Can soft tissue modelling approach impact simulation-based clinical decisions about high tibial osteotomy?

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1. Introduction

Varus angular deformity in the lower limb results in deviating the mechanical tibiofemoral axis from its normal situation. The presence of this deformation leads to putting excessive pressure on the medial compartment and could cause uni-compartmental osteoarthritis. Medial open-wedge high tibial osteotomy (OWHTO) is a surgical procedure that aims to reduce the pressure of the medial compartment and improve joint function by correcting the tibial deformation. However, finding the required correction for each patient is challenging as indicated in the follow-up studies (Hernigou et al. 1987). To overcome this challenge, biomechanical numerical simulations have been used, aiming to find the optimal correction needed to achieve the desired contact force balance between the knee compartments (Zheng et al. 2017; Martay et al. 2018). However, our previously performed systematic review indicated that the existing biomechanical studies tend to oversimplify the problem by neglecting the impact of OWHTO on the ligaments and tendons around the knee (Elyasi et al. 2021). Meanwhile, the review of clinical and cadaveric studies clarified that multiple complications could be related to the alteration of the soft tissue insertions after wedge opening (Elyasi et al. 2021). Therefore, the objective of the current study is to highlight the importance of realistically modelling the connective tissues impacted by OWHTO and to investigate possible impacts on the cartilage stress distribution and therefore on simulation-based decision making. We propose to study the role of the superficial Medial Collateral Ligament (sMCL) that is one of the most impacted soft tissues during OWHTO.

2. Methods

MRI and CT scan images of a healthy subject were used to reconstruct the bones and soft tissue geometries through manual segmentation in Amira software. A model of the tibiofemoral joint was generated in the Artisynth combined Finite Element (FE)-multibody platform (Lloyd et al. 2012). Virtual OWHTO was performed to develop a new model from the same subject after a 10° wedge opening. For that, an oblique cut was simulated on the tibia using a plane perpendicular to the tibial frontal plane. The cut passed through the lateral and medial cortex, respectively, 16 mm and 37 mm distal to the tibial plateaus.

The models included the femoral and tibial cartilages and menisci all modeled with FE components and meshed with hexahedral dominant elements as demonstrated in Figure 1. The cartilages were modelled with isotropic linear elastic material having Young's modulus of 15MPa and a Poisson ratio of 0.45 (Yang et al. 2010). The menisci were modelled with a transversely isotropic linear elastic material having Young's modulus of 20 MPa and the Poisson ratio of 0.2 in the radial and axial directions and Young's modulus of 120 MPa and the Poisson ratio of 0.3 in the circumferential direction (Yang et al. 2010; Martay et al. 2018). To represent the connective tissues, 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 (Blankevoort and Huiskes 1991). The definitions and properties of the bundles were defined based on the literature (Pandy et al. 1997; Xu et al. 2015; Helito et al. 2016), while the number of strands in each bundle was chosen based on the area of their attachment sites.

The femur was fully constrained and the knee flexion angle was fixed at 25.2°. An axial force of 667 N was applied along the tibiofemoral mechanical axis corresponding to the walking force of the subject at 14% gait cycle measured through gait analysis. To investigate the importance of providing a realistic model of the sMCL in biomechanical models that address OWHTO alignment problem, three different approaches were tested towards it. Following the wedge opening, the superficial bundles of MCL were modelled 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 sMCL was released after wedge opening.

3. Results and discussion

Maximal principal stress distribution on the medial and lateral tibial cartilages in OWHTO models with various approaches towards sMCL are presented in Figure 2. The results indicate that the approach taken towards modelling the sMCL after OWHTO can

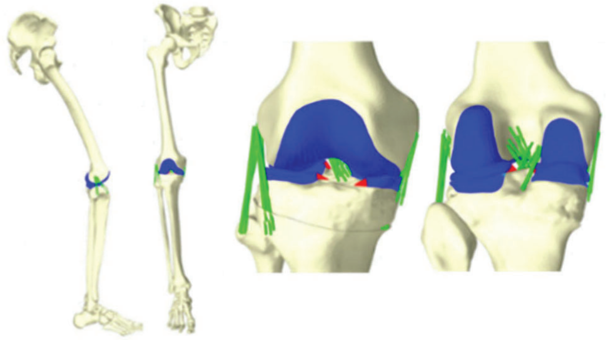

Figure 1. The model of the tibiofemoral joint used to investigate the effect of sMCL modelling approach on cartilage stress distribution after wedge opening.

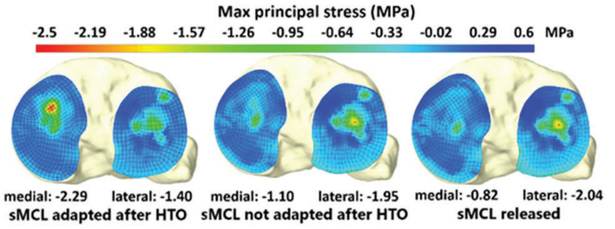

Figure 2. Maximum principal stress distribution on the tibial cartilages after 10° wedge opening. The maximum values for the medial and lateral compartment are indicated for each model.

significantly impact the stress distribution on the tibiofemoral compartments.

The surgical procedure of OWHTO involves an oblique osteotomy from the medial side starting just above the level of the tibial tubercle. As a result, when the sMCL is conserved, its insertion would be lower than the osteotomy cut and thus wedge opening would result in increasing its length and tension. This corresponds to the left image in Figure 2, and the simulation shows that the medial cartilage is noticeably under higher compression compared to the lateral cartilage (maximum principal stress medial: −2.29, lateral: 1.40 MPa). This means that the objective of OWHTO 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 simply by making the assumption that the sMCL is not affected by surgery (middle image in Figure 2). Finally, releasing the sMCL (right image in Figure 2) resulted in reducing the medial stress to 34% of its value when conserving the sMCL. However, in that case, the lateral side experiences the highest stress values among the three models.

We acknowledge the limitation of the study, which is using literature based parameters for the ligament properties rather than using parameters tuned for the subject.

4. Conclusions

The current study clarified that the approach taken towards modelling the sMCL after wedge opening can have a significant impact on the stress balance between compartments. As a result, a clear approach towards the sMCL attachment/release in models of the OWHTO has to be defined to be able to propose relevant simulation-based decisions and make suggestions about the optimal correction for each patient.

Disclosure statement

No potential conflict of interest was reported by the authors.

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