An Electrostatic Model for Assessment of Joint Space Morphology in Cone-Beam CT

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Introduction

- A method of mapping tibiofemoral joint space width (JSW) in cone-beam CT (CBCT) volumes based on an electrostatic model of the joint was developed and implemented.
- Preliminary validation experiments were carried out to determine the feasibility of the method.
- Joint space maps were generated from CBCT volumes of osteoarthritic (OA) and normal knees using this method.

The end-goal of the project is to provide clinicians and researchers with a sensitive, accurate, consistent and automatic tool to track changes in joint space morphology from extremity CBCT volumes.

Background/Problem

- Joint space morphology is both a predictor for risk of load-bearing injury (e.g. tibial slope) and an indicator of progression of diseases such as osteoarthritis (e.g. narrowing due to loss of cartilage).
- The articulating surfaces of joints are complex in shape. Current methods to characterize the joint space either lacks robustness or is highly operator-dependent.

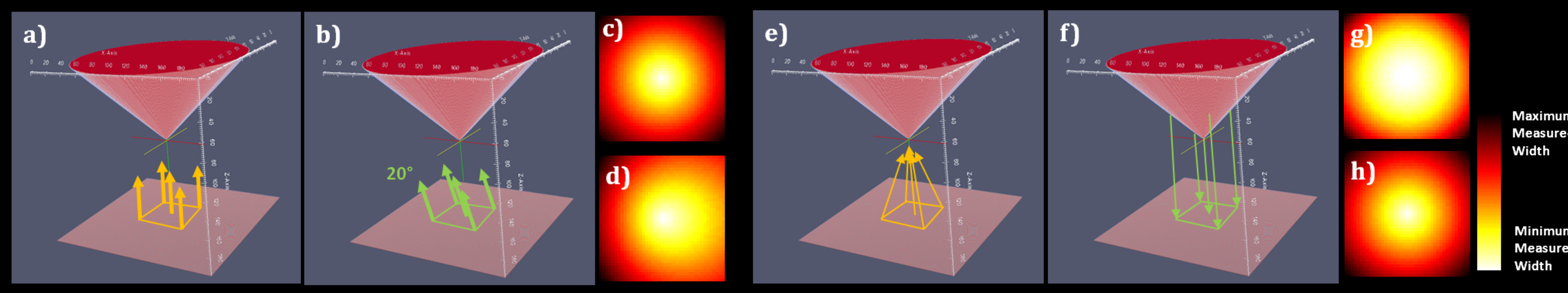
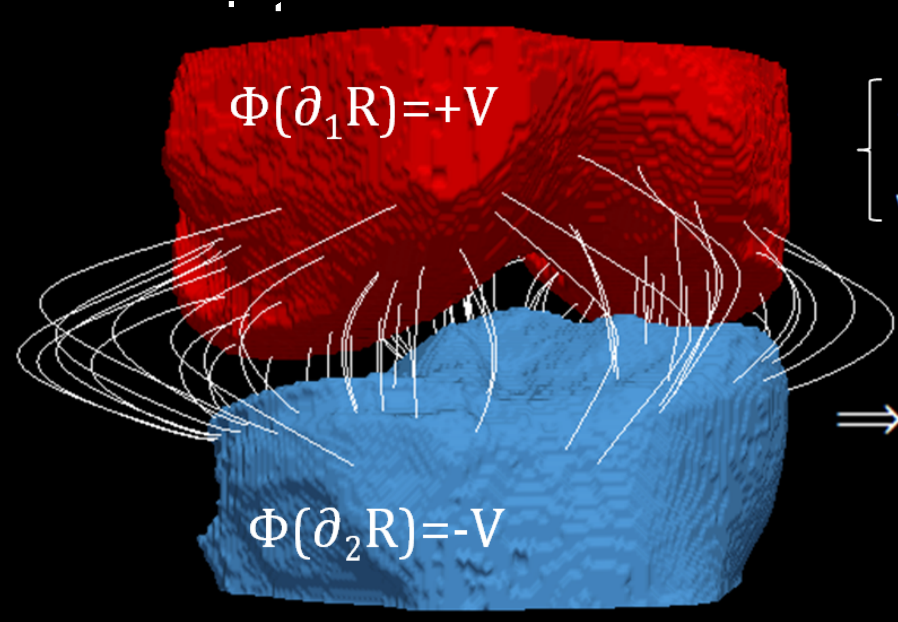


Figure 1 Proposed methods of joint space characterization. (abcd) Projection along the longitudinal axis depends on the definition of an arbitrary direction. (efgh) Closest point distance yields asymmetric measurements that often undersamples the synovial space at protrusions.

Solution

In our method, two articular surfaces of the knee joint are conceptualized as surfaces of differential charge densities, as in a capacitor. Electric field lines emerge from one surface to the other, guided by the electrostatic potential in between. The lengths of these lines and are treated as the joint space width at the corresponding



Definition of electric field

$$\begin{cases} \vec{E} = -\nabla\Phi \\ \nabla \cdot \vec{E} = \dfrac{\rho}{\epsilon_0} \end{cases} \Longrightarrow \nabla^2\Phi = 0$$

Gauss's Law

Laplace equation

$$\Longrightarrow \Phi(a,b,c) \approx \frac{1}{6}[\Phi(a+h,b,c) + \Phi(a-h,b,c) + \Phi(a,b+h,c) + \Phi(a,b-h,c) + \Phi(a,b,c+h) + \Phi(a,b,c-h)]$$

Iteration using Jacobi Method

Figure 2 A basic approach to calculating tibiofemoral distance in the electrostatic model of the joint space. The electrostatic potential (Φ) is solved from the Laplace equation using boundary conditions defined by the shape of the articulating surfaces. Electric field lines could then be found by stepping from one surface to the other using Euler's method.

Resulting Joint Space Width Maps

1. The electrostatic model was applied to the analysis of both OA and non-OA knees to generate joint space width maps.

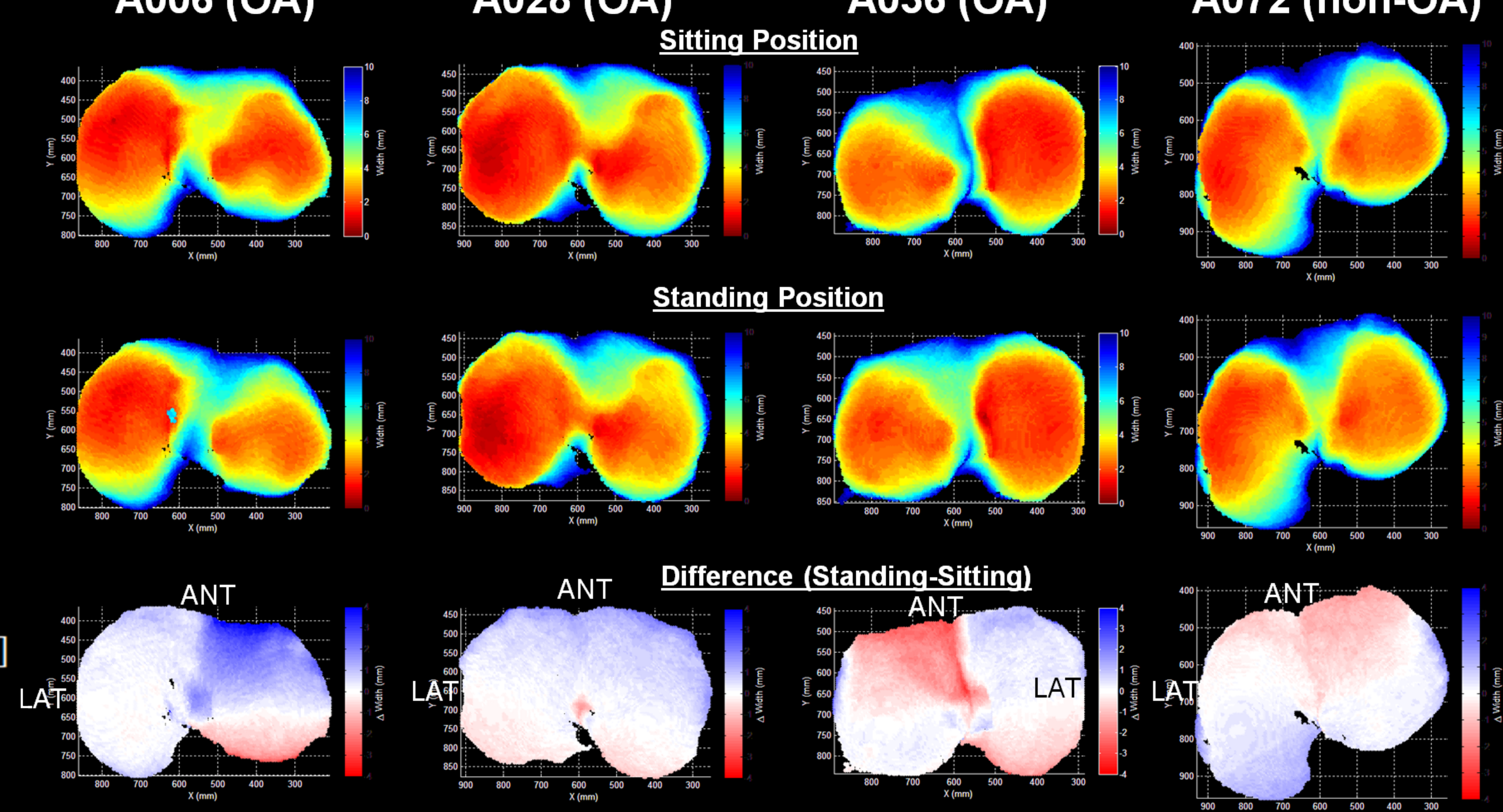


Figure 5 Joint space width maps for 3 OA knees and 1 non-OA knee in sitting, standing positions as well as their difference maps. The method can resolve local changes in joint space width at voxel size (~0.217 mm).

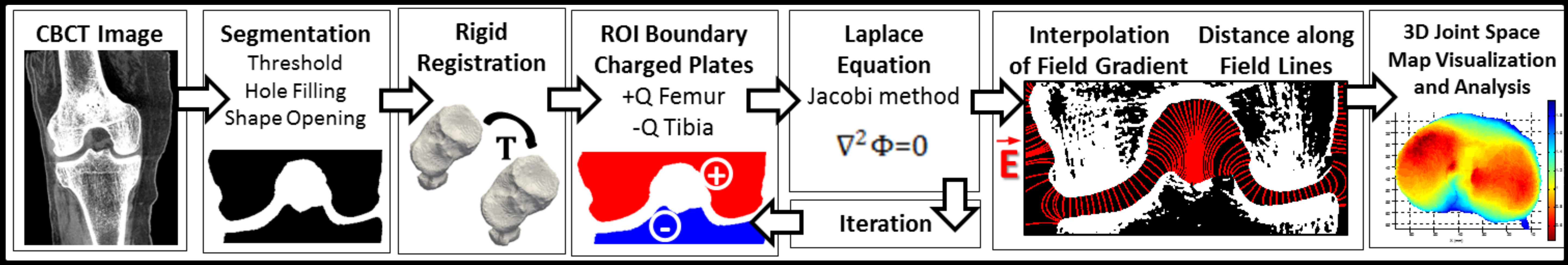


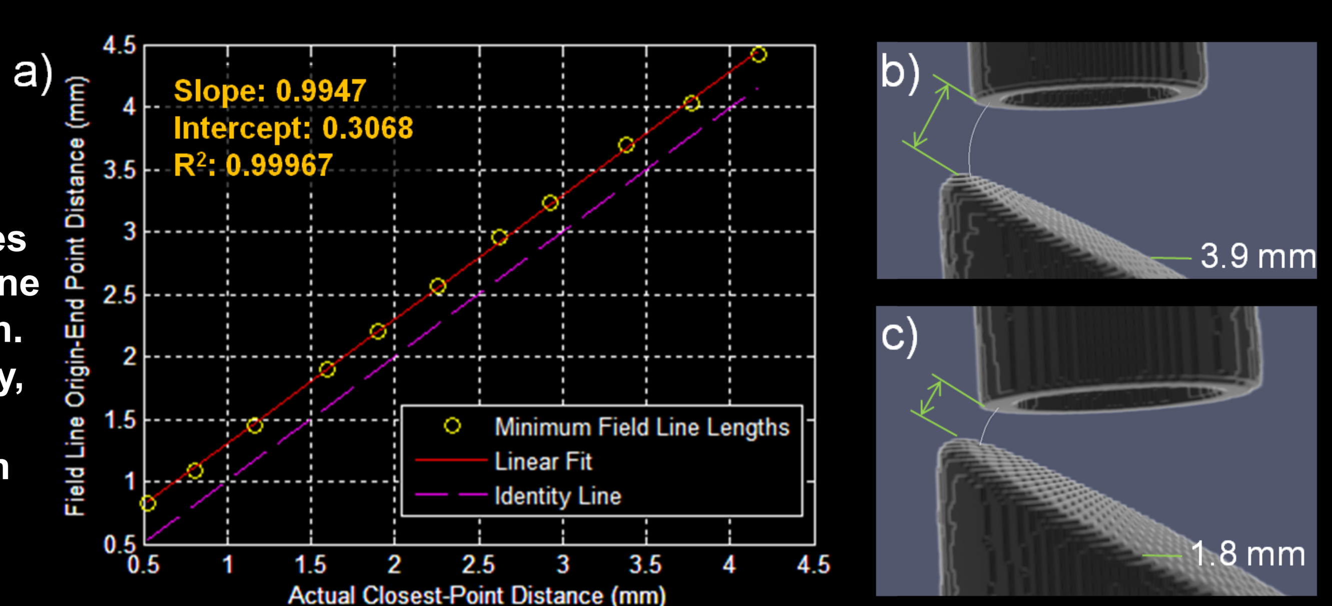
Figure 3 A pipeline was implemented in MATLAB as a set of library functions that takes in DICOM data and generates joint space maps.

The resulting lines are continuously distributed throughout the whole joint, determined solely from the configuration and shape of the articulating surfaces and establish a one-to-one correspondence between the points on the two surfaces.

Phantom Study Results

1. The results from phantom study indicates that the minimum distance measured by the field lines agrees closely with that of the closest point distance.

Figure 4 In the electrostatic model, the analogy to minimum distance between two surfaces is the electric field line with minimum length. In the phantom study, we find a linear relationship between the two lines.



Credits

Qian Cao is responsible for the work presented here.

Lessons Learned

Implementation of segmentation, registration algorithms and numeric solutions to partial differential equations. Basics of CBCT and image reconstruction.

References

Yezzi, A. J., & Prince, J. L. An Eulerian PDE approach for computing tissue thickness. *IEEE Transactions on Medical Imaging*, *22*(10), 1332–9, 2003. doi:10.1109/TMI.2003.817775

Sadiku, Matthew NO. *Elements of electromagnetics*. Oxford university press, 2007.

Future Work

- Correction for differences in knee extension angle.
- More cases (34 OA/non-OA patients and 36 soldiers).
- Interpretation of resulting joint space maps to identify pathologies or abnormalities (e.g. cartilage erosion) via PCA.

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