Steerable needle DBS path planning safeguards deep nuclei and white matter tracts

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INTRODUCTION

Deep Brain Stimulation (DBS) has been increasingly employed to treat motor symptoms of Parkinson's Disease (PD) inhibiting the indirect dopaminergic pathway via the Subthalamic Nuclei (STN) stimulation [1]. DBS planning is challenging due to the risk of haemorrhages, seizures and, importantly, the critical STN position [2]. Therefore, planning algorithms for automatically computing DBS trajectories represent a breakthrough in this field. The capability to calculate a path able to provide an appropriate targeting of the STN also safeguarding the relevant anatomical obstacles (AOs) is a key requisite for a competitive algorithm. In literature, planning solutions able to estimate only rectilinear trajectories (RTs) for rigid electrodes have been proposed, as in [3], [4]. In these cases, the impossibility to follow curvilinear trajectories (CTs) may limit the chances to obtain an optimal targeting of the STN with the proper AOs avoidance. Contrariwise, flexible electrodes can mitigate limitations of their rigid counterparts through their ability to steer along CTs [5]. In particular, the present work focuses on an electrode whose design mimics the EDEN2020* programmable bevel-tip needle, where the displacement among four interlocked sections generates an offset on its tip so that the tool can follow CTs [6].

The aim of this work is to present a planning algorithm for DBS able to estimate a pool of CTs for an accurate targeting of the STN, ensuring a higher level of safety with respect to the standard rectilinear approach.

SUBJECTS AND METHODS

- MRI acquisitions and AOs segmentation - In 15 healthy human controls, a T1-weighted volumetric sequence and a high-resolution diffusion MRI sequence (HARDI: 60 diffusion gradient directions, *b*-value=3000 s/mm^2 and two b0 volumes without diffusion-weighting) were acquired on a 3 Tesla Philips scanner (Ingenia CX) at the Excellence Centre for High Field MR (CERMAC). HARDI datasets were corrected for movement and eddy-current distortions using the FMRIB Software Library (FSL). Diffusion Imaging in Python (Dipy) software was used for q-ball residual-bootstrap fibre tracking (FA threshold=0.1; max turning angle=60°) and bilateral corticospinal tracts (CST) were reconstructed. All images and the reconstructed tracts were co-registered to the Montreal Neurological Institute (MNI) space (resolution: 2 mm × 2 mm × 2 mm) by 3D affine transformation using the FSL FLIRT registration tool. Specifically, for HARDI images, the b0 volume was firstly co-registered to the MNI image, then the same transformation was applied to the tracts, while the T1 volumetric images were directly co-registered to the MNI volume. All MR images thus reside in the same space as the targets (STN) and the AOs [thalamus (THA), globus pallidus (GP), caudate nucleus (CN)] obtained from the segmented atlas in 3D Slicer©. In this work, preliminary tests were conducted bilaterally on one case-study.

- Selection of target points (TPs) and entry points (EPs)
The TPs were established on the anterior STN on the basis of current clinical practice [2]. In a selected 1cm-diameter entry area (EA) on the caudal middle frontal gyrus, 10 EPs resulted viable for 10 obstacle-free RTs, following the procedure described in [5] (cfr. *Fig. 1*).

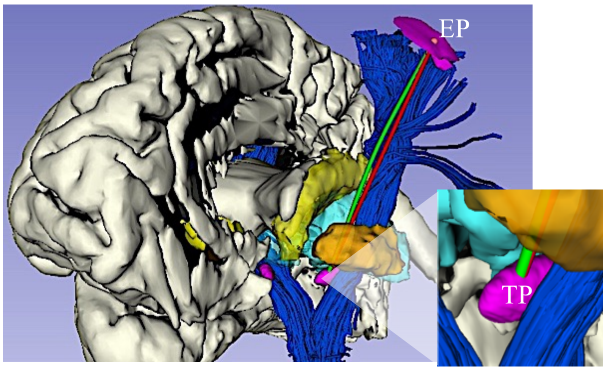

Fig. 1: Planning case on the left hemisphere. RT (red) and CT (green) are shown. EP is located on the purple EA, while TP is placed within the left one of the STN (fuchsia). The picture shows THA (cyan), GP (brown), CN (yellow) and CST (blue).

- Algorithm - The curvilinear planning algorithm is similar to the one proposed in [5]. In the present work, the interpolation step is performed using Non-Uniform Rational Beta Splines (NURBS), which allow to obtain a more precise tuning of the trajectories thanks to NURBS local controllability. The method benefits from a genetic algorithm (GA) for minimizing a fitness function:

$$F_{fit} = \alpha P_{saf} + \beta \ell + \gamma \mathrm{SD} + \delta P_{fea}$$

it includes, respectively, the points exceeding a distance threshold from the AOs, the trajectory length, the standard deviation of the curvature (k) and the points beyond the curvature limit (k_{max}).

- 1st test: RTs vs CTs - The RTs, formerly computed for identifying the EPs on the two hemispheres, were compared against the CTs in terms of distance from the AOs. The EPs and TPs were kept constant. An electrode with outer diameter (EOD) of 1.3 mm was considered. For the flexible electrode, a k_{max} of 0.015 mm^{-1} was considered, as reported in [6]. The minimum (d_{min}) and

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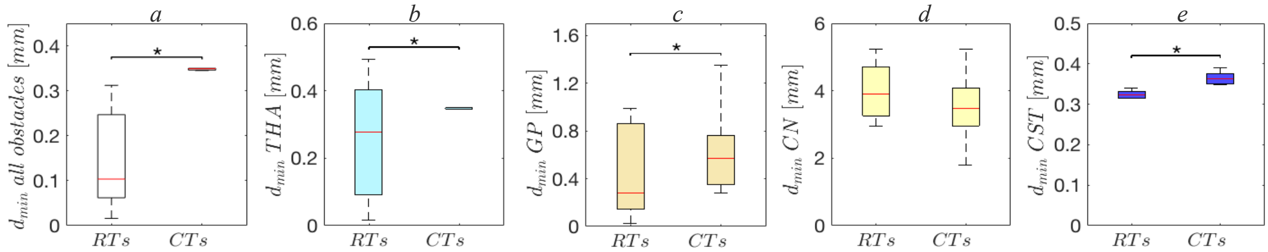

Fig. 2: Comparison between RTs and CTs in terms of minimum distance from the AOs.

mean distance ($\bar{d}$) from THA, GP, CN and CST were computed both for the RTs and the CTs.

- 2nd test: feasibility study - As a reference model, the objective of the test was to evaluate the performance of the curvilinear planner in response to variations in EOD and k. Again, the STN were set as target. The EPs that had given origin to the best and worst CTs in the 1st test were used to evaluate the best and worst-case scenarios.

- 3rd test: targeting STN's centre of mass (COM) - A better PD clinical outcome can results by placing the tip of the electrode in the proximity of STN's COM, as stated in [3]. The aim of the test was to verify the ability to find viable RTs and CTs using these points as targets.

RESULTS

- 1st test: CTs are safer than RTs - Overall, the value of the d_{min} was significantly greater in 100% of the computed CTs with respect to the corresponding RTs (*Fig. 2a*), while $\bar{d}$ resulted larger in 15 over the 20 CTs examined. The CTs kept a greater d_{min} also examining each AO independently (*Fig. 2b,c,d,e*). Statistical significance (Lilliefors test for data normality, pairwise comparison with Wilcoxon matched pairs test, $p<0.05$) is proved for the global d_{min} as well as the THA, GP and CST evaluation.

- 2nd test: viable CTs can be planned for larger EOD by increasing k - Five EODs were tested, starting from the standard 1.3 mm applied in clinic up to 2.5 mm. The value of k was augmented stepwise from 0.015 mm^{-1} (the minimum for computing a viable trajectory) to 0.055 mm^{-1}. The performance in terms of d_{min} from the AOs in response to variations in EOD and k was computed (*Fig. 3*). Viable trajectories could be determined even for a 2.5mm-EOD with a k of 0.055 mm^{-1}.

- 3rd test: only CTs allow to reach the COMs of STN - In this experiment, the existence of RTs and CTs able to reach the COMs of the STN using the same EPs from the previous tests was assessed. In this scenario, no RTs could be found, while a total of 6 and 3 CTs (with $\bar{d}$ equal to 1.36 mm and 1.16 mm) were estimated for the left and right hemisphere, respectively.

DISCUSSION AND CONCLUSIONS

This work aimed at proving the benefits of using steerable electrodes, associated with a bespoke curvilinear planner, for safety and targeting optimization in DBS. Compared to a rectilinear approach, the curvilinear planner was able to determine solutions which, in most of the cases, could provide a larger d_{min} from the AOs (*Fig. 2*), even with the most conservative value of k_{max}. With a larger k_{max}, better results were

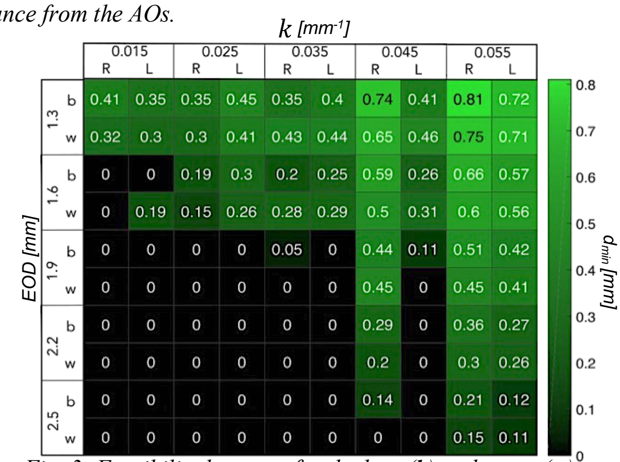

*Fig. 3: Feasibility heatmap for the best (**b**) and worst (**w**) EP of the right (**R**) and left (**L**) hemisphere.*

obtained (*Fig. 3*). The same test, performed over multiple EODs, demonstrated that solutions for curvilinear planning do exist. A further point is represented by the possibility to reach the COMs of the STN, accessible exclusively by using a curvilinear approach.

Overall, such notable results may be traced back to the combination of NURBS and GA implemented in CTs planning which demonstrates, on average, larger d_{min} and $\bar{d}$ (+145%, +22%) and a reduction in the rate of failure (-62%) with respect to [5].

In conclusion, our algorithm is able to compute CTs that precisely reach the targets, preserving the AOs more efficiently than standard RTs.

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