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Pose-matching MRI-CT co-registration via dynamic X-ray for creating subject-specific neck musculoskeletal models

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Introduction

Magnetic resonance imaging (MRI) and computed tomography (CT) are commonly used as the "gold standard" to image soft and hard tissues, respectively. The reconstructed 3D muscular models from MRI and skeletal models from CT must be combined in order to create subject-specific musculoskeletal models. However, this MRI-CT co-registration is challenging for complex structures with a substantial number of degrees of freedom such as the cervical spine, because the poses used in two modalities would not have completely coincided. In addition, due to its complex 3D geometry, vertebral bone models segmented from MRI can be subject to volume loss as compared to CT-based bone models, which further compounds the uncertainty and difficulty in the co-registration process [1]. In this study, we present a novel approach that takes advantage of dynamic X-ray data to identify the best matching pose and employs principal component analysis (PCA) to align the bones, thus optimizing the creation of subject-specific neck musculoskeletal models.

Methods

We used CT and MRI scans of the neck region, and dynamic X-ray captures of a neck flexion-extension motion collected from five healthy subjects (all male, aged 21–32 years). The CT and MRI scans were first segmented in Mimics 20.0 platform to create 3D vertebrae models. A previously validated CT-model-based tracking algorithm was applied to the dynamic X-ray images to obtain the 3D neck vertebral kinematics [2]. The 3D point clouds of the reconstructed vertebrae models were then exported into MATLAB and the vertebral foramen at the middle height of each vertebra was fitted by a circle with a least-squares method. The centroids of the fitted circles at all levels (C1-C7) were then fitted by a cubic polynomial to characterize the cervical spine curvature. The cervical spine curvature in the MRI was compared with the dynamic X-ray series to identify the best matching pose that minimized the curvature discrepancy measured as Fréchet distance [3]. Next, a PCA algorithm was applied to the point clouds of vertebrae models in both modalities to define the orientation of the superior vertebra with respect to the inferior vertebra. Lastly, the differences in 3D vertebral orientation between vertebra models in MRI and the matching dynamic X-ray frame were quantified as the target registration errors (Figure 1). The CT-based skeletal model with the best matching pose identified in the dynamic X-ray series was thus integrated with the MRI-based muscular model to create anatomically accurate subject-specific neck musculoskeletal models.

Results and Discussion

The overall mean curvature discrepancy between the two modalities was 0.34 mm of Fréchet distance. The average 3D orientation difference was greater in flexion-extension (1.28º) than in axial rotation (0.34º) and lateral-bending (0.05º) (Table 1). The greater flexion-extension differences found in the upper (C1-C2 and C2-C3) and the lower (C6-C7) cervical spine may be attributed to a more flattened cervical spine curvature found in the MRI model. The greater axial rotation differences in the upper cervical spine (C1-C2, and C2-C3) could be explained by the fact that the C1-C2 joint is the atlanto-axial joint where C1 and C2 may pivot around one another. In addition, some of the differences in both axial rotation and lateral-bending could be due to that flexion-extension motions captured by dynamic X-ray were performed not strictly in the mid-sagittal plane.

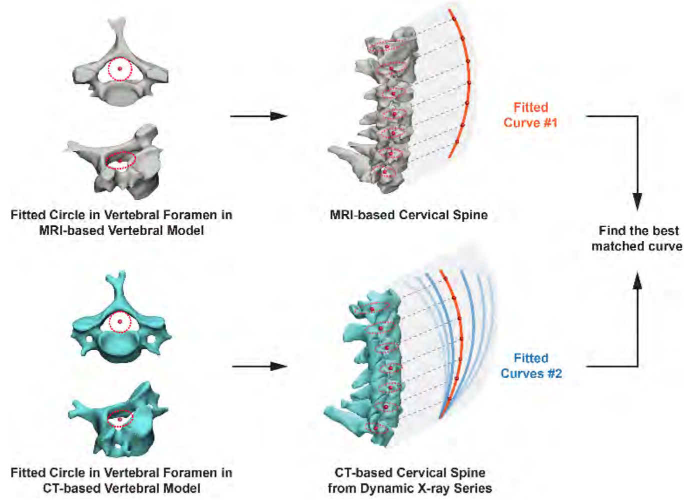

Figure 1: Pose-matching MRI-CT registration process via dynamic X-ray.

Table 1. 3D orientation differences (mean and standard error) between the MRI and best matching CT models. FE, AR, and LB denote flexion-extension, axial rotation, and lateral-bending, respectively.

	C1-C2	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
FE	3.71	5.00	1.03	0.47	1.49	-4.04
(º)	(1.97)	(0.95)	(2.56)	(1.81)	(2.02)	(2.80)
AR	1.06	1.92	0.26	-0.04	-0.87	-0.29
(º)	(1.93)	(2.17)	(2.99)	(2.93)	(0.56)	(1.50)
LB	-0.89	0.28	-1.06	0.95	-0.69	1.68
(º)	(1.25)	(0.62)	(0.54)	(1.02)	(0.73)	(1.11)

Significance

The proposed approach to MRI-CT co-registration by utilizing dynamic X-ray data provides a novel solution to the problem of pose variation across the modalities, a major obstacle hindering the development of complex yet accurate subject-specific musculoskeletal models.

References

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