Patient-specific hyper-elastic biomechanical models for clinical DIR confidence quantification

John Neylon, Sharon Qi, Yugang Min and Anand P Santhanam
Department of Radiation Oncology, University of California, Los Angeles, CA, USA

UCLA Health
Radiation Oncology

Abstract

The accuracy of clinical multi-modal deformable image registration (DIR) is difficult to quantify. A framework was previously developed to validate a deformable registration algorithm (DIR) by generating patient-specific, GPU-based biomechanical models from head-and-neck (HN) patient CT scans and creating clinically realistic ground truth deformations[1]. We now aim to expand the model's applicability to quantify DIR confidence for clinical registrations between the planning CT and daily positioning images.

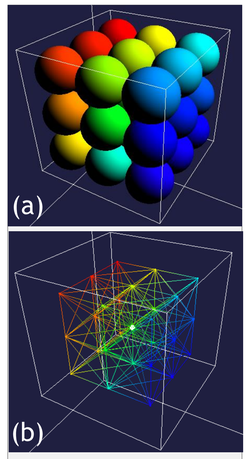


Fig 1. An example of the mesh lattice (b) created for a cube of elements (a). Principle stretches can be calculated directly from the 26 isotropic connections about each element.

Hyper-Elastic Implementation

Most biological tissues exhibit hyper-elastic response for larger deformations. Hyper-elasticity was implemented using a generalized Ogden material model, which allows experimentation with a variety of strain-energy functions by adjusting the parameters *N* and α, such as Neo-Hookean and Mooney-Rivlin:

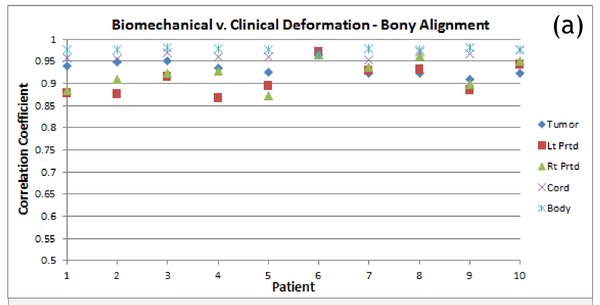
$$W = \sum_{p=1}^{N} \frac{\mu_p}{\alpha_p}\left(\lambda_1^{\alpha_p} + \lambda_2^{\alpha_p} + \lambda_3^{\alpha_p} - 3\right), \text{ with } 2\mu = \sum_{p=1}^{N} \mu_p \alpha_p.$$

From the mesh lattice (Fig. 1), the principle stretches (λ) about each element can be found directly. Principle Cauchy stretches can then be calculated from the partial derivative of the strain energy function with respect to the principal stretches. With principle Cauchy stress for each element, the internal force vector can be computed, and velocity can be updated directly, assuming near-linearity for small time increments. The model was integrated using a second order implicit Euler integration, employing the trapezium rule according to Heun's method.

Matching Daily Observed Anatomy

Daily imaging modalities (CBCT, MVCT) typically suffer from poor image quality, or completely different tissue response (MR), making intensity based registration problematic. The previously developed model can be deformed to match the observed daily anatomy and used to create a ground truth DVF with a corresponding kV-quality simulated CT image set. DIR performance can then be quantified by comparing the DIR and model generated DVFs, producing a confidence margin for the clinical registration.

To validate the model deformations in our previous work, registration was performed between the planning CT and final weekly kVCT of clinical patient data. The DVF for the bony anatomy was applied to the model created from the planning CT, after which the soft tissues were allowed to deform according to the elastic material model. The correlation was then calculated between the model anatomy and observed target anatomy. This methodology will be adapted to reproduce the observed posture and output high quality simulated CT data with a known DVF.



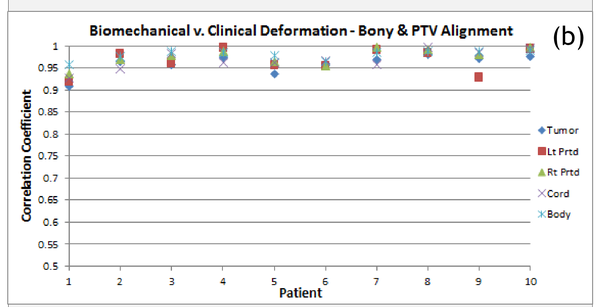


Fig 4. (a) shows the correlation of model generated data sets with induced soft tissue deformation from posture changes applied to bony anatomy. (b) shows the correlation after the inclusion of tumor regression to the model.

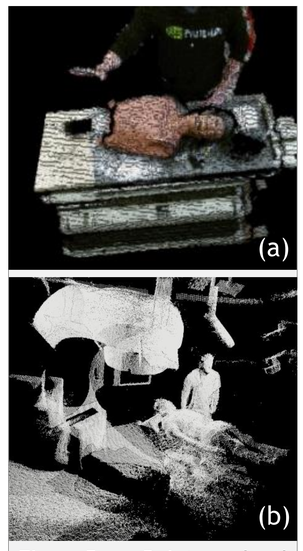


Fig 5. Point cloud renderings of optical surface tracking using Kinect. (a) shows a mock treatment table with phantom. (b) shows a full treatment room with gantry, patient on table, and attendant.

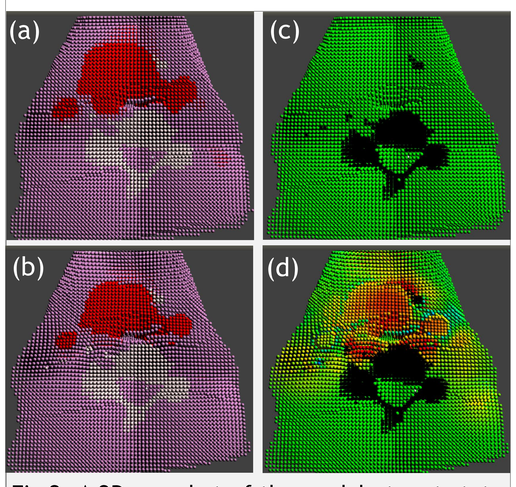


Fig 2. A 2D snapshot of the model at rest state (a) with tumor delineated as red and its deformed state representing 10% tumor volume reduction is shown in (b). The corresponding color-coded strain maps for these states are shown in (c) and (d).

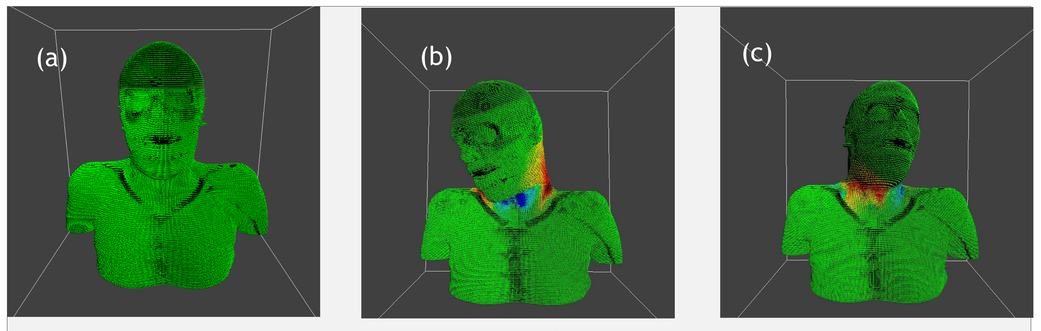


Fig 3. (a) shows how the structures are instantiated as a systems of particle systems, each with bounding box to identify possibly collisions. (b) displays the full model. (c) applies a slight rotation of the head, and (d) introduces tumor regression of 40%. (e-f) apply extensive head rotations, displaying the robustness and stability of the model under large deformations.

Results

Figure 2 illustrates how the model simulates tumor regression, displaying contours and strain map for the anatomy before and after a 10% reduction in tumor volume.

Figure 3 shows preliminary results for the biomechanical model after significant posture changes applied to patient data. Posture changes were performed by controlling the skeletal anatomy, rotating the cranium atop the vertebral column. Frame by frame computations increase in computational cost compared to a linear elastic implementation, but the expansion to a multi-GPU framework should allow the model to maintain an interactive frame rate > 30 fps.

Correlation between the model generated data and the observed clinical deformations are shown in figure 4. When tumor regression was also accounted for in the model, the lowest correlation of the structures analyzed was >0.9. This illustrated the model is capable of simulating deformations very close to clinically observed deformations, and validated the model's ability to ultimately generate ground-truth deformations to be used for DIR confidence quantification.

Conclusion

A biomechanical modelling approach could effectively bridge the gap to facilitate multi-modal DIR, specifically between CT and MR where direct registration is not feasible. The ability to apply anatomical and physiological knowledge to the deformation could also improve the reliability of the daily deformation tracking for soft tissues, when utilizing lower quality modalities such as MVCT and CBCT.

In the future, we look to incorporate real-time optical surface tracking (preliminary results in Fig. 5) to control the model and track intra-fraction motion during treatment.

References

[1] Neylon, J., Qi, X., Sheng, K., Staton, R., Pukala, J., Manon, R., Low, D. A., Kupelian, P., and Santhanam, A., "A GPU based high-resolution multilevel biomechanical head and neck model for validating deformable image registration," Med Phys 42(1), 232-43 (2015).