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Kinematic Analysis of Manual, Collaborative and Robotic Surgical Retractor Holding

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Abstract: Surgical retractor stability is crucial for precision and safety. This study quantifies kinematic performance of manual, collaborative, and robotic retractor holding using 6-DOF tracking at 80 Hz during ex-vivo porcine liver retraction. Robotic assistance reduced position deviation from 133 mm (manual) to 0.74 mm (99.4%), tremor intensity by 99.6%, and path length from 9.3 m to 0.17 m (98%). Effect sizes ranged from d=1.03 to d=2.64. Collaborative mode achieved intermediate stability (50% deviation reduction, 93% path reduction) while preserving adjustment capability. Results establish objective metrics for retraction quality assessment and demonstrate that passive robotic assistance achieves submillimeter precision while addressing personnel shortages in open surgery.

I. Introduction

Open surgery continues to represent a substantial proportion of general surgical procedures yet faces increasing personnel shortages. In Germany, surgical residency positions decreased 12% since 2017 [1] while procedural demand grew 2.5% annually pre-pandemic [2]. This workforce crisis contributes to inefficient resource utilization, with qualified surgeons performing routine assistance tasks like tissue retraction [3].

Tissue retraction represents the most personnel-intensive surgical bottleneck, requiring continuous human presence without demanding high-level expertise. Biomechanical studies quantify human limitations. Physiological tremor operates at 8-12 Hz [4] with millimeter-scale amplitude, amplified by instrument length, resulting into 6% performance degradation per operative hour in manual retraction setup [5]. Robotic systems offer the potential for consistent performance, yet their adoption in open surgery remains limited compared with minimally invasive platforms such as the da Vinci system (9,900+ units installed) [6]. A major factor is the absence of objective metrics to evaluate critical tasks, particularly tissue retraction quality, which limits efforts to establish standardized assessment methods.
This gap highlights the need for objective methods capable of capturing task-specific performance in open-surgery robotics. In this work, we introduce such a method by providing a 6-DOF kinematic framework that objectively evaluates retractor stability across three operational modes.

II. Material and methods

This study tested the hypothesis that technological assistance reduces high-frequency instabilities (tremor) and minimizes low-frequency instabilities (drift, residual motion) significantly, leading to increased procedural consistency during retractor holding.

Five surgical trainees each performed three 45-minute standardized liver retraction tasks on fresh ex-vivo porcine liver models (elastic modulus 2-4 kPa, chosen for biomechanical similarity to human liver [7]) positioned in a simulated surgical situs (Fig. 1). A Mikulicz liver retractor was mounted on the end plate of a UFACTORY Lite 6 robotic arm with lockable joints and equipped with optical markers. Three-dimensional pose data (position and orientation) were captured continuously using the Polaris Vega XT optical tracking system (Northern Digital Inc., Waterloo, ON, Canada) at 80 Hz.

Three retraction modes were designed to systematically isolate the effects of robotic stabilization:

Manual mode – Participants held the retractor entirely by hand throughout the task, representing current standard practice without technological support.

Collaborative mode – Participants positioned the retractor using the robotic arm in free-moving mode. Once released, the arm maintained its pose but allowed repositioning at any time to compensate for tissue slippage, simulating adaptive assistance (Fig. 1).

Robotic mode – Participants positioned the arm once at the beginning, after which all joints were locked. No adjustments were permitted, even during tissue slippage, representing maximal stabilization.

This three-mode design enabled systematic evaluation: Manual mode established baseline performance reflecting current clinical practice, while collaborative and robotic

modes isolated the contributions of tremor elimination (present in both assisted modes) versus drift reduction through complete immobilization (robotic mode only). The collaborative mode specifically tested whether adaptive repositioning could maintain stability benefits while accommodating tissue dynamics.

Raw tracking data (median 80 Hz) underwent quality control: Data points with invalid orientations (null quaternions from tracker occlusion) were removed, and the rate of tracking losses quantified macroscopic instability. Holding phases were manually segmented using heavily smoothed velocity profiles (120-second simple moving average, empirically validated; inter-rater reliability ICC: 0.998 endpoints, 0.952 start points).

Three stability metrics were computed on 0.5s smoothed holding phases: (1) Tremor intensity (Welch method, 8-12 Hz band), reported in $\times 10^{-4}$ mm², quantified high-frequency instabilities; (2) Maximum position deviation (mm) from average holding position measured worst-case drift; (3) Path length (m) captured cumulative low-frequency motion. Sensitivity analysis (0.1s, 1.0s smoothing) confirmed robustness.

III. Results and Discussion

Manual mode showed massive instabilities: 133±78 mm deviation, 9.3±3.5 m path, 5.57×10^{-4} mm² tremor. Collaborative mode reduced these to 67 mm, 0.6 m, and 0.11×10^{-4} mm². Robotic mode achieved 0.74±0.18 mm, 0.17 m, and 0.02×10^{-4} mm².

Tremor was reduced 98% (collaborative) to 99.6% (robotic), with 8.22 Hz peak confirming physiological origin. Path length decreased 93% (collaborative) and 98% (robotic). Effect sizes ranged d=1.03-2.64. Coefficient of variation dropped from 58.8% (manual) to 24.3% (robotic), demonstrating skill-independent consistency.

The hypothesis was confirmed with distinct trade-offs: manual allowed adjustment but showed instability; robotic provided maximum stability but prevented slippage correction; collaborative achieved substantial stabilization (98% tremor, 93% path reduction) while preserving repositioning capability—a practical compromise for dynamic workflows.

Robotic precision (0.74 mm) approximates stereotactic neurosurgery standards (1-2 mm) [7], though exceeding open surgery requirements. The 9.3 m manual path suggests substantial fatigue potential, reduced 98% robotically. Given workforce crises (residency -12%; 90% hospitals understaffed), these results quantify assistance potential for the retraction bottleneck.

To expand this evidence, future studies should incorporate a higher number of probands as well in-vivo evaluations to cover realistic surgical scenarios.

IV. Conclusions

This study provides quantitative evidence that passive robotic assistance elevates surgical retractor stability to precision comparable to stereotactic standards while eliminating physiological tremor and drift inherent to manual holding. The collaborative mode balances high stability with operator oversight for fail-safe operation. These findings establish the methodological foundation for objective retraction quality assessment and support investigation of robotic holding systems as clinically viable tools for addressing personnel shortages in open surgery.

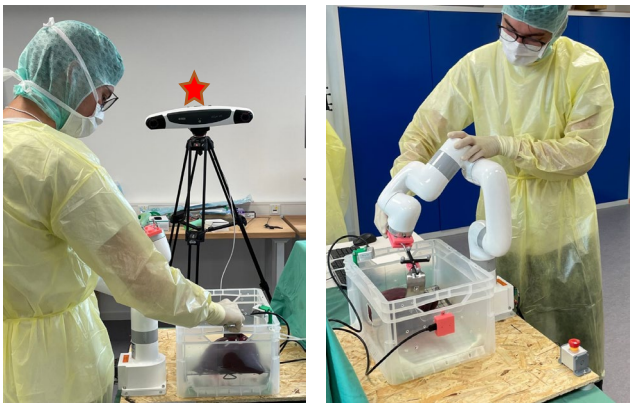

Figure 1: (Left) Experimental setup with Polaris's tracking system (red asterisk) and UFACTORY Lite 6 arm; (Right) Collaborative retraction mode.

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Author's Statement

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