

From CT Images to Optimal Screw Configuration: A Comparative Study of Metaheuristic Algorithms for Cortical Bone Trajectory Screw Placement

Yi-Rou CHOU^{1,2}, Furen XIAO¹, Ming-Hong CHEN³

¹ Institute of Medical Device and Imaging, National Taiwan University College of Medicine, Taipei, Taiwan

² Institute of Integrated Science and Technology, Graduate School of Engineering, Nagasaki University, Nagasaki, Japan

³ Division of Neurosurgery, Department of Surgery, Far Eastern Memorial Hospital, New Taipei City, Taiwan

ABSTRACT

Optimizing the seven-dimensional configuration for Cortical Bone Trajectory (CBT) screw placement from preoperative CT images is computationally demanding. Our previous Particle Swarm Optimization (PSO) framework achieved outstanding accuracy, successfully generating bilateral trajectories (two screws per vertebra) in a commendable 88 seconds. To build upon this milestone and explore new algorithmic possibilities, this study comprehensively evaluates three optimization strategies: Nelder-Mead (NM) for local search, alongside PSO and Differential Evolution (DE). Across 30 trials targeting the L5 vertebra, NM offered rapid execution but struggled with unsafe local optima. Conversely, DE maintained PSO's high-fidelity accuracy while further reducing bilateral computation time by 45%, averaging just 48 seconds. These findings highlight DE as an exceptionally robust and rapid engine for automated surgical planning.

MOTIVATION & PREVIOUS WORK

- **The Clinical & Computational Challenge:** Cortical bone trajectory (CBT) screw fixation provides robust pullout strength, but calculating the optimal, patient-specific 7D configuration to maximize bone engagement and avoid neurovascular breaches is computationally demanding.
- **Building Upon a Strong Foundation:** Our previous Particle Swarm Optimization (PSO) framework achieved a commendable milestone, generating highly accurate bilateral trajectories in just 88 seconds.
- **The Research Objective:** To explore further possibilities, this study evaluates alternative algorithms against our PSO baseline to identify the ultimate engine balancing high-speed calculation and anatomical safety.

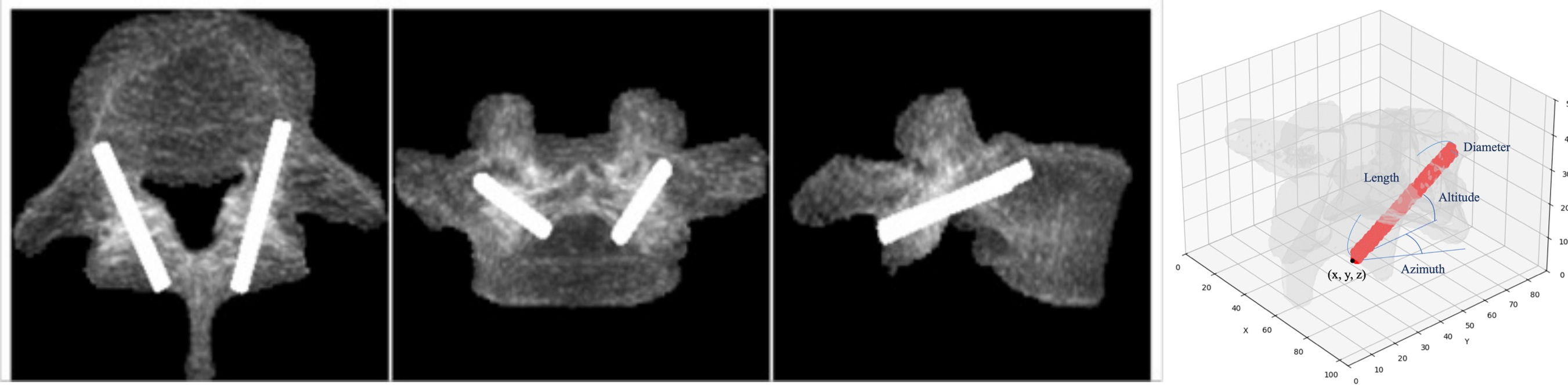


Fig. 1 Representative PSO cortical bone trajectory planning results for L5.

METHODOLOGY

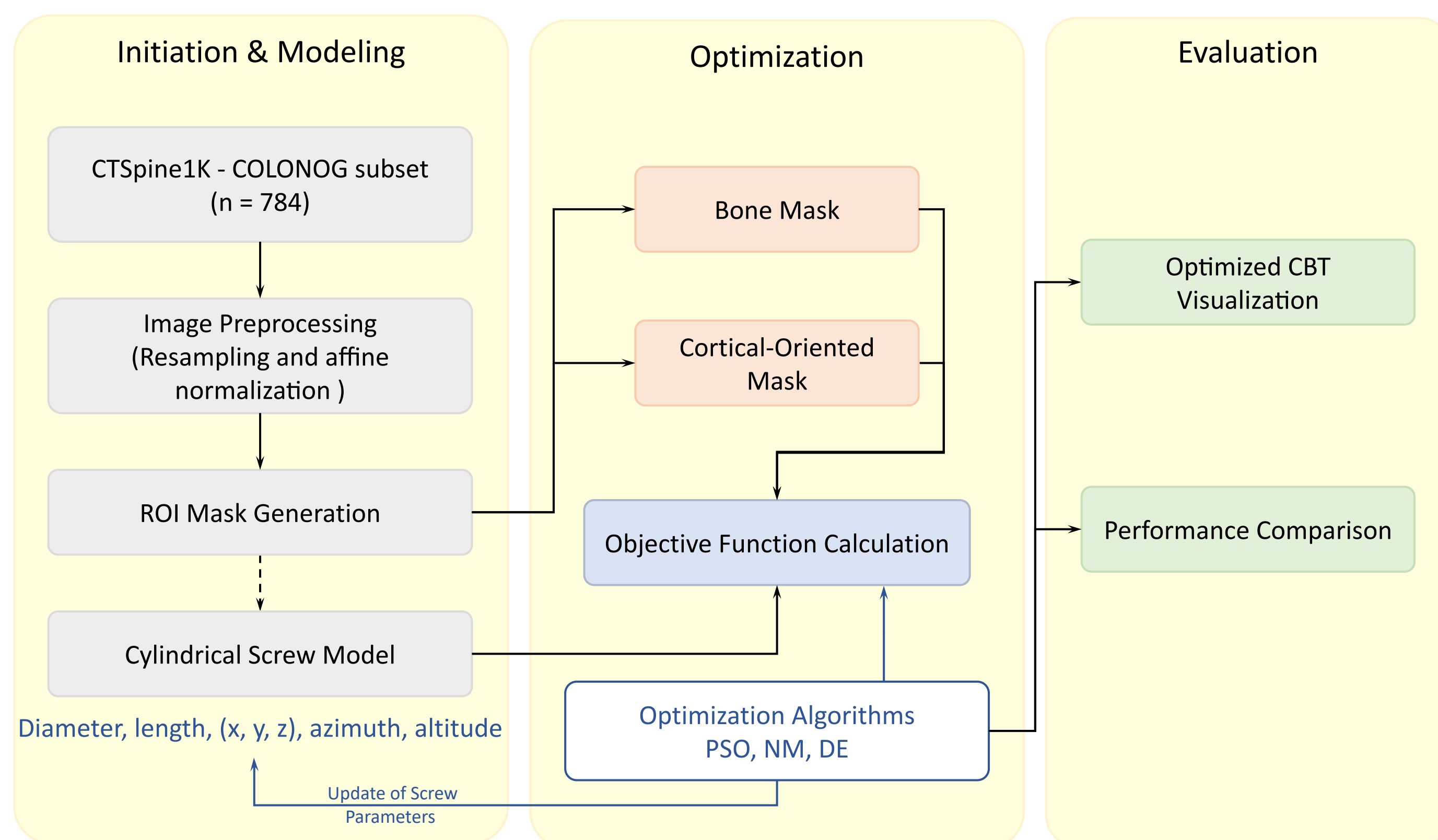


Fig. 3 The proposed computational framework for CBT trajectory planning. The workflow is systematically divided into three modules: (1) **Initiation & Modeling** for patient-specific ROI extraction and spatial constraints, (2) an **Optimization** engine where three distinct algorithms (PSO, NM, and DE) iteratively update the 7D screw parameters based on mask-guided objective functions, and (3) final **Evaluation** of trajectory performance.

Algorithm Characteristics in 7D Multimodal Space

- **Particle Swarm Optimization (PSO):** A population-based global search method. It delivers high-fidelity accuracy but demands excessive computational time for complex anatomical constraints.
- **Nelder-Mead (NM):** A gradient-free local search technique. While offering extremely rapid execution, it is highly vulnerable to being trapped in unsafe local optima.
- **Differential Evolution (DE):** Utilizes robust vector mutation mechanisms. It efficiently navigates the complex, multimodal objective function, achieving PSO-level accuracy while easily bypassing local traps.

RESULTS

- **Efficiency and Robustness Evaluation of Optimization Algorithms**

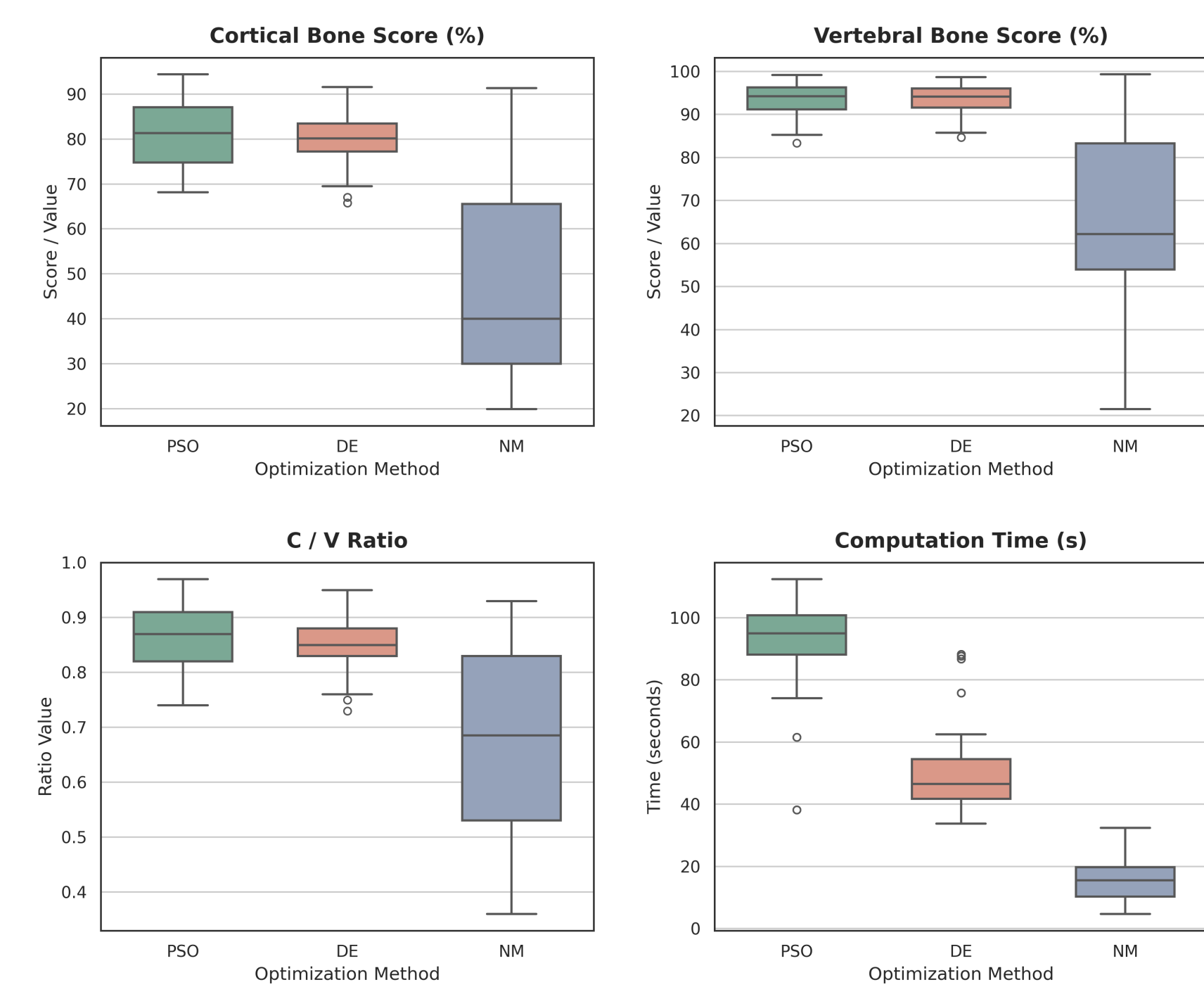


Fig. 4. Box plots comparing PSO, DE, and NM across four metrics: Cortical Bone Score, Vertebral Bone Score, C/V Ratio, and Computation Time. DE achieves accuracy comparable to PSO while reducing computation time by ~45%, whereas NM shows high variance and poor stability.

- **Performance Comparison: DE Optimizes the Accuracy-Speed Trade-off**

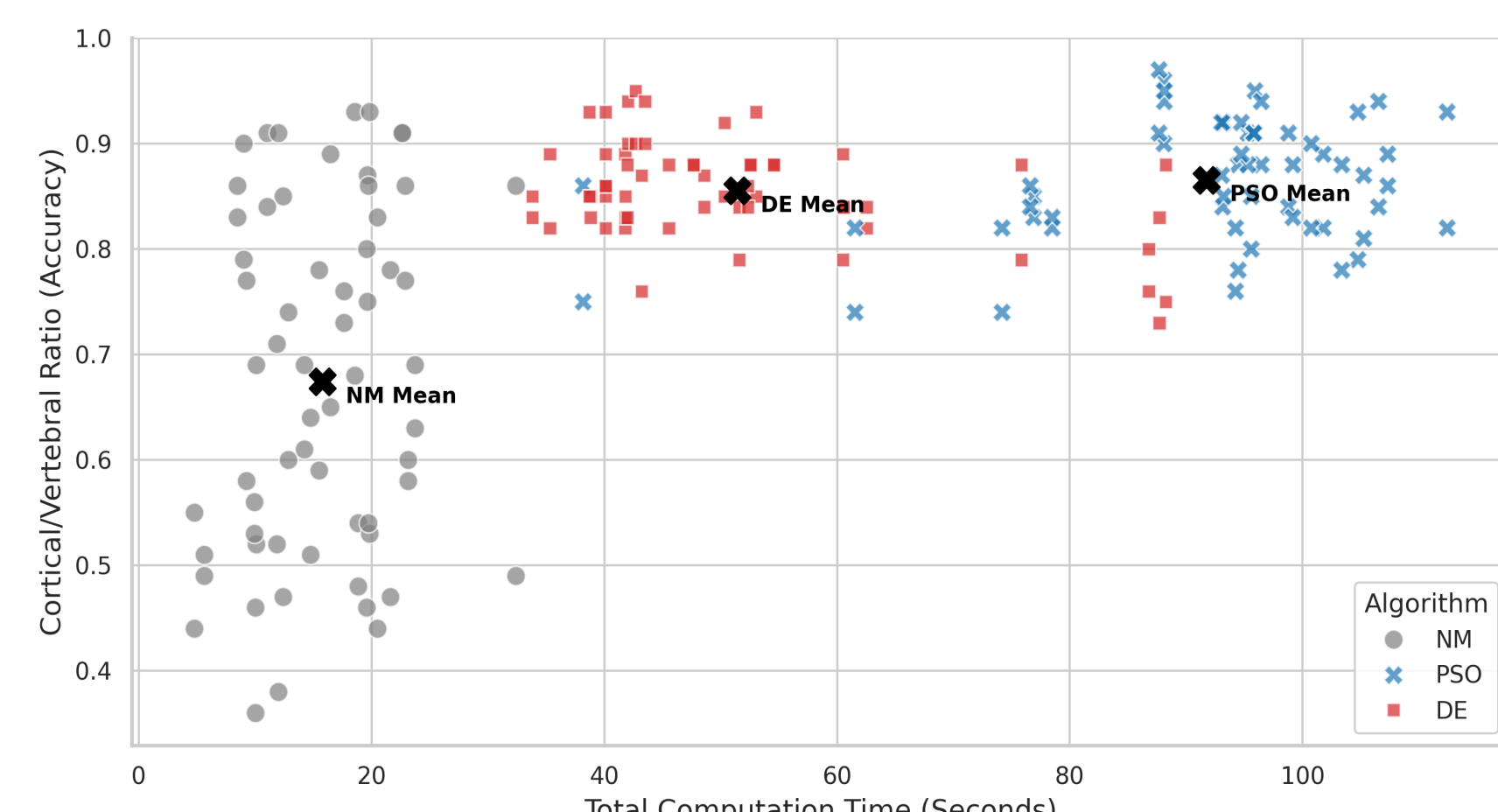


Fig. 5 Trade-off between accuracy and computation time across 30 independent trials on 10 L5 vertebrae. DE achieves comparable accuracy to PSO while reducing computation time by ~45%.

- **Table 1 Quantitative Performance Comparison of Optimization Algorithms.**

Method	Vertebral Bone Score	Cortical Bone Score	C/V Ratio	Time (s)
PSO	93.55	81.02	0.87	91.73
NM	66.11	45.39	0.67	15.78
DE	93.65	80.16	0.86	51.41

CONCLUSIONS

- **The Algorithmic Trade-off:** While NM proved unacceptably unstable and fell into local optima, our PSO baseline maintained robust accuracy but remained computationally heavy.
- **DE as the Definitive Engine:** DE perfectly bridged this gap. It maintained the uncompromising high-fidelity anatomical safety of PSO while accelerating the bilateral computation time by 45%.
- **Clinical Impact:** These findings position DE as an exceptionally reliable and rapid algorithmic engine, successfully bringing voxel-level precision closer to scalable, real-time surgical workflows.

REFERENCE

- [1] Y. -R. Chou, F. Xiao and M. -H. Chen, "Automated Planning of Cortical Bone Trajectory: A Novel Technique for Pedicle Screw Placement Using Particle Swarm Optimization," *2025 Second International Conference on Artificial Intelligence for Medicine, Health and Care (AIXMHC)*, Taichung, Taiwan, 2025, pp. 258-259, doi: 10.1109/AIXMHC65380.2025.00054.