Spinal cord gray and white matter segmentation using atlas deformation

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Target audience. Researchers interested in segmenting gray and white matter in the human spinal cord.

Purpose. The spinal cord gray matter contains neurons that are responsible for major functions such as locomotion and primary reflexes. Being able to quantify its morphology can help in the diagnosis of amyotrophic lateral sclerosis (ventral horn atrophy) or chronic pain syndromes (dorsal horn atrophy). Similarly, segmenting the white matter enables quantification of axon microstructure in diseases such as multiple sclerosis. Given the limited spatial resolution of MRI (~0.5 mm) and low white/gray matter contrast in spinal cord, advanced image-based methods are required to automatically segment the gray matter with high robustness and accuracy[1]. The recent introduction of a group-wise slice-based registration framework enabled automatic segmentation of white and gray matter[2]. Despite its robustness, this method is limited by the use of simple rigid transformations and by the initial description of spinal cord variability, which depends on the training dataset. Here we take advantage of the new MNI-Poly-AMU template and atlas of the spinal cord[3, 4] to automatically segment the gray and white matter using a registration approach. In addition, we show that using a smooth deformation enables to maintain the consistency of white matter topology for parceling white matter tracts using existing atlases[5].

Methods. Acquisition. T_2-weighted (T_2w) and T_2*-weighted (T_2*w) images were acquired from five healthy subjects on a 3T MRI system (TIM Trio, Siemens Healthcare) using the standard head, neck and spine coils. Parameters were: T_2w, 3D slab-selective fast spin echo, TR = 1500 ms, TE = 119 ms, flip angle = 140°, bandwidth = 723 Hz/voxel, voxel size = 1×1×1 mm^3; T_2*w, 2D spoiled gradient echo sequence with multiple echoes (MEDIC), axial orientation, TR = 540 ms, TE = [5.41, 12.56, 19.16] ms, flip angle = 35°, bandwidth = 200 Hz/voxel, voxel size = 0.5×0.5×5 mm^3 The three echoes were averaged and the resulting image was denoised using non-local means denoising algorithm[6] Processing. Following registration of the MNI-Poly-AMU template to the T_2w image and co-registration between the T_2w and T_2*w images (SyN transformation[7]), the gray matter probabilistic atlas from the MNI-Poly-AMU template was warped to the T_2*w image (see Figure 1). The gray matter template was then deformed to the T_2*w image using SyN transformation with cross-correlation similarity metric[8]. Following registration, all warping fields were concatenated and then applied to the atlas of white matter tracts[5]. Validation. Gray matter segmentations were compared with manual segmentations using 2D Dice coefficients after being thresholded at 0.25. Topology conservation of the registered white matter tracts was assessed by (i) visual inspection of all 30 tracts, (ii) computing the proportion of voxels outside the spinal cord segmentation and (iii) calculating the overlap between the white matter tracts and the gray matter.

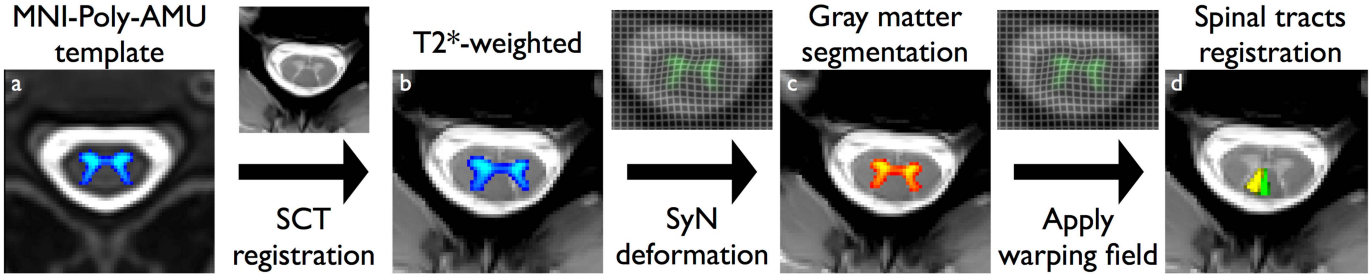

Figure 1. *Pipeline of the internal structure atlas deformation based on gray matter segmentation. First, the MNI-Poly-AMU template (a) is registered on the subject T_2*w image using the Spinal Cord Toolbox (SCT) (b). Second, the template gray matter probabilistic map (blue overlay on b) is deformed using SyN transformation to segment the subject gray matter (c). Finally, the resulting warping field is applied on the atlas of white matter tracts (d), producing accurate parcellation of the internal structure of the white matter. Here, the dorsal columns (cuneatus (yellow) and gracilis (green)) are shown as an example.*

Results. Figure 2 shows examples of spinal cord gray matter segmentation from three subjects as well as registration of the white matter atlas. 2D Dice coefficients of gray matter segmentation results on the five subjects after deformation are 0.79 ± 0.05 compared to 0.65 ± 0.09 before deformation. The topology of the white matter atlas was successfully maintained after deformation. Indeed, the proportion of white matter voxels falling outside the spinal cord was 3.25 ± 2.13 % before deformation and 0.85 ± 0.71 % after deformation, while the percentage of white matter voxels covering the gray matter was 5.46 ± 1.84 % before deformation and 6.51 ± 1.96 % after deformation.

Discussion. Gray and white matter were successfully segmented on T_2*-weighted images from five healthy subjects, leading to a robust and accurate registration of the MNI-Poly-AMU template and atlas of white matter tracts. The fairly small Dice coefficients can be explained by the low probability of the gray matter atlas at the dorsal edge of the spinal cord, yielding null voxels when binarizing the atlas for calculating the Dice, whereas the manual segmentations covered the entire dorsal horn. Note that the white and gray matter atlases are probabilistic maps and therefore have common regions depending on the threshold that is chosen for covering measurements. A current limitation of the proposed method is that susceptibility artifacts (signal drop out) can corrupt gray matter structure, resulting in wrong deformation results. Voxel classification using machine learning algorithms can be used as a preprocessing step to allow larger deformation in difficult cases to increase robustness and accuracy. In conclusion, automatic segmentation of spinal cord gray matter will help to improve specificity of spinal cord atrophy measures and for the interpretation of functional MRI results, while the white matter tract registration with maintained topology will help to quantify metrics of axon microstructure. The proposed method is freely available at http://sourceforge.net/projects/spinalcordtoolbox/.

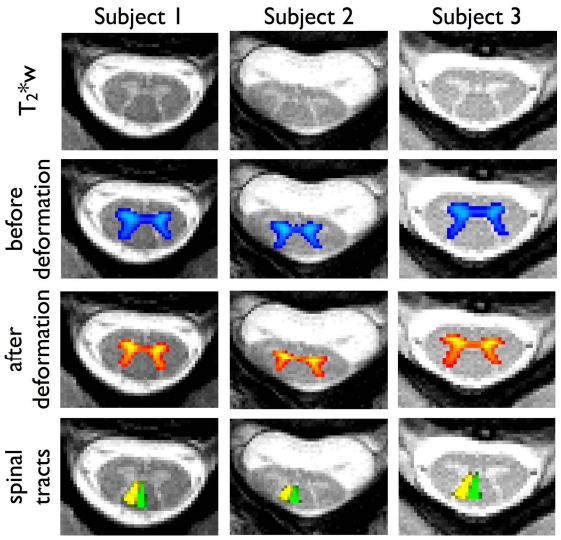

Figure 2. *Results of gray matter segmentation on three subjects. First row shows initial T_2*w images. Second and third rows show the MNI-Poly-AMU template registration results of gray matter segmentation, respectively. Fourth row demonstrates the white matter atlas topology conservation.*

References. 1. Yiannakas MC, et al., NeuroImage, 2012;63(3):1054-9. **2.** Asman AJ, et al., Medical image analysis, 2014;18(3):460-71. **3.** Fonov VS, et al., NeuroImage, 2014;102P2:817-827. **4.** Cohen-Adad J, et al. OHBM. 2014. **5.** Benhamou M, et al. ISMRM. 2014. **6.** Coupe P, et al. MICCAI. 2006. **7.** Avants BB, et al., Medical image analysis, 2008;12(1):26-41. **8.** Avants BB, et al., Frontiers in neuroinformatics, 2014;8:44.

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