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3D ultrasound-based strain assessment of the knee medial collateral ligaments: A Novel In-Silico Optimization and validation platform

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Abstract

This paper introduces a novel in-silico platform for designing, optimizing and validating 3D ultrasound speckle-tracking algorithms that target the biomechanical characterization of knee collateral ligaments. The platform is based on a numerical model of a cadaveric knee following knee arthroplasty (TKA) with a posterior stabilized implant and with experimentally obtained subject-specific material properties of knee collateral ligaments. Applying the platform to develop a 3D ultrasound speckle-tracking algorithm shows promise as the resulting algorithm is capable to capture subtle deformations and strain patterns, with root mean square errors of 0.10 and 0.72 for maximal and minimal principal strains, respectively. However, optimization and in-silico validation are currently limited to one specimen and loading scenario, necessitating further research. Nevertheless, this work lays the foundation for advancing ultrasound-based biomechanical assessments from 2D to 3D, particularly in knee arthroplasty, with the potential for broader clinical impact on musculoskeletal health assessments.

1 Introduction

Ultrasound (US) imaging is a widely employed clinical technique to assess the structural and geometric characteristics of soft tissues, including tendons and ligaments. However, understanding the biomechanical properties of these tissues, such as their tensile strength and viscoelastic behavior, is equally crucial for a comprehensive evaluation of their health [8]. However, current methods utilize US speckle tracking to analyze tissue deformations, primarily in larger structures like the patellar and Achilles tendons [11, 3, 9], and only to a lesser extent, in smaller structures such as medial and lateral collateral ligaments [6, 4]; this despite its significant potential to objectively inform ligament balancing during knee arthroplasty [12]. Nonetheless, these techniques are currently restricted to two-dimensional ultrasound imaging associated with important limitations including, but not limited to, capturing outof-plane motions [10]. To overcome these limitations, the implementation of a three-dimensional (3D) ultrasound system has been suggested as a potential solution. However, there is a lack of tools capable of accurately assessing reference 3D strains within ligaments, which is a prerequisite for the optimization and validation of a 3D speckle tracking algorithm as well as transitioning these findings from laboratory settings to clinical practice. The concept of in-silico ultrasound simulation emerges as a prospective approach to address this challenge. Hence, the objective of this study is to introduce a novel in-silico platform for designing, optimizing and validating 3D ultrasound speckle-tracking algorithms that target the biomechanical characterization of knee collateral ligaments.

2 Method

The in-silico platform is based on a numerical knee phantom of a cadaveric knee that underwent total knee arthroplasty (TKA) with a posterior stabilized implant [7]. Bones and implants were reconstructed from CT-scans and modelled as rigid bodies. Medial and lateral collateral ligaments were segmented from MRI-scans and used for defining hyperelastic finite element models in Abaqus (Simulia, USA) based on the Holzapfel-Gasser-Ogden formulation [13]. The knee specimen underwent experimental characterization by applying a dynamometer-controlled 10 Nm valgus moment at a 30° knee flexion angle. During, reference knee kinematics were obtained with a six-camera 3D motion capture system (MX40+,Vicon Motion Systems, Oxford, UK). Based hereon, subject-specific knee collateral ligaments material properties have been previously defined using a gradient descend approach by minimizing root mean square errors with reference knee kinematics [7]. The numerical knee model was utilized as input for simulating ultrasound scans through FIELD II [5]. Within this simulation, strains and deformations were imposed onto ligament tissue, with ultrasound simulations performed at constant time intervals as represented in Figure 1.

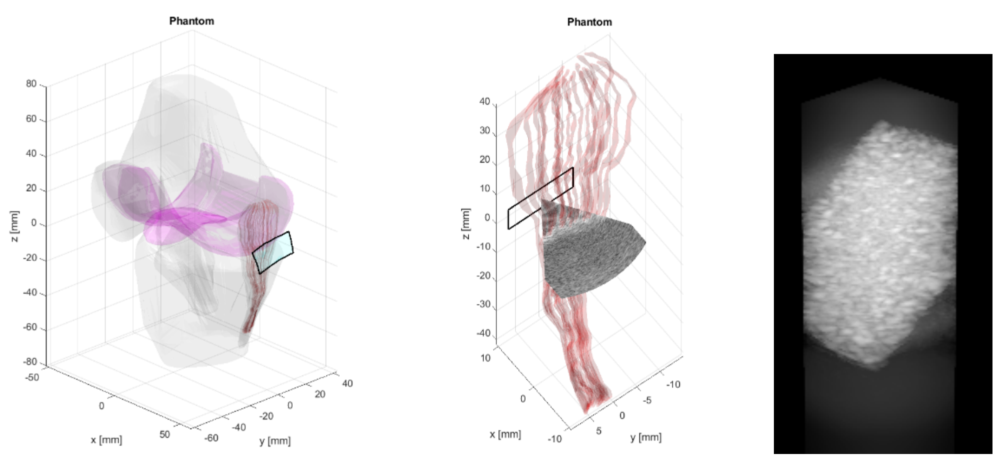

Figure 1: In-silico representation of the post-TKA knee with collagen fibers distribution (left/middle) with a 2D slice (middle) of the whole 3D ultrasound generated data (right).

To illustrate the application potential of the platform, it was used to adapt a previously validated 2D ultrasound speckle tracking method for knee collateral ligaments [2] to accommodate 3D ultrasound data using MATLAB (MATLAB R2021b, The MathWorks, Inc., Natick, MA, USA), Initially, a set of nodes constituting a 3D mesh is manually defined. For each frame, an optimization kernel was centered at each node's position, and a corresponding optimization search window was similarly centered at the same node's position in the subsequent frame. The highest normalized cross-correlation value between the kernels and search windows was utilized to calculate the preliminary displacements. Following median filtering, the calculated displacements were added to the present position of each node, thus defining their estimated positions in the subsequent time frame. This iterative process was applied across all nodes and frames. Following, the entire procedure was repeated in reverse, commencing from nodes in their last computed positions and moving from the final frame to the initial frame. An average was calculated for each frame based on the forward and backward tracking outcomes, resulting in a single displacement matrix. Additionally, the entire process was reiterated after modifying the initial node positions to mitigate any bias resulting from initial node definition. Following previous published work [2], the displacement along each dimension was limited to ±0.3 mm. Consequently, for every trial, a total of 27 displacement matrices were generated, each corresponding to a distinct set of initial node positions which were then averaged for each trial. Strains were then computed for each node at each frame using the small strain approximation [14] and were averaged over all nodes. Subsequently, computed strains were converted to principal strains for every frame. To further illustrate the optimization potential of the in-silico platform, kernel and search windows size were optimized by targeting the smallest root mean square error of both maximal and minimal principal strains, where principal strains from Abaqus are taken as reference. For the comparison, a nonrigid image registration approach [15] has been tested on the same ultrasound-simulated data [15].

3 Results

The application of the 3D speckle tracking algorithm yielded principal strains with a root mean square error of 0.10 and 0.72 for maximal and minimal principal strains, respectively (see Figure 2). In contrast, when employing a nonrigid image-based registration approach on the identical ultrasound-simulated data, higher root mean square errors were observed, measuring 2.57 for maximal principal strain and 0.83 for minimal principal strain. Notably, our findings underscore the superiority of the presented framework, showcasing that block-matching outperforms the nonrigid image registration approach [15] in accurately assessing strains within the medial lateral collateral ligament.

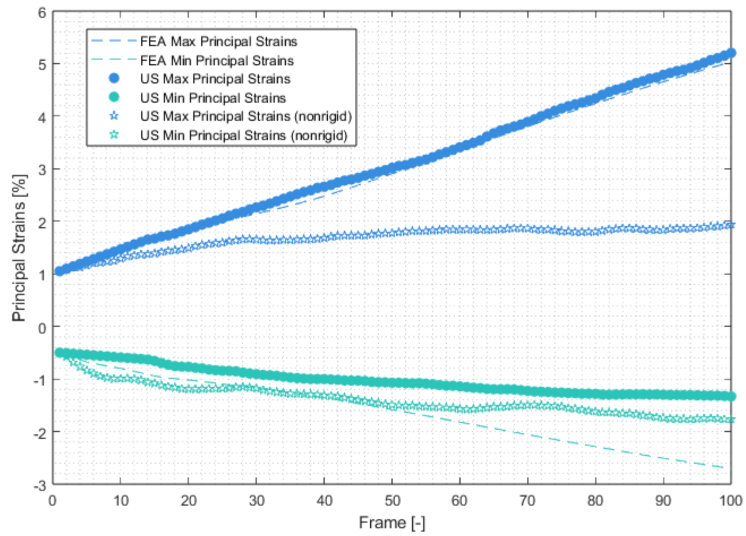

Figure 2: Principal strains comparison between reference strains (FEA) and US assessed strains with the presented 3D speckle tracking algorithm. Results from a nonrigid image registration approach is also presented as comparison

4 Discussion

This study introduced ultrasound simulation to design and optimize a 3D strain tracking algorithm. Furthermore, its application demonstrated that the developed speckle tracking algorithm shows promise in assessing 3D strain in medial collateral ligaments. Indeed, initial results result in strain patterns with a smaller root mean square error than the 2D speckle tracking algorithm [2]. Interestingly, the resulting algorithm demonstrates strain accuracy comparable to a prior 3D tendon strain estimation algorithm applied to the presumably less challenging Achilles tendon [1]. However, the current optimization has only be performed in one specimen and one loading scenario. Future research will focus on extending the simulation platform to multiple specimens and loadings scenarios, as well as performing complementary sensitivity analyses. Upon implementation, the extended platform will be applied to further optimize the defined speckle tracking algorithm and enhance its accuracy, generalizability, and reliability.

5 Conclusion

To conclude, this research presented and verified a unique 3D speckle tracking algorithm designed for evaluating strains in medial collateral ligaments through ultrasound simulation. The algorithm proved its efficacy in capturing deformations and strain patterns, yielding promising outcomes in a specific specimen and loading scenario. To enhance its adaptability, forthcoming investigations should include sensitivity analyses and validations across diverse specimens and loading conditions. This study lays the groundwork for progressing 3D ultrasound-based biomechanical assessments, especially in knee arthroplasty, opening up the possibility of broader clinical applications.

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