A New Compliant RCM Mechanism for Robotic Neuroendoscopy

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INTRODUCTION

Neuroendoscopy is a Minimally Invasive Surgery (MIS) procedure that uses an endoscope to access brain targets through a small cranial opening, the burr hole, which defines a Remote Center of Motion (RCM) for all movements of the instrument.

Many systems have been designed to enforce this the pivot point, enabling controlled instrument motions while keeping the entry point fixed [1]. These include double parallelograms [2], spherical mechanism [3], and software-based approaches [4]. This study focuses on a new type of mechanical RCM based on a compliant joint. Specifically, starting from the innovative design proposed by Rommers, the Tetra II joint [5], we propose a new compliant RCM mechanism adapted and optimized for robotic neuroendoscopy. The expected advantages of this design include reduced footprint, friction, wear, backlash, and complexity while enabling precision compared to other traditional mechanisms [6].

The Tetra II is designed using three interconnected flexible tetrahedrons. All edges of these tetrahedrons point to a fixed spot in space, forming the joint's RCM. However, the direct use of this joint for the intended robotic neuroendoscopy application poses issues regarding sterility, visual encumbrance, and quick disconnection from the endoscope. Our proposed design addresses these issues, leading to a structure that respects the clinical requirements. Specifically, we consider endoscopic third ventriculostomy as our primary clinical application. In this case, we consider the endoscope's workspace 50mm away from the burr-hole, with maximum lateral displacements of 30mm. Considering typical anatomical dimensions, these should cover all clinical cases [7].

Here, simulations are used to evaluate the workspace and the RCM stability of the new mechanism, and real experiments are conducted to validate the results. Finally, the optimization is performed through simulations that consider various joint parameters and fatigue analysis.

MATERIALS AND METHODS

Mechanism Modifications

We modified the original design by repositioning the end-effector from the original central axis to the side of the structure, and also by shifting the fixed portion inward

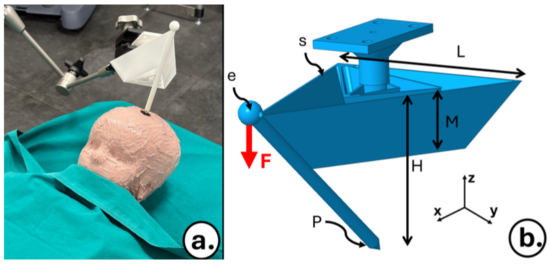

Fig. 1 a. Use case of the compliant joint in a neurosurgical scenario. **b.** Proposed design modification to satisfy neuroendoscopy requirements.

(Fig. 1.b). These modifications facilitate the design of a quick-disconnect system for the endoscope and the use of a sterile drape over the robotic mechanism, which shall provide separation between the sterile and non-sterile system components.

Simulation and Validation

Simulations of the compliant mechanism were conducted in Ansys 2023 R1. These were used to evaluate both the workspace and the fatigue of the mechanism. The initial simulation considered Nylon PA12 as the construction material and focused on analyzing the expected endoscope motions allowed by the mechanism. This material was selected to facilitate the validation of the simulation using 3D-printed physical prototypes.

The motion simulations return the displacements of both the actuation point and the RCM point (points P and e in Fig. 1.b). These results were obtained by applying a 0.5 N force along the z-axis at point e.

An experimental setup was developed with a real 3-D printed compliant mechanism to validate the simulated results. The device was secured to a plate, and a 0.5 N load was applied, as in the simulation, along the z-axis. Physical displacements were measured using an NDI Aurora electromagnetic tracker.

Optimization

A second simulation study focused on mechanism design optimization. This was based on fatigue analysis using Ansys. However, in this case, the mechanism material was set to titanium due to its superior fatigue strength and proven biocompatibility for use in surgical environments. Key parameters optimized included the tetrahedron dimension (L), joint height (H), tetrahedron height (M), and edge thickness (s), shown in Fig. 1.b. These parameters were varied to identify configurations that maximized the

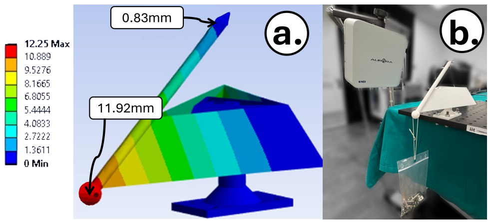

Fig. 2 a. Simulated structural displacements. **b.** Setup used for experimental validation.

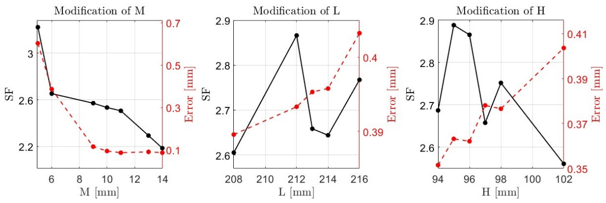

Fig. 3 Graph illustrating the relationship between SF values, Error displacement, and the variables M, L, and H.

safety factor (SF) while maintaining RCM displacement errors below an acceptable $0.5mm$ threshold. This value was chosen by analyzing the accuracy of the Cosman-Roberts-Wells (CRW) Stereotactic Frame [8].

The SF coefficient correlates to the component's lifespan and reliability. Higher values mean greater stress resistance, longer service life, and lower failure risk. The displacement error is the RCM point movement. A perfect RCM mechanism would have zero movement.

The optimization process began with identifying critical loading scenarios. This allowed the selection of designs that ensure robustness for the intended use case. For this, forces were simulated and rotated around the x-y plane to achieve the displacements needed to satisfy the workspace requirements. Subsequently, the actual mechanism optimization process was carried out considering the most challenging direction and changing the design parameters. This started considering the following values: $L = 200mm$, $H = 80mm$, $M = 30mm$, and $s = 0.8mm$.

RESULTS

The motion simulations considering a device built in Nylon PA12 and a 0.5 N force along the z-axis resulted in $11.92mm$ and $0.83mm$ as the displacements measured at the actuation and RCM points. These results were then validated by the experiments with the physical prototype, which showed mean values of $11.72 \pm 0.36mm$ at P and $0.84 \pm 0.10mm$ at e over ten loading trials, which correspond to respective absolute errors of $0.2mm$ and $0.01mm$.

The final optimized mechanism presented the following parameters: L=$212mm$, H=$95mm$, and M=$6mm$. It was noted that increasing the parameter s did not improve SF. Therefore, s was increased only at the most stressed edges. In this configuration, the displacement of the endoscope to reach the desired workspace corresponded to $43.9mm$. The actuator force decreased from $17N$ to $4.6N$ from the initial configuration to the optimized one, showing a 72% reduction. The optimization result demonstrated significant improvements concerning the original design. Starting from an RCM displacement error of $0.472mm$ and an SF of 0.911, the final optimized mechanism presented an RCM displacement of $0.36mm$ and an SF value of 2.88, demonstrating a 317% improvement in this last metric.

DISCUSSION

The obtained results demonstrate that the proposed compliant mechanism can meet the performance required for neuroendoscopy while also ensuring durability and robustness. The initial validation step involving a real physical mechanism was crucial to attest to the correctness of the simulations, providing high confidence in the results regarding the reliability and motion capabilities of the optimized device. Considering the obtained results, the compliant RCM mechanism demonstrates a SF of 2.88, ensuring suitability for repetitive use even in case of minor manufacturing defects. At the same time, the RCM displacement error of 0.36 mm remains significantly lower than that of standard CRW stereotactic headframes.

Furthermore, the simulation study demonstrated that increasing the thickness of only the most stressed edges can improve structural resistance without compromising the required flexibility for operation or adding unnecessary weight to the device.

The force required to move the endoscope to the desired orientation decreased from $17N$ to $4.6N$, allowing the use of smaller motors and further reducing the weight and footprint of the system.

The next steps of this work will include the fabrication of the optimized design in titanium and an experimental validation of the expected performance. This will be followed by the implementation of an actuation mechanism for closed-loop motorized control of this joint, the integration of a neuroendoscope holder, and finally, end-user trials using a custom-developed head phantom [9].

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