EasyChair Preprint

№ 13322

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May 16, 2024

The 7th International Conference on Multibody System Dynamics
June 9-13, 2024, Madison, WI, USA

Comparison of contact detection algorithms for patellar tracking and contact force estimation

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Abstract

The patella serves as a vital component in the knee joint, functioning as a crucial relay mechanism that acts like a pulley for the extensor system. This enhances the leverage of the quadriceps, thereby increasing the strength of active knee extension. The patellofemoral joint, refers to the connection between the patella and the femur. This joint is designed as a gliding mechanism, allowing the patella to move smoothly within the trochlear groove located at the lower end of the femur. The patella is essentially a sesamoid bone embedded within the quadriceps tendon, and its role is pivotal in the proper functioning of the knee joint. Patellar instabilities can result in elevated pressure, patellar tilt, subluxation, or even dislocation.

To address these challenges and improve treatment outcomes, orthopedic surgeries increasingly rely on musculoskeletal models and simulations [1]. These tools offer the ability to make objective predictions about post-treatment functionality and empower healthcare professionals to explore various treatment options for individual patients. By employing these tools, the treatment planning process becomes more objective, enabling clinicians to customize and optimize clinical outcomes based on each patient's unique characteristics. There are two primary approaches for defining a mechanical system: Multibody Dynamics (MBD) and the Finite Element Method (FEM) [2]. In the Finite Element Method, each body is discretized into finite elements, forming a mesh that represents the geometry and physical properties of the components. While numerous FEM studies have explored the patellofemoral joint [3]–[5], the time-intensive nature of FEM, which includes pre-processing, processing, and post-processing, limits its clinical applicability. Given this constraint and the expectation of minimal elastic deformations in the involved bones, the MBD approach has emerged as a viable solution, offering a computationally efficient method to address clinical knee joint concerns. However, no work on MBD simulation was found that included a comparison of the patellar movement and forces with experimental results, primarily due to the invasive nature of such experiments.

Nevertheless, a significant computational challenge arises when implementing contact within a multibody dynamics framework, particularly in the area of collision detection [6]. Effectively and efficiently modeling the complex interaction of contacting bodies with realistic precision is a demanding task. When these colliding bodies have intricate 3D geometries, a general collision detection algorithm is required. A simple approach consists in approximating the freeform surfaces with discretized mesh elements and subsequently confirming their proximity or overlap [7]. It is worth noting that the quality and efficiency of these polygonal surfaces and tools can vary. In cases where precise descriptions of specific shapes are necessary, mathematical equations, such as non-uniform rational B-spline (NURBS) surfaces, and analytic 3D geometry formulations, have proven to be effective alternatives in prior applications.

In this study, the authors aimed to simulate the mechanical system without considering elastic deformations in the bones, a requirement for high-performance computing. Therefeore, rigid-body multibody dynamics formulations were applied. A comparative analysis between two collision detection methods employed to simulate interactions between rigid bodies was conducted. The first method is a mesh-to-mesh collision detection algorithm, which discretizes the bodies into triangular mesh surface elements. The second method employs analytical surface expressions to offer closed-form solutions for addressing the contact problem.

Computational efficiency was taken into account, and the histories of the patellar position, orientation, and pressure during its motion were compared with experimental measurements obtained from a sensorized 3D-printed test bench. The forces were validated by comparing them with measurements from load cells and a pressure sensor, while the motion trajectory of the patella was validated by contrasting the simulated coordinates against those registered by the optical motion capture system. This comparison was conducted by calculating the root mean square error between the respective pairs of data sets for the two collision detection methods and with different 3D models of the femur for each one (Figure 1).

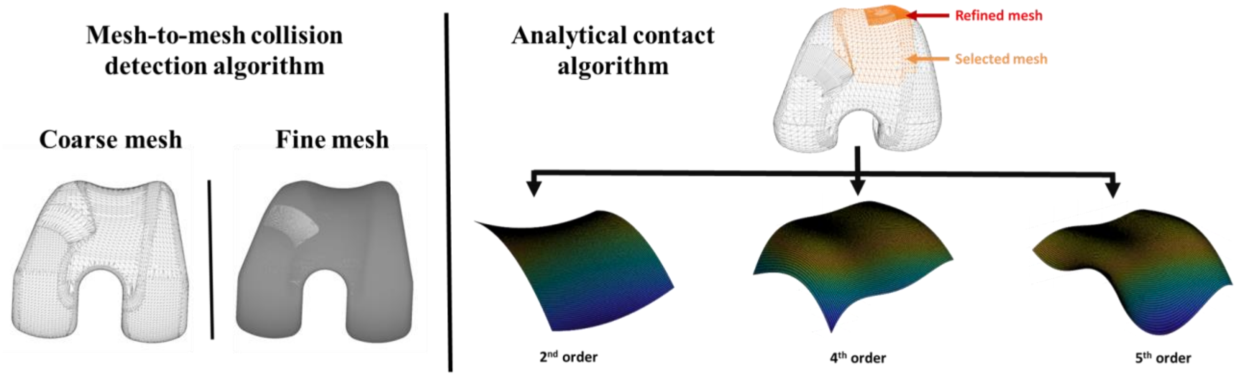

Figure 1: 3D models of the femur considered.

Funding

Grant OTR0123 funded by Pixee Medical. Grant PID2022-140062OB-I00 funded by MCIN/AEI/10.13039/501100011033 and by "ERDF A way of making Europe", by the European Union. Grant ED431C 2023/01 by the Galician Government. Moreover, F. Michaud would like to acknowledge the support of the Galician Government and the Ferrol Industrial Campus by means of the postdoctoral research contract 2022/CP/048.

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