Robotic Endoscopic Transnasal Skull Base Surgery in Clinical Practice: A Systematic Literature Review

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3.1 Introduction

Endoscopic transsphenoidal surgery has recently evolved into endoscopic transnasal skull base surgery (ESBS), which has revolutionized the surgical treatment of sellar and parasellar pathologies [1, 2]. Surgical indications for this approach, which

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takes advantage of the natural corridor provided by the two nostrils and nasal cavities, have expanded thanks to the so-called "extended" approaches, which are usually used to treat complex, even transdural, pathologies. As a consequence, the need for bimanual dissection became evident, and the so-called "two nostrils - four hands technique" was developed [3]. The increasing complexity of ESBS has also led to a significant increase in operating times: physiological tremors and the difficulty of coordinating the movement of the endoscope with surgical instruments in a narrow working space might then become an issue. To address this problem, some teams have suggested the use of a robotic endoscope holder, which should reduce the fatigue of the surgical team and provide both a steady vision and precise micro-movements to optimize the view [4–9].

The use of robotic systems indeed offers a potential solution [8], but the use of robotics in neurosurgery has seen a slower implementation as compared to other specialties [1, 10].

Different prototypes have been described for ESBS [9, 11, 12], but only recently preliminary clinical evaluations have been reported [13–15].

This chapter is a systematic review of the literature to provide a comprehensive critical overview of robotic systems that have been developed for ESBS and evaluated in a clinical setting.

3.2 Material and Methods

A systematic review of papers was performed on PubMed and Scopus using the following search terms and strings to retrieve papers published until August 2022:

– "transnasal AND robotic AND skull base surgery"
– "holder AND robotics AND skull base"
– "endoscopic endonasal AND robot AND pituitary surgery"
– "transsphenoidal AND robotics AND endoscopic AND skull base"
– "clinical evaluation AND robotics AND skull base AND transnasal".

The systematic review is reported according to the PRISMA guidelines [16].

3.2.1 Inclusion and Exclusion Criteria

Studies were included if they reported a clinical evaluation of the robotic system in ESBS and were published in English.

Records were excluded if they were review articles with no novel information or if they reported exclusively preclinical data.

Articles were imported into the reference management software Zotero (Corporation for Digital Scholarship, Roy Rosenzweig Center for History and New Media, George Mason University; Version 6.0.93) and duplicates were removed.

Titles and abstracts of selected records were examined by A.M. and non-relevant citations were excluded.

For each study, the following information was extracted: (1) authors and year of publication, (2) name of the robotic system, (3) function of the robotic system, (4) number of enrolled patients, and (5) key findings.

3.3 Results

A total of 66 studies were identified after the initial search and removal of duplicates. After a review of the abstracts and titles, 10 were selected for full-text analysis. Of these, five articles were included in this systematic literature analysis [13–15, 17, 18]. Articles were excluded for the following reasons: review article (n = 2), preclinical evaluation, or technical descriptions only (*n* = 3). Figure 3.1 shows the flow chart according to the PRISMA statement.

Clinical studies included in the review were divided into the following categories: transoral robotic skull base surgery + ESBS, robotic armrest, and robotic endoscope holders.

The results of this systematic review are summarized in Table 3.1.

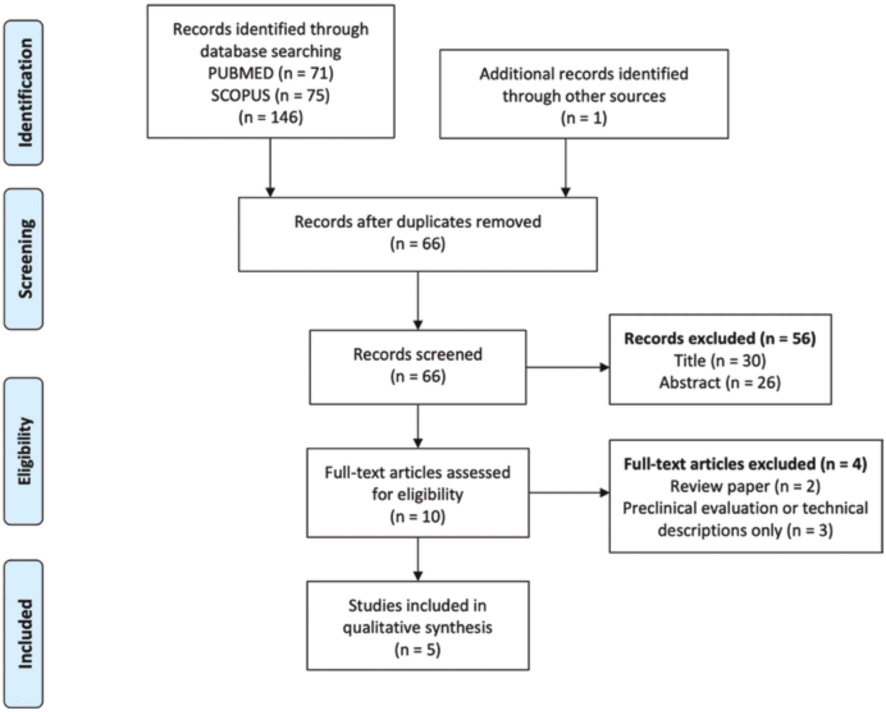

Fig. 3.1 Flow chart according to the PRISMA statement

Table 3.1 Clinical applications of robotic systems in endoscopic skull base surgery: Summary of the results of the systematic literature review, reporting the robotic systems that have been applied to endoscopic skull base surgery (see text for further details)

First Author (year of publication)	Robotic System	Function	Approach	No. of patients enrolled	Intraoperative complications	Key findings
Carrau et al. (2013) [18]	da Vinci (intuitive surgical; Sunnyvale, CA)	–	Transoral / endoscopic endonasal	2	No complications related to the use of this system	– TORS approach for inferior aspects and EEA for superior aspects of tumor resulted in favorable operative outcomes – EEA-TORS combined technique evades many of the morbidities related to open approaches (i.e., issues related to skin incision, need for bony osteotomies, and risk of osteonecrosis)
Ogiwara et al. (2017) [17]	iArms (DENSO Corp.)	Armrest	Endonasal / Transsphenoidal	43	No complications related to the use of this system	– Three modes: Transfer (free), arm holding (hold), and arm free (wait) – Reduced fatigue, hand trembling, and improved surgeon comfort
Hintschich et al. (2021) [13]	ENDOFIX exo (AKTORmed, barbing, Germany)	Endoscope holder	Endonasal / Transsphenoidal / Prelacrimal-transmaxillar / combined endonasal and external /Transoral	30	No complications related to the use of this system	– Electromagnetic manual support arm to hold the endoscope with six DoF – Fixed clamp, easy to sterilize, and low cost
Mattheis et al. (2021) [15]	Endoscope robot® (Medineering, Munich, Germany)	Endoscope holder	A combined approach transnasally and laterally via a small skin incision (orbital decompression)	8	No adverse events or complications	– Endoscopic orbital surgery – Safe and effective endoscope support
Zappa et al. (2021) [14]	Endoscope robot® (Medineering, Munich, Germany)	Endoscope holder	Endonasal / Transsphenoidal	21	No complications related to the use of this system	– Objective advantages for visualization – Subjective benefits for "complex" scenarios – Subjective limits for first positioning

3.3.1 Transoral Robotic Surgery (TORS) Combined with an Extended Endonasal Approach (EEA-TORS)

Carrau et al. [18] described the use of a combined TORS approach and ESBS, which was studied on anatomical specimens, and then applied clinically to two patients (Table 3.1).

In the first clinical case, an MRI of the neck and skull base revealed an infiltrating tumor with probable origin in the nasopharynx and extending to the sphenoid sinus, clivus, middle cranial fossa, and infratemporal fossa with striking perineural involvement of V3. A transpterygoid EEA with surgical navigation assistance exposed the tumor adequately except for that part that extended below the level of the hard palate, which was addressed with TORS using the da Vinci surgical system.

The second patient presented an extensive tumor, compatible with a chordoma, involving the posterior and middle cranial base that extended to the cranial cervical junction and down to C1/C2. Endonasal approach was useful for exposure of the tumor down to C1, while a transoral approach was chosen to remove the tumor extending to C2.

The Authors concluded that TORS and ESBS are complementary techniques that, when combined, provide excellent exposure to the posterior skull base, nasopharynx, and infratemporal fossa. The main advantage of TORS for managing skull base tumors is the ability to reach the posterior skull base below the level of the Eustachian tube, which is the inferior limit of the EEA. This study confirms the current limits of robotics, as the ESBS phase was not performed with the robot [5].

3.3.2 Robotic Armrest

Ogiwara et al. [17] described the iArms (DENSO Corp.), a robotic armrest that allows neurosurgeons to rest their non-dominant arm, which holds the endoscope, thus reducing fatigue and increasing stability. The system has three modes: transfer (Free), arms holding (Hold), and arm free (Wait). When the surgeon's arm is placed on the arm holder, the mode changes from Wait to Hold. When the surgeon's arm moves to the desired position and holds still, the mode changes from Free to Hold. The mode is changed from Hold to Free with a click action by the surgeon's arm.

The authors reported on the application of this robotic device to endoscopic endonasal transsphenoidal surgery and evaluated their initial clinical experience with 43 patients with different pathologies (i.e., 29 with pituitary adenoma, 3 with meningioma, 3 with Rathke's cleft cyst, 2 with craniopharyngioma, 2 with chordoma, and 4 with other conditions). The intelligent armrest proved to be safe and effective. The main limit of the system is that it does not substitute the surgeon's arm but is indeed an armrest [5, 8].

3.3.3 Robotic Endoscope Holders

The ENDOFIXexo system [8] (AKTORmed) is a robotic endoscope holder, originally used for abdominal procedures and then successfully modified for sinus surgery. Hintschich et al. [13] reported its use in a clinical trial of 30 patients, of whom 11 underwent transsphenoidal resection of a pituitary adenoma. This holder is an electromagnetic manual support arm to hold the endoscope and it has six different degrees of freedom (DoF). It combines three fundamental requirements of an endoscope holding arm: intuitive maneuverability, flexibility, and high stability; thus, the surgeon can operate in a bimanual action. However, in transnasal surgery, the accessibility is restricted to the posterior ethmoid and the sphenoid sinus or dependent on the partial resection of the nasal septum. With a bimanual action, endoscopic surgery may not be limited to paranasal sinuses and the frontal skull base, but expand to other operating sites.

Recently, Zappa et al. [14, 19] described a hybrid robotic solution for ESBS in a preclinical [19] and clinical [14] setting (*Endoscope Robot*®, Medineering, Munich, Germany). It is a compact robot that was specifically developed to work as an endoscope holder during transnasal interventions and is made of a robotic arm coupled with a smaller robot that acts as an endoscope holder. The positioning arm has seven DoF: it can be driven in every position of space by the simultaneous manual unlocking of two joints (Fig. 3.2). Its distal end is connected to the endoscope holder. Once attached to the holder and positioned inside the nasal cavity, the endoscope can be oriented upward, downward, or laterally using the joystick of a foot pedal (Fig. 3.2). Furthermore, it can be moved in or out by pressing different pads on the foot pedal. Also, a specific button has the function of making the robot return to a previously saved "home position" at any moment during surgery.

Zappa et al. provided a preclinical evaluation of the potential advantages and surgeons' first impressions of a hybrid robotic solution for ESBS. Endoscope Robot® seems to provide a benefit to the single surgeon with experience in bimanual endoscopic surgery [19]. The Brescia group then described the first clinical series of robotic endoscopic transnasal surgery, providing a clinical evaluation of the potential advantages of this novel hybrid solution and the surgeons' subjective impressions (Table 3.1). Twenty-one patients underwent robot-assisted endoscopic transsphenoidal surgery for different pathologies (i.e., 16 pituitary adenomas, 3 chordomas, 1 craniopharyngioma, and 1 pituitary exploration for Cushing's disease) for a total of 23 procedures (one patient underwent two endoscopic revisions of a skull base reconstruction) [14].

When compared to a matched, historical cohort of patients, clinical results were comparable. Video analyses of the two cohorts (hand-held endoscopy vs. robotic) documented significant differences in endoscope lens cleaning and position readjustments, as they were significantly less frequent in the robotic procedures. Subjective advantages reported by surgeons included smoothness of movement, image steadiness, and improvement of maneuvers in narrow spaces and with angled endoscopes.

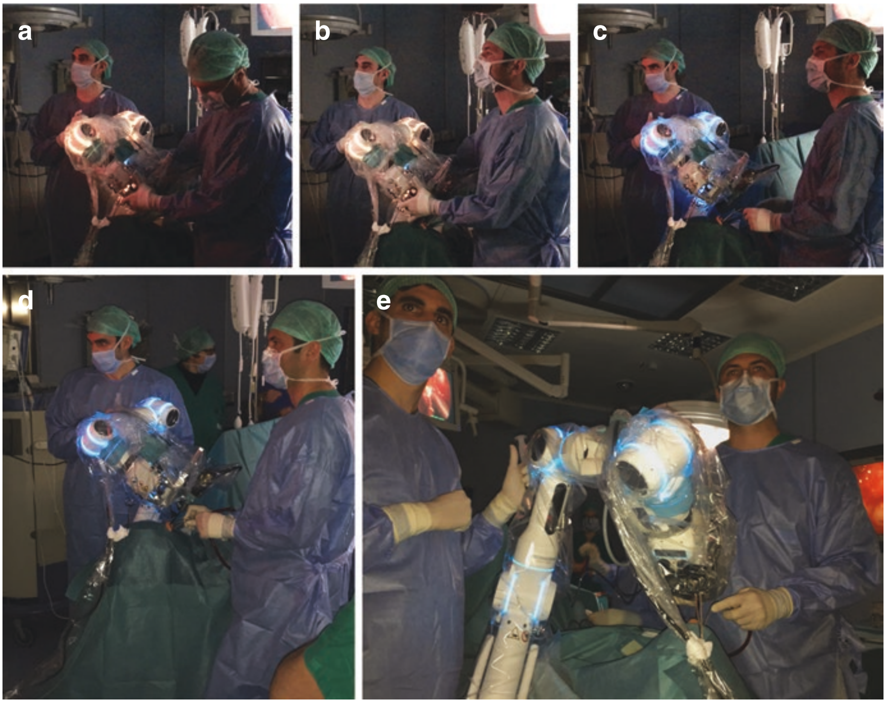

Fig. 3.2 Clinical evaluation at the University of Brescia. (**a**–**c**) Sequence (from a 5-seconds video) of Endoscope Robot® positioning in the operating room for endoscopic transnasal skull base surgery. The system is unlocked, and the surgeon manually positions the robotic endoscope holder (**a**, **b**) in the nose; this is usually performed after the nasal corridor has been created. The system is then locked and ready for use (**c**). (**d**, **e**) Surgeons' positions during the robotic phase (i.e., bimanual and during tumor removal) of endoscopic transnasal skull base surgery: the endoscope is held by the robot, which is controlled by a foot pedal (see text for further details)

The present limits of the system were also highlighted: intraoperative endonasal positioning always took less than 8 min, but was the less valued robotic phase due to the perceived weight of the system when the robotic holder had to be fully unblocked for significant changes in the endoscope position (i.e., from outside the surgical field to the intranasal corridor—Fig. 3.2). Furthermore, an ergonomic limit became evident, as the primary surgeon's weight is predominantly on the right foot during the robotic phase, as the left is used to control the movements of the robot.

The same robotic system was recently applied to endoscopic orbital surgery by Mattheis et al. who reported the results of orbital decompression with Medineering Robotic Endoscope Guiding System [15]. The system, though, is no longer commercially available.

3.4 Discussion

The aim of this review was to depict the clinical use of robotic systems in ESBS and identify the potential benefits and limitations for future optimizations.

Despite different preclinical studies have been published, this review confirms that, clinical experience on robotic ESBS is sparse and scattered on different robotic models.

Prototypes described in preclinical evaluation have some limitations, including bulky dimensions, poor ergonomics, inefficient control, and limited precision [4, 5]; this aspect probably explains why most of them have not been tested in clinical practice yet.

Only two robotic endoscope holders have been described in clinical studies [13–15], while others reported the use of a robotic arm rest [17] or transoral robotic surgery combined with an extended endonasal approach [18].

The very limited experience with the da Vinci system (only 2 cases in 2013, and none published thereafter) witness the difficulty to adapt to ESBS robotic systems that were conceived for different clinical scenarios.

The most promising prototypes are those helping the holding of the endoscope (armrest or endoscopic holder), allowing for an easier bimanual dissection.

The benefits of those robotic systems included reduced operator fatigue, especially in case of lengthy bimanual procedures, in small working spaces; stability of endoscopic image; absence of misunderstood verbal commands between the surgeon and assistant since the robot can be controlled directly by the primary surgeon [8, 14].

Endoscope Robot® is apparently the best option so far, since it can guarantee a wider degree of maneuverability (with robotic-controlled micro-movements for fine adjustments) to optimize visualization during any phase of dissection. Besides the previously cited advantages, one of the most relevant benefits perceived with this system is the robotic maneuvering of angled endoscopes or any endoscopes close to the target and in narrow spaces [14]. Despite the potential benefits, Zappa et al. [14] also underlined the present limits of the system: the main one is the perception of the weight of the system at the first positioning inside the surgical corridor. Near future developments are expected to address this limitation, as the arm that holds the small robotic holder is robotic as well.

Another possible drawback of the application of robotic systems to ESBS is the need to design and develop dedicated models for this kind of surgery, which is rare and performed in a few, highly specialized centers. As a consequence, the commercial interest of the companies to invest in these solutions may represent a limiting factor. Overall, we believe that the robotic phase of ESBS is just at its dawn: the current hybrid solutions have already shown benefits even in the clinical setting. The need for close collaboration with the industry and engineering research centers is evident and of paramount importance for future developments.

3.5 Conclusion

A few clinical applications of robotic endoscopic skull base surgery have been described. To improve the present results, a true multidisciplinary collaboration is required, with novel solutions in terms of robot control to fully exploit the advantages of robotic holders for endoscopic skull base surgery.

Disclosure The Authors declare no Conflict of Interest.

References

1. Cote DJ, Ruzevick J, Strickland BA, Zada G. Commentary: hybrid robotics for endoscopic Transnasal Skull Base surgery: single-Centre case series. Oper Neurosurg. 2021;21(6):E471
2. Doglietto F, Prevedello DM, Jane JA, Han J, Laws ER. A brief history of endoscopic transsphenoidal surgery—from Philipp Bozzini to the first world congress of endoscopic Skull Base surgery. Neurosurg Focus. 2005;19(6):1–6.
3. Castelnuovo P, Pistochini A, Locatelli D. Different surgical approaches to the sellar region: focusing on the "two nostrils four hands technique." Rhinology 2006 44(1):2–7.
4. Bolzoni Villaret A, Doglietto F, Carobbio A, Schreiber A, Panni C, Piantoni E, et al. Robotic Transnasal endoscopic Skull Base surgery: systematic review of the literature and report of a novel prototype for a hybrid system (Brescia endoscope assistant robotic holder). World Neurosurg. 2017;105:875–83.
5. Madoglio A, Zappa F, Mattavelli D, Rampinelli V, Ferrari M, Schreiber A, et al. Robotics in endoscopic transnasal skull base surgery: Literature review and personal experience. In: Control systems design of bio-robotics and bio-mechatronics with advanced applications [Internet]. Elsevier; 2020 [cited 2021 Feb 7]. p. 221–244. Available from: https://linkinghub.elsevier.com/retrieve/pii/B9780128174630000083
6. Chan JYK, Leung I, Navarro-Alarcon D, Lin W, Li P, Lee DLY, et al. Foot-controlled robotic-enabled endoscope holder for endoscopic sinus surgery: a cadaveric feasibility study. Laryngoscope. 2016;126(3):566–9.
7. Blanco RGF, Boahene K. Robotic-assisted skull base surgery: preclinical study. J Laparoendosc Adv Surg Tech A. 2013;23(9):776–82.
8. Pangal DJ, Cote DJ, Ruzevick J, Yarovinsky B, Kugener G, Wrobel B, et al. Robotic and robot-assisted skull base neurosurgery: systematic review of current applications and future directions. Neurosurg Focus. 2022;52(1):E15.
9. Nimsky C, Rachinger J, Iro H, Fahlbusch R. Adaptation of a hexapod-based robotic system for extended endoscope-assisted transsphenoidal skull base surgery. Minim Invasive Neurosurg MIN. 2004;47(1):41–6.
10. Madoglio A, Roca E, Tampalini F, Fontanella MM, Doglietto F. Robotics in Neuroendoscopy. In: Al-Salihi MM, Tubbs RS, Ayyad A, Goto T, Maarouf M, editors. Introduction to robotics in minimally invasive neurosurgery [internet]. Cham: Springer International Publishing; 2022[cited 2022 Aug 21]. p. 39–55. Available from: https://doi.org/10.1007/978-3-030-90862-1_4.
11. Wurm J, Dannenmann T, Bohr C, Iro H, Bumm K. Increased safety in robotic paranasal sinus and skull base surgery with redundant navigation and automated registration. Int J Med Robot. 2005;1(3):42–8.
12. Wei X, Zhang Y, Ju F, Guo H, Chen B, Wu H. Design and analysis of a continuum robot for transnasal skull base surgery. Int J Med Robot [Internet]. 2021 Dec [cited 2022 Aug 15];17(6). Available from: https://onlinelibrary.wiley.com/doi/10.1002/rcs.2328

13. Hintschich CA, Fischer R, Seebauer C, Schebesch KM, Bohr C, Kühnel T. A third hand to the surgeon: the use of an endoscope holding arm in endonasal sinus surgery and well beyond. Eur Arch Otorhinolaryngol. 2022;279(4):1891–8.
14. Zappa F, Madoglio A, Ferrari M, Mattavelli D, Schreiber A, Taboni S, et al. Hybrid robotics for endoscopic Transnasal Skull Base surgery: single-Centre case series. Oper Neurosurg. 2021;21(6):426–35.
15. Mattheis S, Schlüter A, Stähr K, Holtmann L, Höing B, Hussain T, et al. First use of a new robotic endoscope guiding system in endoscopic orbital decompression. Ear Nose Throat J. 2021;100(5_suppl):443S–8S.
16. Moher D, Liberati A, Tetzlaff J, Altman DG, for the PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. BMJ. 2009;339(jul21 1):b2535.
17. Ogiwara T, Goto T, Nagm A, Hongo K. Endoscopic endonasal transsphenoidal surgery using the iArmS operation support robot: initial experience in 43 patients. Neurosurg Focus. 2017;42(5):E10.
18. Carrau RL, Prevedello DM, de Lara D, Durmus K, Ozer E. Combined transoral robotic surgery and endoscopic endonasal approach for the resection of extensive malignancies of the skull base: combined TORS and EEA for resection of extensive malignancies of Skull Base. Head Neck. 2013;35(11):E351–8.
19. Zappa F, Mattavelli D, Madoglio A, Rampinelli V, Ferrari M, Tampalini F, et al. Hybrid robotics for endoscopic Skull Base surgery: preclinical evaluation and surgeon first impression. World Neurosurg. 2020;134:e572–80.