Artificial Intelligence and Robotics in Skull Base Surgery: AI-Driven Motion, Safety, and Dexterity Enhancements

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Background

Robotic skull base surgery is challenged by narrow corridors, constrained instrument trajectories, and the constant risk of injury to critical neurovascular structures. Artificial intelligence (AI) offers solutions through tremor suppression, motion smoothing, trajectory optimization, predictive safety envelopes, and computer-vision–guided navigation in the pituitary and parasellar region.

Methods

A structured PRISMA-based review identified cadaveric, phantom, and preclinical studies between 2020 and 2025 that evaluated robotic platforms with AI-enabled functions for skull base surgery.

Extracted data included platform design, AI capabilities, validation environment (simulation, cadaveric, preclinical), and stage of clinical readiness.

Technical AI Functions in Skull Base Robotics

- Tremor filtering and motion smoothing
- Machine-learning trajectory optimization
- Virtual safety envelopes around ICA and clivus
- Computer-vision anatomy and instrument recognition
- Adaptive soft/continuum robot path shaping

Architecture of AI Assistance

Signal Processing and Active Control → Machine-Learning Trajectory Planning → Imaging-Derived Virtual Fixtures → Computer-Vision Feedback

Results

Dexterity: Handheld robotic systems enable articulated 360° motion and precise maneuvering around critical neurovascular structures in cadaveric skull base models.

Safety: Haptic-assisted drilling with imaging-derived virtual fixtures guides instruments away from the ICA, optic apparatus, and clivus in preclinical studies.

Adaptive Access: Soft and continuum robots with AI and computer vision conform to patient-specific anatomy to dynamically tailor surgical corridors.

Stability: Tremor compensation and virtual-fixture control demonstrate feasibility of anatomy-aware handheld tools, though clinical adoption remains limited.

Trajectory: Current systems are preclinical; near-term AI aims to add ML-based trajectory optimization and patient-specific safety envelopes.

Take-Home Messages

- AI-enabled robotics is shifting skull base surgery from rigid instrumentation to intelligent, anatomy-aware assistance
- Motion stabilization and virtual safety envelopes directly address the primary drivers of catastrophic skull base complications.
- Soft and continuum robots expand reach through narrow corridors while preserving gentle, controlled manipulation.
- Integrated AI planning, navigation, and intraoperative guidance aim to maximize safe resection without compromising cranial nerve or endocrine function.
- Over the next 3–5 years, regulatory clearance, validation studies, and surgeon training will determine the pace of clinical adoption.

Capability → Safety → Access → Outcomes → Adoption

Platform type	Key AI function	Validation stage
Handheld dexterity-enhancing robot	Tremor filtering, motion smoothing, trajectory optimization	Cadaveric / phantom
Haptic-assisted drilling system	AI-derived virtual fixtures, predictive safety envelopes near ICA and clivus	Preclinical laboratory
Soft-pouch / continuum robot (6-DOF)	Computer-vision-guided, anatomy-conforming path shaping	Cadaveric / preclinical

Conclusions

Robotic skull base surgery has evolved from conceptual prototypes to validated preclinical platforms.

AI now serves as an intelligence layer that augments surgeon expertise, stabilizes motion, and enhances safety in high-risk skull base corridors.

These advances support maximal safe resection while preserving cranial nerves, endocrine function, and overall quality of life, and they lay the groundwork for early-phase clinical adoption over the next 3–5 years.

Future Directions and Clinical Implications

- Translation of preclinical AI-robotic platforms into early-phase clinical trials.
- Development of real-time safety envelopes linked to intraoperative navigation and imaging.
- Integration with stereotactic radiosurgery planning for hybrid AI-enabled skull base care pathways.

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