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Design, Optimization, and Experimental Validation of a Handheld Nonconstant-Curvature Hybrid-Structure Robotic Instrument for Maxillary Sinus Surgery

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Abstract**—**Current robotic flexible medical tools employed in maxillary sinus surgery have shown certain limitations in dexterity and stiffness, resulting in large surgical incisions and potential unintended damage to patients. This paper presents a novel 4-DOF handheld nonconstant-curvature hybrid-structure robotic instrument (HNHRI) which is 3.5 mm in diameter and has significant improvement in both dexterity and stiffness. To enhance dexterity and stiffness, a hybrid-structure instrument with multiple layers and nonconstant curvatures is proposed. A compact and lightweight actuation system is designed to fulfill the requirements of handheld surgical device. A flexible section curvature optimization framework is introduced to enhance reachability and dexterity. Through bench-top experiments and simulation surgery, its performance is validated. The flexible section curvature optimization framework increases the reachability to target region to 100% and achieves an average dexterity index of 48% within the maxillary sinus. Compared to current robotic flexible instruments, bending and torsional stiffness are improved by 197% and 150%, respectively. Utilizing the HNHRI in maxillary sinus surgery offers notable enhancement in both dexterity and stiffness, which has the potential to substantially improve the efficacy and safety of the procedures. These advancements might reduce surgical incisions and minimize surgery-related damage, thereby improving the clinical outcomes for patients.

Index Terms**—**Design optimization, flexible robot, medical robotics, surgical instruments.

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