The effect of soft tissue modeling on tibiofemoral stress distribution in models of high tibial osteotomy and its importance for making simulation-based clinical decisions

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Summary

High tibial osteotomy (HTO) is a surgical procedure to treat unicompartmental osteoarthritis through correcting the lower limb alignment. Biomechanical models have been used for making simulation based decisions on the optimal alignment correction to achieve during HTO. However, in many models generated with this aim, the role of soft tissues has been neglected. Our objective was to investigate the impact that the connective tissues can have on simulation-based decisions.

Introduction

High tibial osteotomy (HTO) is a common surgical procedure used to relieve pain and improve joint function in patients with early-stage unicompartmental osteoarthritis. Its goal is to reduce the pressure of the damaged knee compartment by correcting the limb alignment. However, finding the required correction for each patient is challenging as indicated in the follow-up studies [1]. To overcome this challenge, biomechanical numerical simulations have been used, aiming to find the optimal correction that balances the contact force between knee compartments [2,3]. To our observation, these studies tend to oversimplify the problem by neglecting the impact of HTO on moments produced by the soft tissues. Our objective is to investigate the importance of realistically modelling the connective tissues impacted by HTO on the stress distribution in the cartilages. We propose to study the role of the superficial Medial Collateral Ligament (MCL) that is one of the most important soft tissue in this perspective.

Methods

MRI and CT images of a healthy subject were used to reconstruct the bone and soft tissue geometries through manual segmentation in Amira software. A model of the tibiofemoral joint at 25° flexion was generated in the Artisynth combined FE-multibody platform [4]. Virtual open-wedge HTO was performed on this model to simulate the HTO surgery with a 10° wedge opening. The model included the femoral and tibial cartilages and menisci all modeled with FE components and meshed with hexahedral dominant elements. Anterior and posterior cruciate ligaments, MCL with a deep and superficial layer, lateral collateral ligament, and the knee anterolateral ligament were modeled with bundles of nonlinear springs. An axial load along the mechanical axis of the limb was applied to the tibia at the center of the ankle while the femur was fully constrained and the knee flexion angle was fixed.

During HTO model generation, the superficial bundles of MCL were treated in three different ways: 1) Their length and tension were affected by wedge opening. 2) Their length and tension were not affected by wedge opening. 3) The superficial MCL was released after wedge opening.

Results and Discussion

Maximal principal stress distribution on tibial cartilages was observed in models with the three options for representing the superficial bundles of MCL, as presented in Figure 1. The results indicate that the approach we take towards modelling the MCL after HTO can significantly impact the stress distribution on the tibiofemoral compartments. Assuming that the insertion of superficial MCL is lower than the HTO cut and thus wedge opening results in increasing its length and tension, the maximum principal stress values (medial: -2.29, lateral: 1.40 MPa) show that the medial cartilage is noticeably under higher compression compared to the lateral cartilage. This means that the objective of HTO surgery is not achieved even after 10° wedge opening in this case. The stress in the medial cartilage is reduced to 48% of this value assuming that the superficial MCL is not impacted by surgery. Furthermore, releasing the superficial MCL reduces the medial stress to 34% of this value. This is while the lateral side experiences the highest stress values among the three models. As a result, it seems important to define the approach towards the MCL attachment/release when generating models of HTO as it can significantly impact the stress balance between compartments.

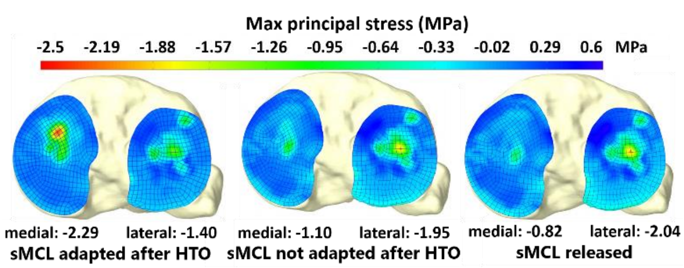

Figure 1: Maximum principal stress distribution on the tibial cartilages after 10° wedge opening.

Conclusions

Our results show that a clear approach towards the MCL in models of the HTO has to be defined to be able to propose relevant simulation-based decisions on the optimal lower limb alignment correction.

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