Development of Computational Multibody Models of Anatomical and Prosthetic Knee Joints as Evaluation Tool for Orthopaedic Interventions and Prosthesis Design

Abstract

The knee represents one of the most complex joint of the musculoskeletal apparatus being characterized by a three-dimensional kinematics which results from the concurrence of translational and rotational motions among the articulating bones forming the joint. The complexity of the knee kinematics derives by the interaction of different anatomical structures. Especially, ligaments play a critical role in defining the range of motion of the knee, since they represent the major articular restraining elements. An alteration of the balancing among the constraining actions exerted by the ligaments, together with the other soft tissue surrounding the joint, leads to modifications in the joint kinematics and, consequently, to the establishment of detrimental intra-articular loading conditions. In fact, ligaments deficiency can result in serious degenerative knee injuries (e.g., osteoarthritis and joint wear). Furthermore, the knee is particularly vulnerable to acute trauma and to the development of arthritis and osteoporosis that are among the main causes for disability and pain in the modern society. Issues related to the knee functionality are relevant for both humans and dogs, indeed, since the joint anatomy and kinematics are comparable between the two species, they shear similar knee injuries as well as relative surgical treatments. In order to alleviate pain caused by pathological conditions and to restore the functionality of the knee joint, when the non-surgical treatments fail, different orthopaedic surgical approaches can be pursued, for instance, corrective osteotomies and prosthesis implantation. Focusing on arthroplasty, a successful surgical outcome depends on various technical factors including accurate bone resection, proper prosthesis positioning, and adequate soft tissue balancing. In the last years, the introduction of even more sophisticated mechanical tools and computer-assisted surgical systems has made it possible to improve the accuracy of the procedures and, thus, enhance surgical outcomes. Nevertheless, essential information, such as intra-articular contact pressure and soft tissues tensioning, remain still challenging or even impossible to measure during a surgical intervention in an operative room.

In this context, the integration of computational simulations into the surgical decision-making process appears as an appealing solution to address this lack of information and to quantify surgical parameters that, usually, are just qualitatively evaluated. In particular, the multibody modelling of joints has been proven to be an effective approach to estimate significative quantities, such as forces related to ligaments, tendons, muscles, and intra-articular contacts, in addition to relative motions between bones. Especially, the development of even more accurate patient-specific biomechanical models, coupled with surgical navigation systems and specifically designed sensing devices, could lead to a better understanding of the joint biomechanics as well as to the implementation of valuable tools aimed at supporting surgeons throughout the pre-, intra- and post-operative phases, providing additional data to foresee consequences of surgical interventions and also improve actual surgical techniques.

In this thesis work, various modelling strategies have been properly exploited to investigate specific orthopaedic issues related to the biomechanical behaviour of the anatomical and artificial knee joint in canine and human subjects, respectively. In detail, three distinct multibody models have been created in order to (1) compare the effectiveness of two alternative osteotomies in treating the anterior cruciate ligament rupture in dogs, (2) interactively investigate the impact of different knee implant configurations on the collateral ligaments tensioning after total knee arthroplasty (TKA) in humans, and (3) compare the performance of two different implant designs for TKA in humans. Overall, the implemented multibody models allowed to obtain realistic kinematics and dynamics results, including ligament tensioning and intra-articular contact force.

Findings of this work would contribute to confirm the feasibility of applying the multibody approach to obtain significative information for improving orthopaedics surgical outcomes, especially, those related to knee arthroplasty. Furthermore, multibody simulations manage to provide a realistic investigation of knee implants performance, which is essential for the implant design developments and optimizations.