A Systematic Quantification of Image Registration Accuracy Using High-Resolution, Patient-Specific, Biomechanical Head and Neck Models

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Purpose

Deformable image registration (DIR) plays a pivotal role in head and neck adaptive radiotherapy but a systematic validation of DIR algorithms has been limited by a lack of quantitative high-resolution ground-truth. We address this limitation by developing a GPU-based framework that provides a systematic DIR validation by generating (a) model-guided synthetic CTs representing posture and physiological changes, and (b) model-guided landmark-based validation.

Methods

The GPU-based framework was developed to generate massive mass-spring biomechanical models from patient simulation CTs and contoured structures. The biomechanical model represented soft tissue deformations for known rigid skeletal motion. Posture changes were simulated by articulating skeletal anatomy, which subsequently applied elastic corrective forces upon the soft tissue. Physiological changes such as tumor regression and weight loss were simulated in a biomechanically precise manner. Synthetic CT data was then generated from the deformed anatomy. The initial and final positions for one hundred randomly chosen mass elements from each internal contoured structure were recorded as ground truth data. The original CT and deformed synthetic CT were then registered using an optical flow based DIR. The process was automated to create 45 postures for several levels of tumor regression. The skull and cervical vertebrae were rotated between 4 and -4 degrees about each axis. Tumor volumes were systematically reduced up to 30%.

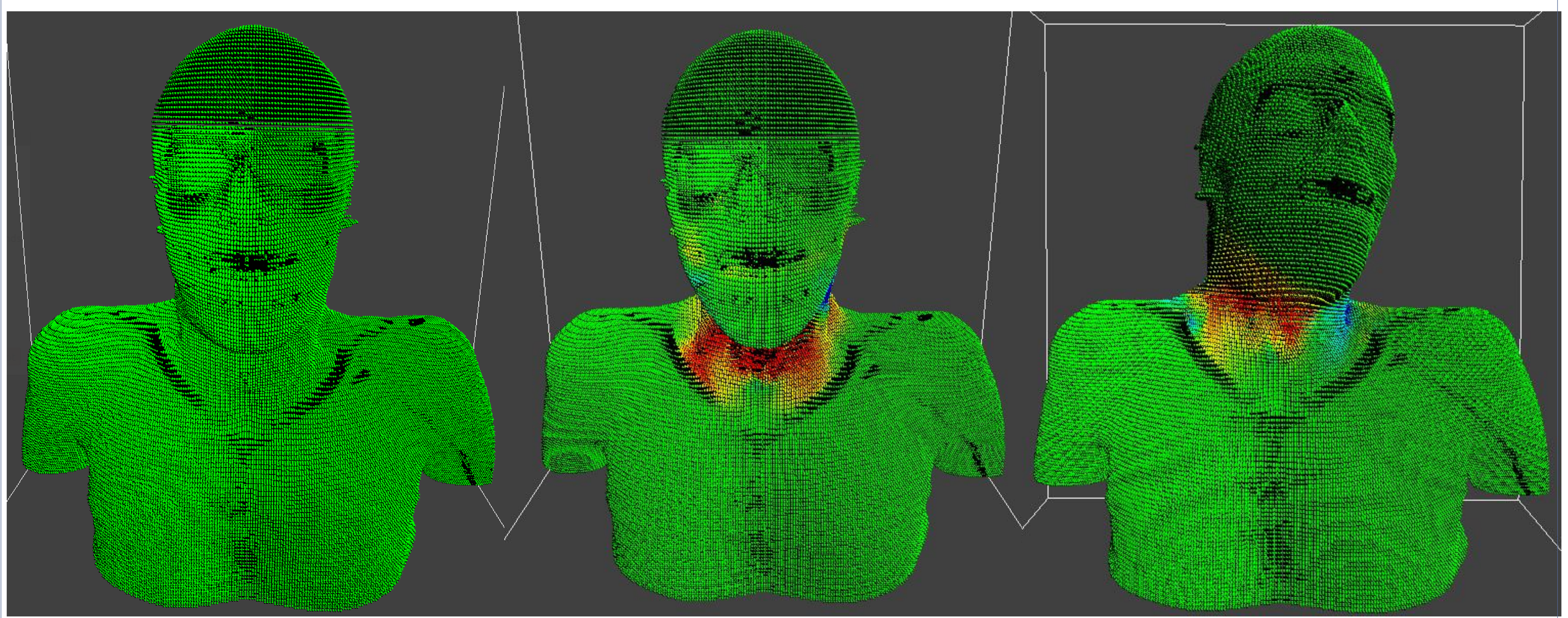

Fig 1. Biomechanical head and neck deformation with all the anatomical substructures. The model before the PTV shrinkage is shown in (a). The strain map for PTV shrinkage of 40% is shown in (b). The strain map differs for rotations in the head and neck posture as shown in (c). The color maps display areas of local stretch (red) and compression (blue).

Table 1. Registration Validation Results Using Simulated Motion and Automatic Landmark Tracking

Average Registration Error (mm)	PTV 1	PTV 2-3	PTV 4-8	Parotids	Mandible	Total
	1.2	1.1	0.86	1.7	2.3	0.93

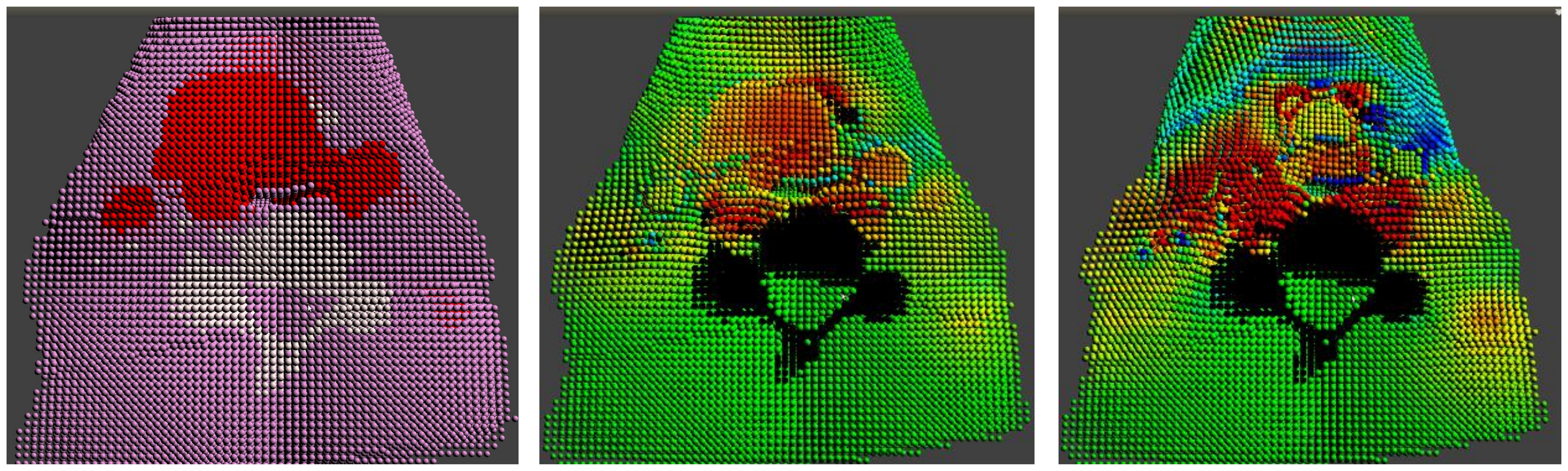

Fig 2. A 2D snapshot of the model at rest state (a) and its deformed state representing 10% and 40% PTV volume reduction is shown in (b) and (c), respectively, while the color map displays areas of local stretch (red) and compression (blue).

Results

Each synthetic data creation took approximately 28 seconds of computation time. The number of landmarks per data set varied between two and three thousand. The validation method is able to perform sub-voxel analysis of the DIR, and report the results by structure, giving a much more in depth investigation of the error. This framework also allows a fast method for optimizing the registration parameters to minimize the resultant error on a patient specific basis. The in-house DIR tool achieved a near real-time speed (30 seconds) for registering each deformed CT with the source CT. The average error in primary target volume, ipsilateral and contralateral parotids for posture changes was observed to be 0.6, 1.2 and 1.06 mm, respectively. The maximum DIR error was observed to be 2.3, 2.4 and 2.9 mm, respectively. For physiological changes, the average error was 3.4, 3.2, and 3.09 mm while the maximum error was 6.3, 8.5 and 8.9 mm, respectively

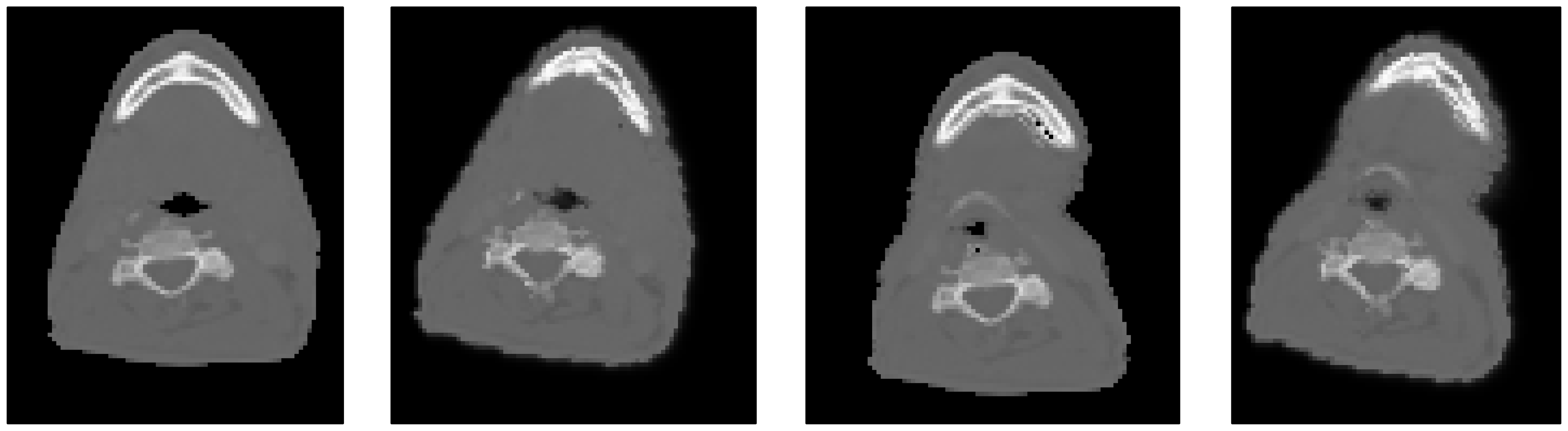

Fig 3. The KVCT slice at rest state (a) and at a state where the neck is rotated by 10 degrees (b) is shown. The KVCT slice representing the same anatomy with the PTV reduced by 30% is shown in (c). The deformation of the model where the skull is rotated by 10 degrees is shown in (d).

Conclusion

We presented a GPU based high-resolution biomechanical head and neck model to validate DIR algorithms by generating CT equivalent 3D volumes with simulated posture changes and physiological regression.

1. J Neylon, X Qi, Ksheng, R Staton, J Pukala, R Manon, DA. Low, P Kupelian, and A Santhanam. A GPU-based high-resolution multi-level biomechanical head and neck model for validating deformable image registration. Medical Physics. 2014. (submitted)