

Real-time hyper-elastic biomechanical models of head-and-neck anatomy for model-guided multi-modal deformable image registrations

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, GPUbased biomechanical models from headand-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 calculated be can directly from the 26 isotropic connections about each element.



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).

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).



Results

frame rate > 30 fps. to the right.

John Neylon, Sharon Qi, Daniel Low nd Anand P Santhanam Department of Radiation Oncology, University of California, Los Angeles, CA, USA

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:

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

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.

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.

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

Figure 4 incorporates posture changes with volume reduction to the head and neck. In the figure, the rows correspond to the volume changes, with the original anatomy in row 1, 50% regression of the primary tumor in row 2, and 15% general weight loss in row 3. Columns 2 and 3 apply a posture change to each of the volumetrically altered anatomies. Column 2 applied a 25-degree rotation to the left about the cranial-caudal axis. Column 3 applied 15 degree rotations about each axis, tilting the head to the right, bending forward at the neck, and turning



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.



Fig 4. Renderings of the contoured structure model for a variety of posture and volume change combinations.

Conclusion

A biomechanical modelling approach could effectively bridge the gap to facilitate multimodal 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 realtime optical surface tracking to control the model and track intra-fraction motion during treatment.

α_n .

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