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In silico evaluation of ligaments elongations during passive knee flexion

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1. Introduction

Detailed knee biomechanics, including ligaments elongations, is essential for many orthopaedic procedures. Difficult access to the ligaments, intertwining of bundles, and identification of insertions are strong obstacles to the accurate evaluation of ligaments' elongations. Consequently, results are sometimes contradictory (Nasab et al. 2016) and there is an important disparity in the number of research studies with ligaments receiving less attention than others. *In silico* studies can be used to compute these elongations (Tomescu 2017) but models still suffer from oversimplifications. Ligaments are complex fibrous connective tissue with various shapes that are most of the time represented by deformable 1D elements. The lack of data on some of the knee ligaments and the oversimplifications of the models limit the understanding of the impact of each ligament structure in the knee biomechanics (Farshidfar et al. 2021). Although improving the knee model's realism seems to be the ideal solution to ensure simulation fidelity, this might unnecessarily increase modelling and computation time. In addition, personalisation of ligaments materials and geometry could be difficult to achieve. With these issues in mind, the evaluation of ligaments' impact on knee kinematics would provide valuable data on which knee ligaments to include and personalise.

This study aims to investigate the role of knee ligaments during passive flexion *in silico* using a detailed biomechanical knee model.

2. Methods

A musculoskeletal knee model of one healthy subject (40 years old, 94 kg, 1.73 m) was designed using an Artisynth (www.artisynth.org) multibody framework (Figure 1. (a), Elyasi et al. 2022).

CT-scans obtained with a low-energy procedure were used to capture the bones (femur, tibia, fibula and patella). A 3D high-definition MRI was performed for soft tissues and cartilages. The quadriceps muscles were modelled with multipoint strands able to wrap around obstacles. The same approach was used to model the knee ligaments, which included the posterior and anterior cruciate ligaments (PCL and ACL), medial and lateral collateral ligaments (MCL and LCL), posterior oblique ligament (POL), anterior lateral ligament (ALL), patellar ligament (PL), lateral and medial patellofemoral ligaments (LPFL and MPFL), lateral and medial patellotibial ligaments (LPTL and MPTL). When necessary, the ligaments were decomposed into different bundles, which were themselves composed of several fibres. The Blankevoort's material model (Blankevoort et al. 1991) was used with material parameters based on experimental data from the literature. The subject underwent five non-weight-bearing MRI sessions from full extension to maximal flexion (approximately 138°). The tibia and fibula were fixed in displacement. Flexion forces were applied on the femoral head to replicate the maximal flexion of the MRI. Forces and ligaments' elongations were computed during the

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flexion. The position of the femur centroid during the simulation was compared to the MRI segmentations to ensure that the simulated kinematic was close to the *in vivo* passive flexion.

3. Results and discussion

The error in the femur centroid position was at most 17 mm, which was considered satisfactory considering the combined translation/rotation motion. The effect of the intertwining of ligaments could be observed at high flexion angles (Figure 1. (b)). Such behaviour explains the difficulties of modelling ligament structures with finite elements. As expected, not all ligaments impacted the knee biomechanics during passive flexion.

Table 1. Ligaments fiber's elongations during knee flexion (normalised by the initial ligament's length).

Ligaments	Min	Max	Mean
ACL	0.1	0.9	0.4
PCL	0.0	0.4	0.2
MCL	0.1	0.5	0.2
LCL	0.0	0.3	0.2
POL	0.1	0.1	0.1
ALL	0.5	1.1	0.8
PL	0.0	0.1	0.0
MPFL	0.2	0.3	0.2
LPFL	0.1	0.3	0.2
LPTL	0.0	0.0	0.0
MPTL	0.0	0.0	0.0

An example of the LCL force-strain curves (Blankevoort's model and simulation) is provided in Figure 1. (b). Most ligaments with multiple bundles and/or fibres exhibited a high heterogeneity in terms of elongations. Ligament fibres' maximal and minimal elongations are summarised in Table 1. The lateral and medial PL bundles, the LPTL, MPTL and the POL produced negligible forces. Consequently, these ligaments could be removed in future work to simplify flexion simulations. The differences in ligament fibres' elongations might be explained by the proposed model which enabled ligaments to wrap around bones. In addition, ligament torsion and mediolateral and anteroposterior elongation differences could be computed thanks to the

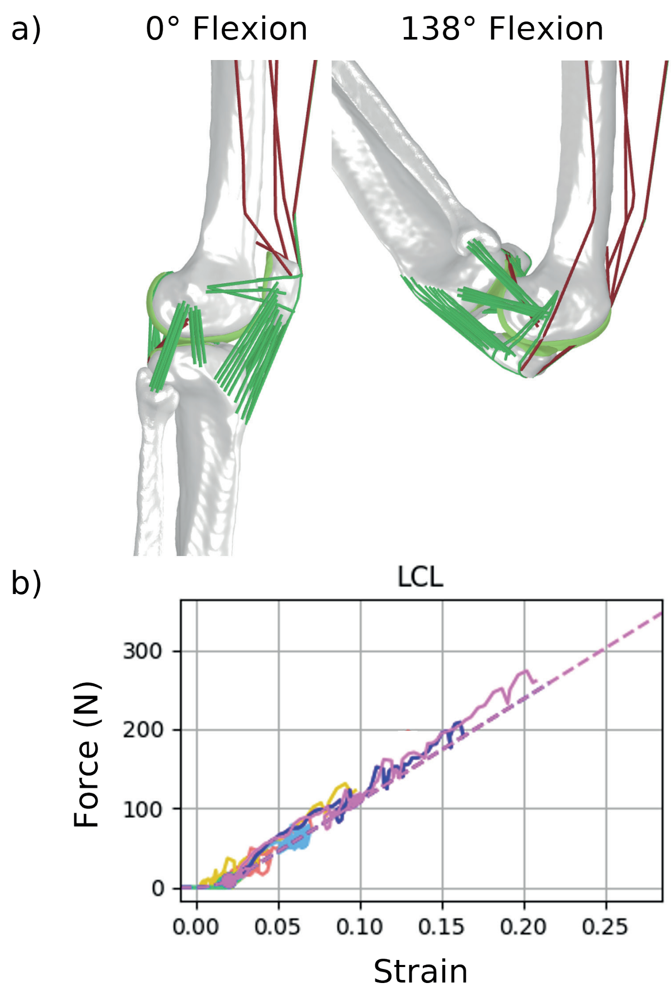

Figure 1. (a)Model with ligaments. (b) LCL fibers force-strains curves (dot line: Blankevoort's model, solid lines: simulations).

fine description of the ligaments with multiple strands, which is close to the real 3D geometry of the ligaments. Such behaviour could not be observed with 2D imaging techniques nor with oversimplified ligament models. Experimental measurements are also tedious to obtain for some ligaments due to the lack of accessibility. The large variability of methods inherently complicates the comparison with literature data.

4. Conclusions

Ligament elongations play a significant role in knee biomechanics and could be a valuable metric for many clinical applications (knee osteotomy, total knee arthroplasty, ligamentoplasty etc.). The lack of gold-standard measurement methods and modelling approaches results in a high variability of reported elongations. The proposed model enables the computation of ligaments' heterogeneous elongations during flexion. Future work includes the conduct of an experimental campaign on cadaveric samples to validate the proposed model.

Conflict of Interest Statement

None.

Contributor Roles

Nolwenn Fougeron: Conceptualization, Methodology, Writing original draft; Investigation, Visualization. Yohan Payan: Conceptualization, Methodology, Funding acquisition, Writing-review & editing; Supervision, Project administration. Antoine Perrier: Data curation, Conceptualization, Methodology, Funding acquisition, Resources, Writing-review & editing; Supervision.

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