

Influence of Quadriceps Malalignment on Simulated Patellofemoral Kinematics Following Total Knee Arthroplasty

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Abstract

Although implant designs and surgical techniques for total knee arthroplasty (TKA) have advanced considerably, patellofemoral complications remain common, affecting approximately 10% of cases. The patellofemoral joint enables smooth motion of the patella along the femoral trochlear groove. Nonetheless, abnormal tracking can result in elevated contact pressures, subluxation, or even dislocation. Previous studies have suggested that preoperative quadriceps malalignment may contribute to poor postoperative outcomes [1]. Musculoskeletal modeling and simulation offer a way to objectively predict postoperative function and evaluate alternative surgical and alignment strategies. Given the expectation of minimal elastic deformations in the involved bones and implants, the exploration of the multibody dynamics (MBD) approach has emerged as a viable solution, offering a computationally efficient methodology for investigating patellofemoral joint mechanics [2]. Therefore, the objective of this study is to determine whether patellofemoral joint simulations can accurately predict patellar tracking after TKA, assess how quadriceps malalignment alters patellofemoral mechanics, and explore whether such simulations can support improved component positioning.

In this work, the knee model consisted of three rigid segments—the femur, tibia, and patella, each with its corresponding implant (Figure 1)—connected by four soft tissue structures: the collateral ligaments, the patellar tendon, and the medial patellofemoral ligament. The three-dimensional bone geometries and tendon attachment sites of a patient with quadriceps malalignment (QTAx of 43°) were reconstructed from medical imaging, while the implant geometries were provided by the manufacturer. The femur was fixed in place, and the movement began with the knee flexed at 80°. A full extension–flexion cycle was then simulated by replicating quadriceps contraction at a constant speed.



Figure 1: Unbalanced contact forces during patellofemoral joint simulation after TKA in a patient with

quadriceps malalignment.

The anatomical structures and implant components were modeled using triangular surface meshes. During knee extension, the femoral and tibial implants remained in contact, and this interaction was modeled using a mesh-to-mesh contact detection algorithm. In contrast, the patellar implant has a spherical geometry, allowing it to be modeled as a simple primitive and enabling the use of a more efficient sphere-to-mesh contact algorithm [3] between the patellar and femoral components. Tendons were represented as multiple linear springs connected in series, with spherical bodies acting as intermediary nodes. This setup allowed the tendons to wrap realistically around bones and implants, reproducing the natural curvature of muscle and tendon paths as they interact with the skeletal structures. The spherical bodies facilitated accurate force transmission and improved contact detection during motion. Consequently, the same efficient contact-detection strategy was applied to simulate tendon wrapping around the bones. Frictional (tangential) forces were not included in the model, while the normal contact force was computed using the Flores formulation [4].

As a result, the simulations enabled detailed observation and quantification of patellar tracking and mediolateral imbalances in contact forces acting on the patellar button (Figure 1) induced by quadriceps malalignment. Numerical predictions were validated experimentally using a sensorized 3D-printed knee rig, with simulated kinematics and contact forces showing strong agreement with experimental measurements. Furthermore, the high computational efficiency of the MBD approach—characterized by short processing times for both initial position setup and full knee flexion–extension cycles—enabled rapid testing of multiple implant configurations to support identification of the most suitable treatment option.

References

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