EFFICIENT MULTIPLE-CONTACT DETECTION FOR PATELLOFEMORAL JOINT SIMULATION AFTER TOTAL KNEE REPLACEMENT

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INTRODUCTION

Although implant design and surgical techniques for total knee replacement (TKR) have improved, complications persist, with approximately 10% of cases involving patellar issues [1]. The patellofemoral gliding joint enables the smooth movement of the patella along the trochlear groove at the lower end of the femur. Poor patellar tracking can lead to complications such as increased contact pressures, patellar subluxation, or dislocation. To address these challenges and improve treatment outcomes, musculoskeletal models and simulations can provide objective predictions of post-treatment function, allowing clinicians to explore various treatment options for patients. Given the expectation of minimal elastic deformations in the involved bones, the exploration of the multibody dynamics (MBD) approach has emerged as a viable solution, offering a computationally efficient methodology for addressing clinical knee joint concerns [2]. However, incorporating contact mechanics into a multibody dynamics framework presents a major computational challenge, particularly in collision detection. In this work, the authors propose an efficient multiple-contact detection approach to accurately and efficiently simulate the complex interactions between contacting bodies while maintaining the required realism for multibody system analysis.

METHODS

In this study, the leg model consisted of three separate rigid bodies connected by ropes to mimic the muscles and tendons: the femur, the combined tibia and foot, and the patella. The 3D geometries accurately replicated the experimental knee test rig [3], including the supports, bones, and implants. The femur was fixed, and leg extension was simulated by mimicking quadriceps contraction. This was achieved by pulling a rope connected in series to both a load cell and the patella to measure the generated tension. The movements of the load cell, tibia, and patella were recorded using an optical motion capture system with 12 optical markers placed on the various bodies. The simulation was guided by the experimentally measured positions of the load cell, and the measured motions of patella and tibia were utilized to experimentally validate the simulation results, as indicated by the red markers in Fig. 1.

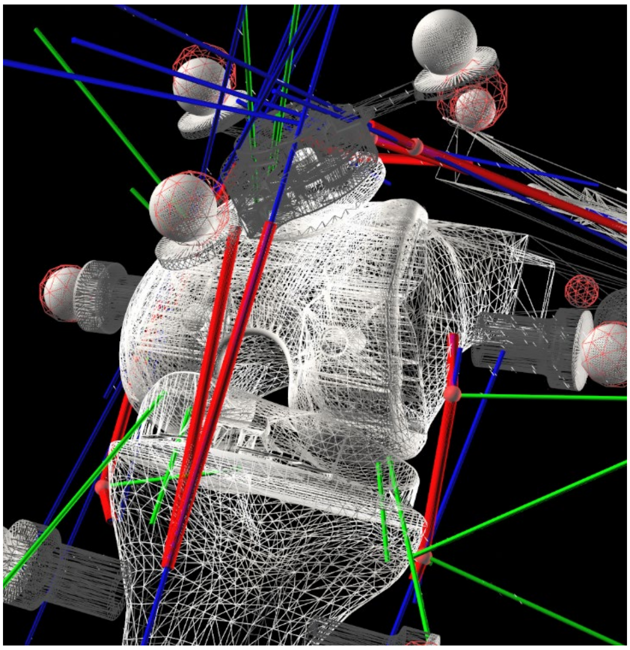

Fig 1: Patellofemoral joint simulation with multiple-contact detection (green) and spring forces (blue).

The complex 3D geometries of the bodies were approximated using meshes composed of triangular faces. The femoral and tibial implants were in contact during leg extension, and a mesh-to-mesh contact detection algorithm was employed for this interaction. In contrast, since the patellar implant is spherical, it was approximated as a primitive object, enabling the use of a more efficient contact detection algorithm to identify contact between the femoral and patellar implants. This was achieved by applying a sphere-to-mesh detection algorithm [4], which checks for intersections or contact by calculating the closest points between the sphere's surface and the mesh. This method ensures efficient and accurate detection of contact between the spherical object and the complex 3D surfaces.

Ropes, representing muscles and tendons in the experimental setup, were modeled as multiple linear springs connected in series, with spherical bodies serving as intermediary connection points. This modeling approach allowed the ropes to wrap around bones and implants realistically, simulating the natural path of muscles and tendons as they interact with the skeletal structure. The use of spherical bodies helped guide force transmission and improve the accuracy of contact detection during movement. Consequently, the efficient contact detection technique was also applied to simulate the wrapping of muscles and tendons around the bones or implants. The model includes a total of three muscles and six tendons, which are divided into 18 springs connected through 9 spherical bodies.

The tangential forces (friction) were not considered, while the Flores model was selected for the normal force [5].

RESULTS AND DISCUSSION

In total, the simulation had to manage the contact detection and calculation for 11 pairs of bodies. The simulation of the initial position took only 4.1 s, while the simulation of a complete knee extension and flexion took 74 s, corresponding to 34 times the real duration. The motion observed in the patella and tibia showed good correlation with the experimental measurements. However, the numerous spring parameters needed adjustment to improve the match with experimental data. The total force exerted by the muscles during the simulation was noisy, with some very high peaks due to the guiding restrictions, which hindered the use of larger time steps and slowed down the simulation. In future work, a proportional-integral-derivative (PID) controller will be implemented to guide the system more smoothly.

CONCLUSIONS

The simulation demonstrated high computational efficiency, with low processing times for both the initial position setup and full knee extension and flexion. Future work will further optimize the system's performance by fine-tuning parameters and implementing a PID controller to reduce noise and improve stability.

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