Robotic Spinal Fixation using a Steerable Drilling, Flexible Pedicle Screws, and Shape-Sensing for Osteoporotic Vertebrae

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Aims: Spinal fractures frequently require spinal fixation (SF) surgery to return stability to the patient's spine. Traditional SF relied on rigid drilling tools and rigid pedicle screws that follow straight trajectories. As a result, screws are placed in low BMD regions, leading to complications like loosening and pullout [1]. To address these limitations, we propose a SF framework using a concentric tube steerable drilling robot (CT-SDR), flexible pedicle screws (FPS), and optical frequency domain reflectometry (OFDR) sensor to enable patient-specific fixations using curved drilling to target high BMD regions of the bone.

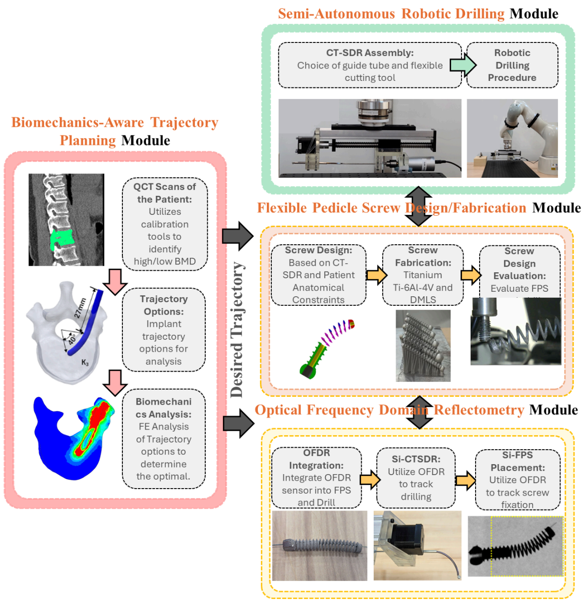

Fig. 1 Framework with four modules vital for ensuring optimal fixation throughout the vertebral body. It consists of the Biomechanics-Aware Trajectory Planning Module, Semi-Autonomous Robotic Drilling Module, the Flexible Pedicle Screw Design/Fabrication Module, and Optical Frequency Domain Reflectometry Module

Materials and Methods: The *Biomechanics-Aware Trajectory Planning Module*, which utilizes quantitative CT scans to map BMD distributions throughout the vertebral body. Finite element analysis (FEA) is then used to evaluate various trajectories and identify the path that minimizes stress and strain. Once the path is determined, the *Semi-Autonomous Robotic Drilling Module*, consisting of the CT-SDR system (i.e., CT-SDR attached to a KUKA robot arm), executes the drilling operation. This process is shown in Fig. 2. The *Flexible Pedicle Screw Design and Fabrication Module* is used to manufacture and insert the screw into the drilled trajectory. Simultaneously, the *Optical Frequency Domain Reflectometry Module* is used to track CT-SDR and FPS placement.

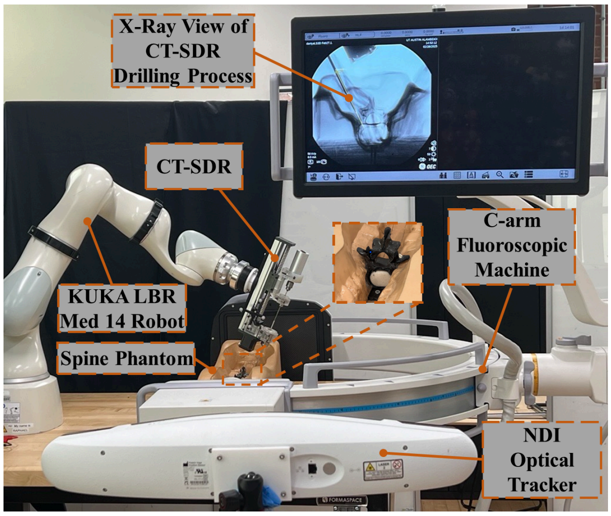

Fig. 2: Drilling setup consisting of the CT-SDR, KUKA LBR Med 14 Robot, NDI Optical Tracker, and a C-arm fluoroscopy machine for intraoperative imaging.

Results: Our framework successfully identifies optimal SF trajectories, as demonstrated by a reduction in maximum stress within the vertebral body from 1.011 GPa to 0.197 GPa based on FEA (Fig. 3A and 3B) [2]. Calibration and registration results confirmed that the CT-SDR system is capable of precise entry, with a mean positional error of just 1.14 mm for the rigid drill tip and 1.74 mm for the flexible drill tip (Fig. 3C and 3D). The FPS reliably conformed to both planar and out-of-plane paths, with average deviations of 1.44% and 0.78%, respectively, from the ideal 50 mm curvature set by the CT-SDR (Fig. 3E and 3F) [3].

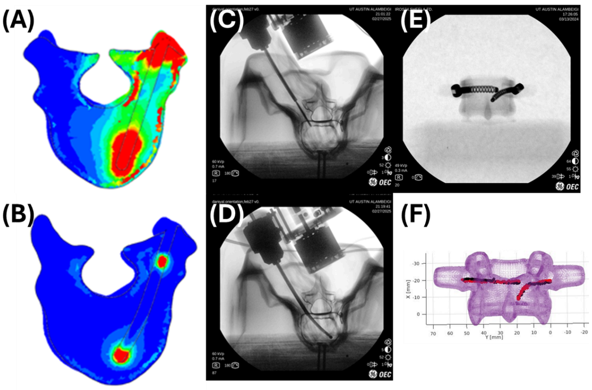

Fig. 3: Finite element analysis in (A) and (B) shows stress distributions for a straight and a 69.5 mm radius of curvature respectively, with the curved path demonstrating reduced peak stress. (C) and (D) depict CT-SDR drilling procedure where a rigid drilling tool is used to create the initial straight pilot hole (C), followed by a flexible tool to generate the curved trajectory (D). E) and F) show the X-ray and MATLAB view of the FPS following a planar and out-of-plane fixation.

Conclusions: This work presents a SF framework that integrates patient-specific biomechanics, curved drilling, flexible implants, and shape-sensing to improve SF outcomes. By combining these components together, the system enables safe and precise fixation along curved trajectories. Future work will focus on cadaveric testing.

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