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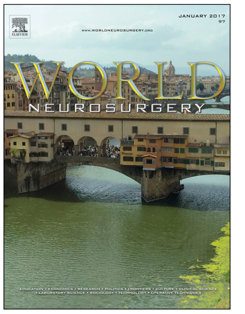

Robotic transnasal endoscopic skull base surgery: systematic review of the literature and report of a novel prototype for a hybrid system (BEAR)

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Robotic transnasal endoscopic skull base surgery: systematic review of the literature and report of a novel prototype for a hybrid system (BEAR)

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Keywords: endoscopic skull base surgery; prototype; review; robotics

Abbreviations: BEAR: Brescia Endoscope Assistant Robotic holder; CM: co-manipulation; CT: computed tomography; DOF: degrees of freedom; EM: Emergency Management; ESBS: endoscopic skull base surgery; FDA: Food and Drug Administration; IMU: inertial measurement unit; LED: Light Emitting Diode; NR: Not Reported; S.I.M.O.N.T®: SInus Model Othorino Neuro Trainer; TM: tele-manipulation; TORS: transoral robotic surgery.

Robotic transnasal endoscopic skull base surgery: systematic review of the literature and report of a novel prototype for a hybrid system (BEAR)

Abstract

Background: Although robotics has already been applied to several surgical fields, available systems are not designed for endoscopic skull base surgery (ESBS). New-conception prototypes have been recently described for ESBS.

Aim of the study: To provide a systematic literature review of robotics for ESBS and describe a novel prototype developed at the University of Brescia.

Material and Methods: PubMed and Scopus databases were searched using a combination of terms, including Robotics OR Robot and Surgery OR Otolaryngology OR Skull Base OR Holder. The retrieved papers were analyzed, recording the following features: interface, tools under robotic control, force feedback, safety systems, set-up time and operative time.

A novel hybrid robotic system has been developed and tested in a preclinical setting at the University of Brescia, using an industrial manipulator and readily available off-the-shelf components.

Results: A total of 11 robotic prototypes for ESBS were identified. Almost all prototypes present a difficult emergency management as one of the main limits.

BEAR (Brescia Endoscope Assistant Robotic holder) has proven the feasibility of an intuitive robotic movement, using the surgeon's head position: a 6 DOF sensor was used and two light sources were added to glasses that were thus recognized by a commercially available sensor.

Conclusions: Robotic systems prototypes designed for ESBS and reported in the literature still present significant technical limitations. "Hybrid" robot-assistance has a huge potential and might soon be feasible in endoscopic skull base surgery.

Introduction

Endoscopic skull base surgery (ESBS) is a quickly evolving field and operations complexity has been increasing significantly to fully exploit the advantages of endoscopic vision in different skull base area.[1] The so-called "four hands technique" has indeed become an essential surgical set-up.[2,3] This requires a close collaboration between at least two surgeons, but even in a closely collaborating team various issues can become evident, especially in long and complex operations, e.g. conflicts among instruments and endoscope due to a narrow surgical corridor or suboptimal visualization due to the fatigue of the surgeon holding the endoscope.[4,5]

In the last two decades also robotics has greatly evolved and has been applied to surgery.[6] Commercially available systems that are FDA-approved and can be used for head and neck surgery are represented by da Vinci® Robotic System (Intuitive Surgical) and Flex® Robotic System (Medrobotics). Reports on da Vinci in ENT surgery are many, but mainly limited to thyroid surgery or TORS (transoral robotic surgery) of the oropharynx, base of the tongue or larynx.[7-9] Only recently, some have described TORS to the posterior skull base.[10-12] Many authors, though, emphasize the limitations of da Vinci for ESBS, which include lack of tactile and haptic feedback, a design for soft tissue surgery and need of relatively large working spaces.[13-19] The Flex Robotic System® has been designed for TORS of the larynx and pharynx.[20,21] Schuler et al.[22] recently described its feasibility also for nasopharyngeal surgery via a transoral approach, documenting the need of additional specific instrumentation. Commercially available robotic systems, whose ergonomics and dimensions essentially allow transoral surgery, indeed have not been designed for ESBS and show several limitations when applied to it.

To address part of these issues, new-conception robotic holders have been recently specifically designed for ESBS. In the last few years our team has also developed a prototype for hybrid robotic ESBS.

Aim of the present study is to compare the reported robotic prototypes for ESBS, analyzing their main features and shortcomings, and to describe the novel system that has been developed at the University of Brescia.

Materials and methods

Literature review

A review of papers published between 2004 and March 2016 was performed on PubMed and Scopus with the combined research "(Robotics OR Robot) AND (Surgery OR Otolaryngology OR Skull Base OR Holder)". Articles dealing with laparoscopy, pure engineering issues and describing other technologies were excluded, together with reviews or duplicate studies (Figure 1). Only full-text articles featuring new prototypes dedicated to endoscopic skull base surgery were included.

The following features were evaluated for each system: 1) Surgeon-robot interface; 2) Type of instruments and tools controlled by the robot; 3) Presence or absence of a force feedback; 4) Safety systems; 5) Set-up time and potential operative time; 6) other relevant issues, such as emergency management.

Advanced Robotic Laboratory set-up at the University of Brescia

- *Surgical simulation*

A complete endoscopic system with a 0° endoscope (Karl Störz, Tuttlingen, Germany) was used (Figure 2).

Different models were used to analyze the movements of the prototype, including S.I.M.O.N.T® (SInus Model Othorino Neuro Trainer by ProDelphus, Olinda, Brazil)[23] (Figure 2 and video 3).

- *Engineering instrumentation at the University of Brescia*

Robot and force sensor

An industrial manipulator (Kawasaki RS03N) was used: it is an anthropomorphic robotic arm with six rotational joints and six degrees of freedom (DOF) (Figure 2). It was coupled with a force sensor: its transducer was positioned between the wrist and the endoscope holder. An interface de-composes the total force measured by the sensor into its 6 components (X, Y, Z, TX, TY, TZ) and sends them to the rest of the system via a dedicated Ethernet network (Figure 3).

Movement input devices

A joystick was designed to control the movements of the robotic arm on the frontal plane (four directions) and backwards-forwards, thanks to two different knobs independently activated by the user (Figure 3).[24]

As an alternative, a commercially available input device able to collect movement information and audio from the external environment was used (Microsoft Kinect, - Figures 2 and 3). Active markers glasses (Figure 3) were created to enhance Kinect visualization of head movements:[25] two black external wings were added to normal glasses, each one supporting a LED light connected to an electrical socket.

A dedicated Ethernet network was used to allow a simple and effective communication between all engineering components (Figure 3).

Results

Literature review

The systematic literature analysis retrieved 20 papers, describing 11 robotic prototypes dedicated to endoscopic skull base surgery (ESBS) (Figure 1). The analyzed features for each prototype are summarized in Table 1.

In 2004 Nimsky et al.[26] described the application to transsphenoidal endoscopic surgery of EVO1 prototype, a robotic holder initially designed for ventriculostomies. In 2005, Nathan et al.[27] adapted a voice-controlled laparoscopy positioner, called AESOP, to endoscopic transnasal surgery. Wurm et al.[28,29] described an advanced version of the A73 robotic setup for ESBS. In 2007, Strauss et al.[30] presented a telemanipulated endoscopic holder, whose applicability was then tested in 2011 in an artificial sinus model.[31] In 2008, Xia et al[32] presented an image-guided robotic system to provide mechanical assistance for skull base drilling, which was tested on foam skulls and cadaver heads. In 2011, two different prototypes were presented: by Eichhorn et al.[33-35] described the Tx40 robotic holder whose automatic tracking movements following the tip of surgical instruments could be adjusted by the surgeon via a joystick; Yoon et al.[36] reported on an active bending endoscope prototype with a spring backbone. In 2012, Trevillot et al[37] published a work describing a hybrid solution dedicated to sino-nasal tract, anterior and middle-fossa skull base surgery. This prototype derived from the experimental fusion between Evolap, a prototype positioner built for minimally invasive laparoscopic surgery, and Viper, a conventional six-active degrees of freedom (DOF) industrial robot.[37] In 2013, Schneider et al.[38] presented a "tentacle like" tubular prototype intended to maneuver tiny instruments in transnasal procedures. A feasibility evaluation of telesurgery procedure was published by the same team one year later.[39] In 2015, Cabuk et al.[40] described a haptic-guided robotic system based on a Stewart Platform (SP), developed for holding and positioning the endoscope with a joystick. In 2016, Chan et al.[41] published a cadaveric feasibility study of their Foot-Controlled Robotic-Enabled Endoscope (FREE) Holder for Endoscopic Sinus Surgery controlled by an IMU (inertial measurement unit) attached on the first operator's shoe.

University of Brescia Hybrid Robotic Pre-prototype

In order to evaluate and optimize the operating principles of our robotic holder four dedicated function tests were performed.

1. Fulcrum-centered motion (video 1)

The program "*DelicateInsider*" was developed[24] to estimate the fulcrum position of the rotational movement of the endoscope, analyzing the components of the detected force, and to change the center of the rotation so as not to exert forces exceeding a pre-fixed threshold.

2. Placement test (video 2)

The program "*NewLeadingByNose*"[24] was developed to move the industrial manipulator in place, decoding the interaction of force made up to the end effector. The name of this technique comes from the way the direction is indicated to a horse, pulling the reins.

The aim was to create a program that would allow the industrial manipulator to perform complex trajectories, consisting of many small movements, using the six acceleration components, calculated by the force sensor and enabling the movement through a special signal. The results obtained from this tracking guide were quite poor, since the movement of the arm proved to be very jerky (video 2), most probably due to the variable stiffness of the robot.

3. Safety test

The program *CarefulMovement*[24] stops the current action of the robot and the device is brought into its initial position, as soon as the force sensor measures an interaction exceeding the preset threshold.

4. Navigation tests

After developing the double-knob joystick control of the robot, a system that allowed to move the industrial manipulator through the movements of the surgeon's head was developed.[25]

The last version of the program[24] activates the specific movement command only if one of the luminous markers, positioned on the glasses, enters the respective area shown on the control screen (video 4). This allows the surgeon to move with complete freedom, when the head is in a specific "neutral area", in which the movements do not influence the robotic arm (video 4). If the surgeon enters a sensitive area with the glasses markers, the respective command will be sent to the manipulator, which will move the endoscope in the same direction, until the head returns to the "neutral area". The respective areas are represented on the screen and are overwritten on the Kinect video, which shows the mirrored image of the surgeon (video 4).

Discussion

Prototypes

The systematic literature review identified eleven robotic systems designed for endonasal endoscopic sinus and skull base surgery. Six different features were analyzed for each of them (Table 1).

1) Robot-Surgeon interaction (Interface)

The majority of described prototypes are remotely controlled. The use of a joystick is indeed widely employed in laparoscopic,[42] thoracoscopic[43] and cardiac surgery:[44] nonetheless, its use for ESBS entails that the main operator stops the procedure to directly control the device, or another surgeon is required. Other tele-manipulation modes include the vocal control system, employed by the robotic holder Aesop,[27,45] and the IMU (inertial measurement unit) module, reported by Chan and colleagues,[41] that provides a complex foot control interface.

Other prototypes, the A73[28,29,46] and Tx40[33-35], can perform prefixed tasks in a completely or partially autonomous way, taking advantage of some specific safety systems: nevertheless, this independence may represent an obstacle in the event of an emergency.

Finally, other systems[32,37] are controlled in a "co-manipulation" mode, with surgeon and robotic arm cooperating side-by-side to hold the endoscope.

With BEAR (Brescia Endoscope Assistant Robotic holder) we aimed at developing a hybrid solution, i.e. a robotic endoscope holder that is controlled by the surgeon. Initially a joystick control of the robot was developed: it was soon obvious that this remote control system poorly matches surgical requirements, but it was a necessary preliminary step. We then developed what appeared to us as the ideal solution, being used to wearing glasses during surgery with 3D endoscopy. Adding two light sources to a pair of glasses that are recognized by Kinect sensor, the main surgeon can move the endoscope robotic holder in a fairly intuitive way. To move the camera, the surgeon must bring one of the two markers, identified by two colored dots on his pair of glasses, into one of four areas indicated by an arrow, which correspond to four directions (up, down, right and left). As long as the marker remains in that area, the program keeps sending the respective command to the manipulator. Forward and backward movements are conveyed, moving away from or approaching Kinect.

As compared to the joystick control, the marked glasses mode appeared much more intuitive and can provide autonomy to the first operator, as both hands are available to control surgical instruments. This would enable the surgeon to perform a "hybrid" robot-assisted surgical procedure, maintaining well-defined roles between the surgeon and the robot.

Recently, in order to eliminate the burden imposed by the need of wearing special purpose glasses, a second version of the system has been designed and is currently being tested. This version uses Microsoft Kinect 2.0 sensor, which has higher precision and greater computing power and therefore does not require special glasses for surgeons' recognition.[47] Preliminary results with this sensor are very encouraging. Additionally, the new device incorporates a smart voice recognition system, that greatly enhances the man-machine interface, and requires a much simpler and faster calibration phase.

2) Tool under robotic control

Most research teams developed robotic holders for the endoscope, as a natural evolution of static, hydraulic or pneumatic camera-holding arms used to provide rigid fixation of the framing. Some other teams created robotic holders for: drills,[32] other endoscopic systems,[28,29,46] an active bending endoscope with a spring backbone.[36] Schneider et al[38] developed robotic manipulators for instruments and/or endoscope.

We aimed at developing a robotic endoscope holder, as we believe this is the priority in complex endoscopic skull base surgery: once the “hectic” phase of the approach has been performed, the endoscope might stay in a fairly limited position for a relatively long time, while the lesion is dealt with; this is when a robotic holder might give a true advantage, providing a steady view, together with minor adjustments that are intuitively made by the main surgeon. The team can then concentrate on more difficult and complex tasks.

3) Force feedback

One of the common issues with the use of surgical robots is the lack of force sensitivity and/or haptic feedback. New solutions are being proposed in other surgical fields in which the same issue is faced, e.g. orthopedic robot-assisted knee arthroplasty.[48] Some of the prototypes are equipped with a force sensor, the equivalent of a proprioceptive sensory receptor organ in the human body. The role of this technology, thanks to its transducer, is to measure the force affecting one of its faces by the evaluation of the minimal deformations of its mechanical structure due to the force it is subjected to. On the other hand, a calculator is supposed to elaborate the information received from the transducer and to calculate the total force acting on the robotic arm, by analyzing each of its components (X, Y, Z). The A73[28,29,46], the prototype by Xia et al.,[32] the "Hybrid" by Trevillot et al.[37] and the FREE by Chan et al.[41] were equipped with this technology. This feature is often used to guarantee a basic safety standard for the surgical procedure, thanks to a prefixed force threshold. The latest generation of force sensors based on state-of-the-art technologies are currently being designed and tested to enhance robotic surgery standards.[49]

In our prototype the force sensor was essential to develop many crucial features of BEAR, including fulcrum-centered motion, which was created thinking at the nostrils as a fulcrum, which should not be forced over a set value. In this setting, once the camera has been positioned, its movement has only three degrees of freedom: two rotations centered on the insertion point (move up and down; move right and left) to adjust framing, and the translational movement concordant with the length of the endoscope (move backwards-forwards) to choose the depth of the image.

4) Safety features

Absolute safety for the patient is always the first goal to achieve before any in vivo application. Even in the more widespread laparoscopic robotic surgery, only a few retrospective studies about robotic procedure-related preventable complications have been published, due to their recent utilization.[50] Different safety systems have been implemented in order to avoid accidental injuries to neurovascular structures, based on the type of interface, force feedback availability, and ergonomics. The voice controlled holder Aesop[27,45] allows the user to save up to three different positions in the nasal cavity and then, with a simple vocal command, to automatically go back to one of those following safe, recorded trajectories; moreover, it can be shut off by the vocal command "stop" or manually (in case of emergency).

The SP Robotic System[40] was developed with a tactile feedback system that increases the resistance on its joystick in case of contact or friction with anatomical structures. To compensate the lack of haptic feedback, "Hybrid"[37] and FREE[41] are shut down when a security force threshold is exceeded. On the other hand, Strauss' robotic holder[30,31], although lacking dedicated safety features, is designed so that the endoscope can be easily unfastened from the arm, switching to a traditional operation in case of emergency. A73[28,29,46] is interconnected with a redundant navigation system set on the patient's CT scan data for both telemanipulated and fully automated maneuvers and includes a ''loss of control'' function, which can shut down any robotic action if needed. A similar navigation system also equips Tx40 [33,34,51] and the robotic drilling prototype by Xia et al.,[32] in which some specific zones on the patient's CT scan are indicated as "safe", "boundary" or "forbidden" based on the risk of damage. Passing from a safe to a forbidden zone the resistance offered by the robotic arm increases. Navigation systems seem to be the most effective in increasing surgical accuracy and decreasing intraoperative and postoperative complications.[52-58]

In BEAR, the safety planning was developed as a first phase in view of a future clinical application. Aim of the "CarefulMovement" program is to allow only those movements that are in no way harmful: this means that the maximum value allowed should be around a few Newton. On the other hand, it was evident at the beginning of our tests that this value should not be too low, as the arm would have a high risk of unjustified stops due to the "ground noise" perceived by the force sensor and to the forces generated by accelerations of the arm itself. Trevillot *et al*[37] defined the ideal forces between 20 N (normal friction forces) and 40 N so as not to injure vital structures.

5) Set-up and operative times

Since all prototypes are described in a laboratory setting, their application appears to require a prolonged time compared with the traditional technique, particularly the pre-operative set-up time, except Strauss' prototype,[30,31] and Chan's prototype,[41] whose average set-up time was of a few minutes. The operative time might decrease as the user becomes acquainted with the robotic system, but significant data are still lacking: only a few articles present time measurements of predefined tasks in a preclinical setting.[30,41] Potentially BEAR has a really limited set-up time, as the glasses need to be recognized to start controlling the robot.

6) Other possible issues

Each laboratory-stage prototype needs many refinements before passing the preclinical stage (Table 1). Some essential features are still lacking in the majority of the analyzed robotic systems, the main one being the difficulty in quickly and effectively facing surgical complications[59] and emergency situations, e.g. a massive bleeding from major vessels.[60,61] Ergonomics is a major issue for prototypes adapted from pre-existing ones[27,36,45]. Other issues include excessive force[26,28] or inaccuracy[32] by the robot. Possible difficulties to recognize the vocal command in Nathan's Aesop robotic holder[27,45]may represent a critical issue to its utilization. Finally, all described robotic systems have been deemed too cumbersome for the operating room. Exceptions to this are the "Tentacle like" by Schneider et al.[38,39]and the FREE holder by Chan.[41] Most authors indicate the large dimensions as a shortcoming to improve upon in the further steps of their projects, perhaps using different technologies and dedicated materials. As BEAR has been developed from an industrial manipulator, it shares with other prototypes the limitations of ergonomics, relatively large dimension, and excessive force.

The potential of a hybrid solution, limits of BEAR and future perspectives

Initial reports are available on the advantages of advanced pneumatic holders for transsphenoidal surgery[62] and of endoscope robotic holders for ventricular surgery[63-66] and minimal access neurosurgery.[67] Nonetheless, it has been recently documented that most neurosurgeons seldom use endoscope holders and perceive the available ones as suboptimal, due to different limits, including crude movements, downward drift, loss of depth perception, lack of flexibility, iatrogenic injury, cost, and bulky construction.[68]

The most common shortcomings that inhibit also the clinical application of robotic prototypes are: lack of force or haptic feedback, excessive dimensions compared to the operative space, inadequate safety systems and expected long surgical times. To be really useful, a prototype should therefore be as light and small as possible; its use should enhance surgeon's abilities and save time; multiple, reliable safety systems should be implemented.

We believe that robotics in ESBS can provide an advantage addressing traditional endoscopic technique shortcomings, such as fine tremors and fatigue due to long operative times.[4,5] Based on the results of our systematic review of the literature, we deem that the best surgical outcome could be achieved by performing a "hybrid" procedure, which is conceptually dissimilar from a purely robotic surgery solution: the robotic system holds the endoscope, remaining entirely dependent on the surgeon, with a high safety standard, thanks to force feedback and navigation-based safety systems. Such a robotic holder might be applied to other endoscopic settings in neurosurgery.

As BEAR was built on an industrial manipulator, it is limited by its bulkiness; furthermore, during its testing other limitations became evident (i.e. suboptimal joint movements and excessive inertia). It was therefore not tested in a cadaver setting, as a smaller and more agile robot is needed to foresee a clinical application. Nonetheless, even with its limitation, we believe BEAR proves that available technology makes a hybrid solution possible in the near future and that this might have various advantages, including:

1. relatively easy set-up and limited cost, when compared with pure robotic solutions;

2. the robot is in charge of a relatively simple task, provides an advantage in terms of stability of the image and absence of fatigue, and can be relatively easily controlled;

3. the main surgeon remains in charge of the whole operation: to this account, the solution of a head-controlled robot seems appealing, as it appears of intuitive use, but easier solutions (e.g. foot-controlled joystick) might sooner become available.

BEAR therefore proves that a hybrid solution might soon be feasible and its application to endoscopic skull base surgery would provide an immediate benefit during tumor/lesion removal in complex cases with long operating times, confined working space and need of steady visualization.

Limits of a hybrid solution are the lack of robotic help in handling surgical instrumentation: the surgeon remains in charge of the difficult part of the operation. At present, though a final vision includes a pure robotic solution also in endoscopic endonasal skull base surgery, this seems relatively far, especially in an era of surgical instrumentation that still needs to be optimized for endoscopic skull base surgery itself.

Conclusions

Many new robotic systems prototypes dedicated to endoscopic paranasal sinuses and skull base surgery have been conceived for a minimally invasive transnasal approach to the target, highlighting the difference with the currently available robotic systems, but their application seems at the moment still prevented by excessive dimensions, inadequate safety systems and surgical time prolongation.

Robot-assistance will certainly play an important role in the future of skull base surgery, as long as surgeons abilities and efficacy are incremented, safety standards are respected and surgical time is not significantly prolonged. To achieve these results, a multidisciplinary collaboration is required. We foresee in the near future the clinical application of “hybrid” robot-assisted endoscopic skull base surgery.

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Figure legends

Figure 1. PRISMA 2009 Flow Diagram **of the review process**

Twenty papers, describing 11 different prototypes dedicated to endoscopic skull base surgery (ESBS) were included in the review.

Figure 2. University of Brescia Advanced Robotic Laboratory set-up

Laboratory set-up: both joystick (blue arrow) and marked glasses (yellow arrow) are on the table; the endoscope is held by BEAR (black arrow) and positioned inside SIMONT left nasal cavity; Kinect is positioned so as to optimize the user's head visualization (red arrow).

Figure 3. BEAR (Brescia Endoscope Assistant Robotic holder) system

BEAR system in all its components. Control of the robotic holder can be performed either via joystick or marked glasses.

Video legends

Video 1. "Fulcrum centred" motion

This video shows the conical rotational movement around a pivot point made possible by the *DelicateInsider* program, which also allows a real time change of the point of rotation, represented in the OR by the patient's nostril

Video 2. "Leading by nose"

The "Leading by nose" program allows the surgeon to intuitively change the endoscope position, for example by grabbing it and placing it in contact with the nostril before an endonasal robotic navigation is commenced.

Video 3. Joystick endonasal navigation

This video shows the robotic holder positioning the endoscope in the nostril; using a joystick, the endoscope, which is here simulated by a green tube, is then navigated inside the SIMONT nasal cavity up to the right sphenoid ostium. The endoscope is then removed by the BEAR, which is, in this case, joystick controlled.

Video 4. Tracking marked glasses

This video shows how the robot BEAR functions with the program *TrackingMarkedGlasses.* Once the position of the user's head is registered by Kinect thanks to the marked glasses, the surgeon can see his specular image as contained in a rectangular box. When the surgeon's head exits the box right or left, up or down, or moves closer or further away from Kinect, BEAR moves the endoscope accordingly. If one of the two light markers is accidentally lost, BEAR automatically stops.

Table legend

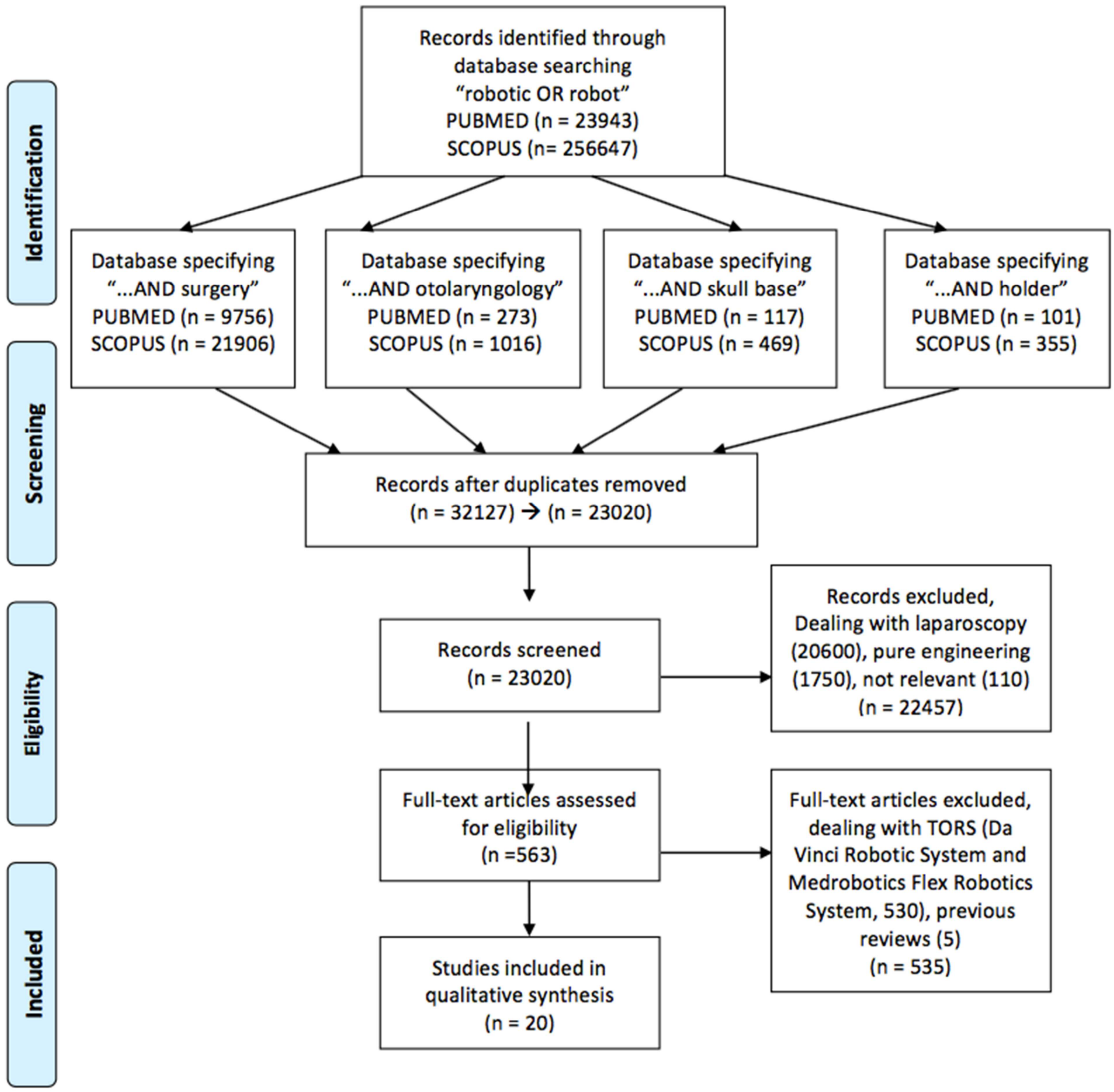
Table 1. Summary of the analyzed features for each described prototype.

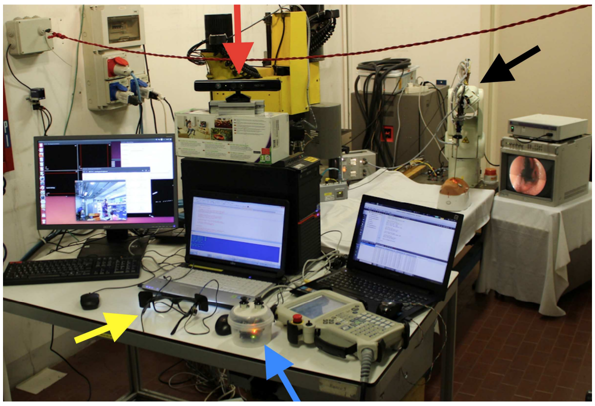
Abbreviations: TM: tele-manipulation; CM: co-manipulation; EM: Emergency Management; NR: Not Reported

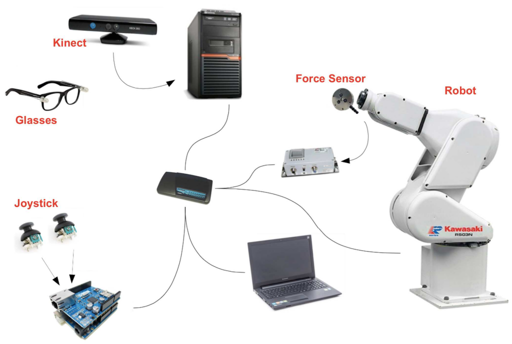
Authors, year of publication	ESBS Robotic Prototype Name	INTERFACE	TOOL	FORCE FEEDBACK	SAFETY FEATURES	SET UP TIME / OPERATING TIME	LIMITATIONS
Nimsky C, et al. 2004[26]	**EVO1**	TM: joystick	Endoscope holder	None	NR	Long / Prolonged	Excessive force, risk of injuries, EM
Wurm J, et al. 2005[28-29]	**A73**	Fully automated maneuvers; TM: joystick	Holder for Neuroptik T30	Yes	3D Navigation system and “Loss of control” mode	Long / Prolonged	EM
Nathan CO, et al. 2006[27]	**AESOP**	TM: voice control	Endoscope holder	None	Three saved positions; vocal command “stop” or manual shut off	Long / Normal	Voice recognition issues, EM
Strauss G, et al. 2007[30-31]	None	TM: joystick	Endoscope holder	None	Easy switch to manual endoscopy	Short (2minutes) / Prolonged	NR
Xia T, et al. 2008[32]	None	CM	Endoscope or drill holder	Yes	Navigation system Safe zone/ Boundary/ Forbidden zones	Long / Unknown	Inaccuracy
Eichhorn KW, et al. 2011[33-35]	**Tx40**	Autonomous tracking movements; TM: joystick	Endoscope holder	None	Navigation system	Unknown / Prolonged	EM
Hyun-Soo Yoon SMO, et al. 2011[36]	None	TM: double joystick	Active bending spring backbone endoscope	None	NR	Long / Prolonged	EM, ergonomics studied for FESS
Trevillot V, et al. 2013[37]	**HYBRID**	CM	Endoscope holder	Yes	Force threshold	Long / Unknown	EM
Schneider JS, et al. 2013[38]	**TENTACLE-LIKE**	TM: joystick	Instruments manipulator	NR	NR	Unknown / Normal	EM
Cabuk B, et al. 2015[40]	**SP ROBOTIC SYSTEM**	TM: joystick	Endoscope holder	None	Haptic feedback in case of contact	Normal / Prolonged	EM
Chan JY, et al. 2016[41]	**FREE**	TM: inertial measurement unit and vocal control	Endoscope holder	Yes	Force threshold, vocal command	Short (<3minutes) / Normal (<7minutes for maxillary antrostomy)	Complex control system

Table 1. Summary of the analyzed features for each described prototype.

Abbreviations: TM: tele-manipulation; CM: co-manipulation; EM: Emergency Management; NR: Not Reported


Identification
Screening
Eligibility
Included
Records identified through database searching "robotic OR robot" PUBMED (n = 23943) SCOPUS (n= 256647)
Database specifying "...AND surgery" PUBMED (n = 9756) SCOPUS (n = 21906)
Database specifying "...AND otolaryngology" PUBMED (n = 273) SCOPUS (n = 1016)
Database specifying "...AND skull base" PUBMED (n = 117) SCOPUS (n = 469)
Database specifying "...AND holder" PUBMED (n = 101) SCOPUS (n = 355)
Records after duplicates removed (n = 32127) → (n = 23020)
Records screened (n = 23020)
Records excluded, Dealing with laparoscopy (20600), pure engineering (1750), not relevant (110) (n = 22457)
Full-text articles assessed for eligibility (n =563)
Full-text articles excluded, dealing with TORS (Da Vinci Robotic System and Medrobotics Flex Robotics System, 530), previous reviews (5) (n = 535)
Studies included in qualitative synthesis (n = 20)




Kinect
Glasses
Force Sensor
Robot
Joystick
Kawasaki

Highlights

- The results of a systematic literature review on robotics for endoscopic transnasal skull base surgery are reported
- A novel prototype, based on the concept of hybrid robotic surgery, is presented in its development
- The advantages and disadvantages of all described prototyped are thoroughly discussed
- The possible advantages of the hybrid solution are presented together with a view of the near future for robotics in skull base surgery