriceps.

## DISCUSSION

In this study a computer model of the patellofemoral joint and its application in orthopaedic surgery was demonstrated. The results of the computer model are in good agreement with the experimental measurements on the same specimen and the results reported in the literature. The predictions of the model for patellar motion with knee flexion is similar to the results obtained experimentally by vanKampen et al (14). Also, the results of the model for location of the patellofemoral joint contact area at different flexion angles is consistent with the experimental results in the literature (15-17). This justifies the conclusion that this model can reasonably simulate the behavior of the patellofemoral joint.

Bruke and Ahmed (18) simulated the Maquet operation in cadaver specimens and measured the patellofemoral contact pressure using sensitive film. They reported the reductions of the contact force as 84% at full extension, 34% at 30 degrees flexion, and about 32% at higher flexion angles following a 1 cm anterior displacement of the tibial tuberosity and nearly doubled reductions for a 2 cm displacement. In a similar study, Lewallen et al (19), suggested that anterior displacement of the tibial tuberosity reduces the contact force consistently in the whole range of knee flexion and the effectiveness of the operation increases with further displacement. These results correlate well with the results of the present study, however, the amounts of the contact force reductions we obtained are slightly lower. The results of ferguson et al (12), on the other hand, are totally different form our results in that they found the reduction of contact force to be most prononuced at 90 degrees flexion. Furthermore, they reported that an additional anterior displacement of the tuberosity beyond 1.2 cm, has no considerable effect on the reduction of contact force. We believe that their results are inaccurate considering the fact that they employed 6 miniature contact stress transducers which only indicate local contact stresses at the insertion sites of the transducers and can not provide any valuable information concerning the contact force or mean contact stress.

Maquet (10) believed that the anterior displacement of the tibial tuberosity, increases the moment arm of the quadriceps significantly and assumed this to be a major factor in the reduction of the joint contact force. The effective moment arm of the quadriceps calculated in this study represents both the geometrical moment arm of the quadriceps and the force ratio of the quadriceps and patellar tendon. Our results suggest that the Maquet operation has no considerable effect in the effective moment arm of the quadriceps. We found no published experimental data in the literature to compare our results however our finding may explain why the clinical outcome of the Maquet operation is not as good as he predicted.

The proximal migration of the contact area on the patella following Maquet operation observed in the present study, is consistent with the experimental results of Fernandez et al (13) and Lewallen et al (10). This is thought to relieve pain by altering the contact zone from the existing cartilage lesions. However, transfer of the contact area away from its initial location across the wide part of the patella in mid flexion angles, increases the cartilage pressure specially near the patellar proximal pole and might be responsible for the poor long term results of the Maquet operation.

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